VOLUME 7

HYDROLOGY and WATER RESOURCES in ARIZONA and the SOUTHWEST

PROCEEDINGS OF THE 1977 MEETINGS OF THE
ARIZONA SECTION—
AMERICAN WATER RESOURCES ASSN.
AND THE
HYDROLOGY SECTION—
ARIZONA ACADEMY OF SCIENCE

APRIL 15-16, 1977, LAS VEGAS, NEVADA

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TABLE OF CONTENTS

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PREFACE

Volume 7 of Hydrology and Water Resources in Arizona and the Southwest is a compilation of the papers presented at the annual meeting of the Arizona Section of the American Water Resources Association. The 1977 meetings were held at the University of Nevada at Las Vegas, April 15-16, 1977. As in previous years, the meetings were held jointly with the Hydrology Section of the Arizona-Nevada Academy of Science.

The publication of this volume of papers and the annual meetings help accomplish the American Water Resources Association objectives of:

(a) providing a common forum for engineers, hydrologists, legislators, lawyers, planners, and physical, biological, and social scientists concerned with water resources;

(b) advancing water resources research, planning, development, management, and education;

(c) collecting, organizing, and disseminating ideas and information concerning all aspects of water resources.

Anyone in the region interested in being affiliated with this endeavor may contact the Secretary-Treasurer for information on Section membership.

The papers constituting this proceedings of the 1977 meeting reflect a broad range of topics of interest to hydrologists, planners, politicians, engineers, and citizens alike. Included are papers on water and reclamation of surfaced mined areas, sedimentation and water quality, the influences of land management practices on water, modeling of hydrologic events, and transpiration of water by phreatophytes. The author affiliation is indicated on each paper.

The officers of the Arizona Section of the American Water Resources Association wish to express their deepest thanks to Dr. William H. Allen of the Arizona State Land Department, who was responsible for setting up the program of the joint meetings. The Arizona Water Resources Research Center, located on the University of Arizona campus, and Sol Resnick, Director, have been very supportive of this publication and the Arizona Section of AWRA, and their assistance is much appreciated.

Linda M. White, Editor
Tucson, Arizona

OFFICERS OF THE ARIZONA SECTION, AMERICAN WATER RESOURCES ASSOCIATION

1977 - 1978

PRESIDENT'S REPORT

The Arizona Section of AWRA continued to be a forum for persons concerned with the water resources of the Southwestern United States. The proceedings of the 1976 annual meeting contained 44 papers (most to date) and were available just 2½ months after the meeting. Twenty-nine individuals joined the section. A student AWRA chapter formed in the 1975-76 school year continued an active program in the 1976-77 school year. To encourage student participation in the annual meeting, the section joined with the Hydrology Section of the Arizona Academy to award $40.00 to students with outstanding papers. Two student award papers were selected in the 1977 meeting, and are designated in this volume. For these activities, the Arizona Section was designated as one of two outstanding state sections in 1977 by the National organization.

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Donald L. Chery, Jr.
President Arizona Section
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HYDROLOGY AND WATER RESOURCES IN ARIZONA AND THE SOUTHWEST, VOLUME 7, p. 1-6.

Proceedings of the 1977 meetings of the Arizona Section of the American Water Resources Association and the Hydrology Section of the Arizona Academy of Science, held in Las Vegas, Nevada, April 15-16.

A WATER SUPPLY DATA BASE

by

J. F. Nunamaker, David E. Pingry and Rex Riley

ABSTRACT

This paper describes a water supply data base being developed for the Colorado River Basin States by the University of Arizona under contract with the Electric Power Research Institute, Inc. This data base is a guide to existing natural, technical, economic, and legal water data and water data agencies in the states of Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming.

INTRODUCTION

Water is one of the most studied and measured resources in the history of mankind. The amount of data available concerning water resources in the U.S. is enormous. Scores of private and public organizations collect and make available water resources information. In spite of the vast amount of time and money spent in accumulating water data it is still extremely difficult to quickly answer a specific question of the form:

> "Can water of a particular quantity and quality be delivered to a particular location for a specified time at an acceptable cost for the proposed use?"

The purpose the the data base design presented in this paper is to quickly and cheaply direct users to the sources of relevant information and data. The following sections describe the nature of existing water supply information and data, the design of the water supply data base structure and the implementation of that design.

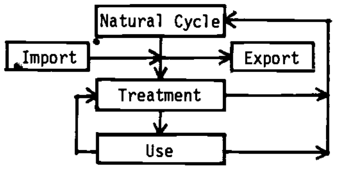
WATER DATA STRUCTURE

The data necessary to provide an answer to the question posed above is extremely complex. An indication of this complexity can be illustrated by reviewing the process of supplying water. The process can be divided into five major sub-processes:

1. Remove water from natural water cycle
2. Alter water quality to meet damand process needs (including natural cycle for return water)
3. Store water
4. Transport water (including importing into and exporting from the region)
5. Return water to natural water cycle

For any single application of this process not all of these sub-processes need be used. For example, before the enactment of water quality laws, water was often removed from the natural cycle, used and returned with no treatment at all. Figure 1 illustrates the possible combination of sub-processes which might exist.

It is quickly evident that collecting some numbers on the quantities and qualities of water available at particular points in the water cycle alone does not answer the question posed above. To answer this question requires information not only on the location, quality and quantity of natural sources of supply, but also on factors which affect the delivery of the water to the point of use.



→ Indicates storage and/or transportation of water

Figure 1 Regional Water Delivery Process

The authors are respectively Professor of Management Information Systems and Associate Professor of Economics at the University of Arizona, Tucson Arizona and Project Manager, Electric Power Research Institute, Inc., Palo Alto, California.

The factors which affect or constrain the supply of water can be divided into four major categories:

1. Natural The natural supply limitation for a region is all the known quantities of water in the natural cycle. Three broad sub-categories would include surface water, groundwater and rainfall.
2. Technical The technical limitations on supply for a region impinge on the subprocess of water delivery. Certain material supplies may be unusable because of lack of implemented technologies in the areas of extraction from the natural cycle, treatment, storage and transportation. In addition, these constraints may limit importation and recycling possibilities.
3. Economic The economic limitations further restrict the delivery of water. Water must be delivered at a cost low enough to make its proposed use economically feasible. Many technically possible alternatives may be ruled out by economic considerations.
4. Legal There are a large number of constraints on water delivery which are not directly associated with the level of technology and the cost of delivery. The constraints are imposed through the political process and include interstate compacts, laws (federal, state and local), agency regulations (federal, state and local) and judicial rulings. In addition to these formal restructions there are a number of supply possibilities which are politically unfeasible. That is, the public knowledge that one of these supply alternatives would be used, in all probability, will stimulate a legal response, either a court challenge or legislative action.

In light of the restrictions outlined above, two important observations can be made about the type of data base needed to answer water supply questions.

1. A useful data base must account for all of the restrictions. Data on the natural supply without information on the other three categories is useless.
2. A useful data base must include more than numbers. It is not possible to quantitatively represent many of the restrictions outlined above.

The implication of these observations is that a useful water data base, that is one which assists the researcher in answering the proposed question, can not be constructed by simply extracting the "100 most important water numbers" from existing sources and organizing them into a new format. Information at that level is of little use. On the other hand, existing data sources are fragmented, requiring a user interested in the water supply situtation in a particular region to seek out sources which have information on all of the natural, technical, economic and legal constraints which are relevant. At the federal level, for example, the user would have to be familiar with 52 computerized data bases.

WATER DATA BASE DESIGN

HOST/SUPPORT DATA BASE DESIGN

The logical question which arises, in light of the discussion above, is "What does a useful data base contain?" As inticated before, the amount of information accumulated on water is enormous. It is in the form of computer accessible data bases, books, articles, research reports, agency reports, files, company equipment descriptions, legal documents, etc. Collectively this data represents the "state of knowledge" in the water area. The problem is that is never "collected." The reasons that this has never happened are obvious. The cost of assembling and organizing all of this data in some coherent manner would be extremely high. In addition, the cost of maintaining such a data base would be extreme. The Benefit-Cost ratio on such a project would be highly unfavorable.

Of course, the solution lies somewhere between the extreme of "100 important numbers" and all of the relevant data. Our approach is to create, in effect, a combination of data and a data dictionary. The strategy is to build a host data base with a structure of the form outlined in Figure 2. The host data base includes pointers to support data bases maintained by other organizations. The host water supply data base includes a central data description of all elements contained in the host data base as well as description of all data elements from the support data bases.

The necessity of the Host/Support approach is obvious when one examines some of the existing (support) data bases. For example, the WATSTORE Data Base maintained by the U.S. Geological Survey consists of 43,000 measurement sites with a number of values being recorded daily. The task of updating and maintaining such a large data base is tremendous. It would be costly to duplicate the updating and maintainance of support data bases of such magnitude. Instead, descriptions of the support data bases are maintained in the host data base. Certain data fields from a support data base which are used frequently or determined to be very valuable are included in the host data base.

The entries in the host data base consist of the following:

1. Number (data values) from other data bases
2. Descriptions of data elements in other data bases
3. Appropriate key works from other data bases
4. Abstracts of articles and research reports
5. References to abstracts of articles and research reports
6. References to laws, regulations and judicial rulings
7. Summaries of laws, regulations and judicial rulings
8. Copies of laws, abstracts and judicial rulings
9. Lists of federal, state and local agencies

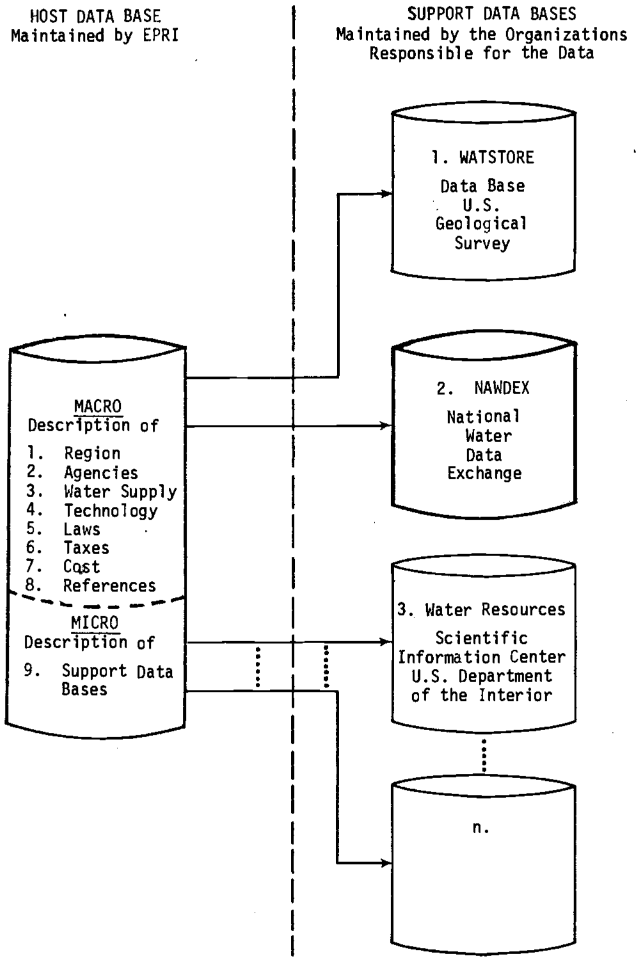


Figure 2 Methodology for the Development of a Water Supply Data Base System

MACRO/MICRO DATA BASE DESIGN

The host water supply data base is a logical data base structure consisting of two physical data bases: Macro data base and Micro data base. The Macro data base is a bibliographic data base with references and sources of information. The micro data base contains detailed descriptions of support data bases such as NAWDEX and WATSTORE. In addition, detailed structures of water data agencies are maintained.

Macro data base. The initial inquiries will be made using the macro data base. Although the macro data base is bibliographic in structure, its "entries" include regions, organizations, laws and data bases as well as the usual bibliographic entries. The queries in this system are made with keywords in the usual manner.

The logical structure of the Macro Water Supply Data Base is illustrated in Figure 3. The proposed scheme of the data base provides maximum flexibility in terms of taking alternative views of the data. A large number of specific queries can be formulated based on the suggested flexible record structure. Examples of the type of queries users will be able to ask are:

1. Which government agencies are responsible in a specific region?
2. Which laws are relevant in a specific region for a given technology?
3. Which technology and costs are relevant for specific regions?

4. Which papers and references are relevant to a specific technology or region?
5. Which supporting data bases are relevant to a specific region?
6. What are the relevant taxes, laws and costs for a specific technology in a given region?
7. Are there any data bases on cost of delivery of water by specific technology?

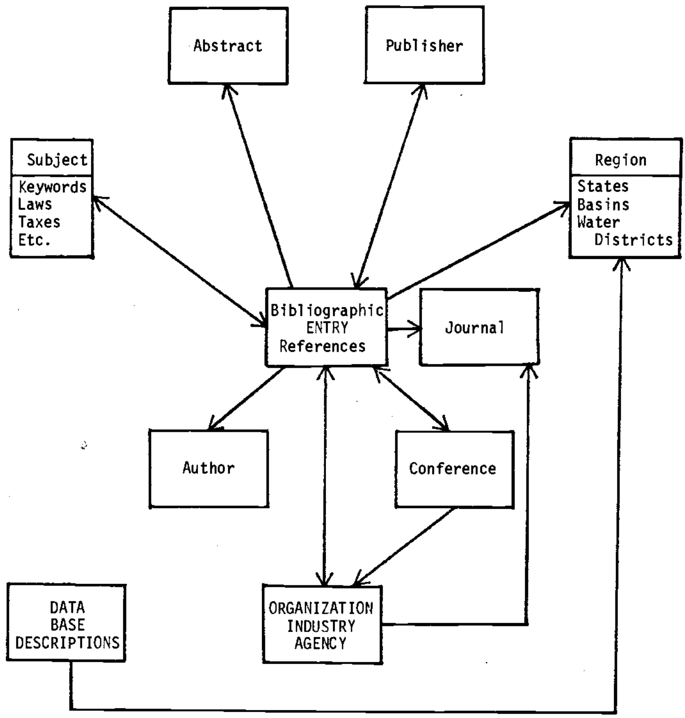


Figure 3 Water Supply Data Base: MACRO STRUCTURE

Micro data base. The other major portion of the host data base is the micro data base. This is probably the most unique feature of the data base design. The micro data base includes detailed information on water data agencies and water data bases. Use is made of a computer language called PSL (Problem Statement Language) and an associated software package called PSA (Problem Statement Analyzer). The combination of these packages (PSA/PSA) facilitates the common description of water agencies and water data bases, and allows for the analysis of their structures and interactions. The PSA system produces a number of "reports" which give the user different views of the interactions.

Users are directed from the macro data base to the micro data base. Data bases and agencies are briefly described in the macro data base. Pointers in the macro data base allow the user to obtain the more detailed information from the micro data base.

WATER DATA BASE IMPLEMENTATION

It was clear early in the design of this data base that anyone interested in the water supply situation in a specific region must have a good understanding of how the various governmental agencies interact to produce water policy. It was felt that one of the most useful services that could be provided would be to produce a guide through the maze of governmental agencies at all levels. To this end, a great deal of effort was expended in collecting information on the organization responsibilities and jurisdictions of the various federal, regional and state agencies. This information is contained in the micro data base. The PSL/PSA software allows the user to trace the links between the various organizations.

In addition, detailed information on water data bases was obtained. This includes a description of the data base contents down to the parameter level. The data bases are also linked to each other and the appropriate water agencies. This feature is particularly useful since a great deal of the data is duplicated in different data bases. The user, with the appropriate information, is in a position to select the data base with the cheapest or most convenient access.

THE REGION OF IMPLEMENTATION

The region defined by the states containing the Colorado River Basin was selected for implementation of the host data base concept. This region includes the states of Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming and is unique in the sense that it contains the full range of water quantity and quality problems.

These states collectively have virtually every major energy-related water problem. The basic unifying feature of these states is the Colorado River Basin. The allocation of this river among the states and among the alternative uses within the states is a continuing and controversial process. The alternative uses are numerous and include domestic oncsumption, industrial consumption, irrigated agriculture, metal mining, coal mining, oil shale processing and power production. Many of these alternative uses are directly energy related. Others are indirectly energy-related. Copper, for example, palys a major role in the energy industry, although it is not an alternative energy source.

The trade-offs associated with water use in the Colorado River Basin are numerous and complex. The area is a major energy and water supplier. In addition, it is a major consumer of energy and water, particularly in the Los Angeles, San Francisco, Denver and Phoenix areas. The application of the Host Water Supply Data base for this region should test power of the data base structure as well as be directly useful for current issues.

To give an overview of data available in the Colorado River Basin states, it is useful to catagorize the data elements and give some summary statistics. In Table 1 the agencies described in the Water Supply Data Base are classified by level of geographic coverage. In addition, the associated computerized data bases are listed along with the data classification (Natural, Technical, Economic, Legal). The regional catagory is used for any organization which overlaps two or more states. This catagory includes the regional offices of federal agencies.

The preliminary summary statistics themselves are impressive. There are 31 U.S. agencies and 2 independent organizations with access to 72 computerized data bases which cover all four data catagories. The most completely covered catagory is natural data group. There are 32 regional and 118 state organizations which have data in the Colorado River Basin States. In Arizona, for example, there are 24 organizations and 10 computerized data bases. This does not include the U.S. data base with Arizona data. For similar information on the other states see Table 1.

Some comment should be made about the character of the data. The natural data tends for the most part to be numbers, that is, measurements of flow, quality parameters, depth to water, etc. The most comprehensive directory of this data is the new NAWDEX system operated by the Geological Survey. In fact, most of the water quality data available is developed through USGS programs. There are also various documents such as the Geological Survey Water Supply Papers which discuss in great detail the various groundwater aquifers. The technical and economic data is mainly held in bibliographic form. References to various studies which cover water supply technologies both from a technical and economic standpoint of view are included in a number of computerized data bases. Some numbers are directly available such as the economic projections included in the Water Resources Council Natural Assessment. The legal data available in the limit is all of the laws and court decisions relating ot those laws. However, there are legal data bases as well as various summary information available in report form and data bases which are useful to the legal layman.

Table 1 Summary Table (Preliminary)

Agency Classification	Data Catagory									
	Total		Natural		Technical		Economic		Legal	
	Data Bases	Agencies	Data Bases	Agencies	Data Bases	Agencies	Data Bases	Agencies	Data Bases	Agencies
Federal	52	31	50	9	22	5	5	4	7	6
Non-Federal U.S.	22	2	21	2	11	2	7	2	4	2
Regional	2	32	2	2	0	0	0	0	0	0
State Totals	41	11B	36	30	0	0	1	1	5	5
Arizona	10	24	10	9	0	0	0	0	0	0
California	14	34	13	9	0	0	0	0	1	1
Colorado	2	16	2	2	0	0	0	0	0	0
Nevada	7	12	6	5	0	0	0	0	1	1
New Mexico	3	14	3	3	0	0	1	1	1	1
Utah	2	11	0	0	0	0	0	0	1	1
Wyoming	3	7	2	2	0	0	0	0	1	1

TOTAL AGENCIES 2B3
TOTAL DATA BASES 117

NOTE: The number of agencies and data bases in the four data categories does not always equal the total number of agencies or data bases because some agencies have more than one data base and some data bases contain several data catagories.

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ARIZONA WATER POLICY: CHANGING DECISION AGENDAS AND POLITICAL STYLES

by

Hanna J. Cortner and Mary P. Berry

INTRODUCTION

This paper argues that it is time to change the conventional style of water politics in Arizona. New political demands and pressures, we posit, require that state government develop the decision-making capabilities for greater involvement in water policy formulation, implementation and coordination. Yet, as this paper demonstrates, research that has focused upon the politics of water policy-making in Arizona reveals a political style in which federal, private and local interests dominate, while the state's fragmented administrative organizations play a limited and subordinate role.

REOCCURRING THEMES IN ARIZONA WATER POLITICS

Several major themes reoccur throughout the literature which discusses the political dimensions of water policy-making in Arizona. Taken together, these themes emphasize that Arizona has yet to develop fully the decision-making capabilities that are required if state government is to play an active and innovative role in water policy.

INFLUENCE OF DISTRIBUTIVE POLITICS

Many of the characteristics and trends of Arizona water politics are a reflection of the distributive style of political decision-making that typically characterizes decision-making within the seven states (Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming) of the Colorado River Basin (Mann 1975a, 1975b). In distributive politics, water projects are locally initiated and defined, but federal financing is sought. Conflicts over water allocations and benefits are settled through coalition building and bargaining. Distributive politics creates a political climate in which everyone appears to win a fair share of the federal largess and to secure the mutual benefits of federally sponsored water development projects (Mann, 1975a, 1975b; Ingram, 1972).

The basin states have been generally supportive of the rewards that distributive politics promise. Nevertheless, state participation in distributive politics has imposed considerable, if seldom recognized, costs on the basin (Ingram, 1974). As the basin has committed itself to federal reclamation and water development projects, other alternatives for achieving the goals of regional economic growth have not been fully studied or debated (National Research Council, 1968). The individual states have incurred significant costs in that they have forfeited the development of independent decision-making and planning capabilities (Ingram, 1974). Another considerable cost is the increase in federal authority over the allocation and utilization of state water resources that have been developed under federal reclamation projects (Hundley, 1975). The water policies pursued by the basin have been piecemeal and inconsistent; there has been no overall plan of development. As a result, many of the critical decisions concerning the long-range environmental and economic future of the basin have been postponed or never sufficiently debated (Ingram, 1974).

ADMINISTRATIVE FRAGMENTATION

State and local administrative arrangements for water decision-making are fragmented. At the state level, the growth in Arizona water agencies has been remarkable,

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The authors are research associate and research assistant, respectively, in the School of Renewable Natural Resources, University of Arizona.

increasing, for example, from four in 1913 to fourteen in 1970 (Null, 1970, p. 115). Today, several agencies including the Arizona Water Commission, State Land Department, Arizona Corporation Commission, Water Quality Control Council, Department of Health Services, and Arizona Power Authority, share responsibility for water decision-making. State water agencies often have a narrow legal mandate to concentrate on specific management tasks, and further, clientele groups exert considerable influence in agency decision-making (Mann, 1963; Null, 1970). Few mechanisms exist to coordinate agency programs and plans with those agencies performing other important natural resource management functions, or to coordinate state activities with activities at the federal or local levels. While efforts have frequently been made to reorganize the decentralized and disjointed administrative arrangements in water and related natural resource areas (Cook, 1968; Null, 1970), there has been strong resistance to the various reorganization proposals.

At the local level, a multiplicity of organizations--city and county departments, irrigation districts, soil and water conservation districts, and water users' associations--exists. Jurisdictions overlap, and conflicts over what consitutes proper management policies proliferate (Hughes, 1971; Straayer, 1970).

DOMINANCE OF THE MAJOR WATER USERS

The state's major water users' associations--composed largely of agricultural interests such as cotton growers, farmers and ranchers--have perhaps been more influential participants in water policy than the state itself (Thomas, 1972; Null, 1970). For example, the Salt River Project (SRP) which originated as a cooperative effort by agrarian interests in the Phoenix area to secure the benefits of water storage and low cost irrigation water derived from federal reclamation projects, is the most influential association of water users. By skillfully cultivating its relations with the U.S. Bureau of Reclamation and adapting its organizational structure to the increasing urbanization of the Phoenix area, the SRP has managed to establish and protect its hegemony in water policy and its interest in obtaining a low cost water supply (Smith, 1972).

In addition to local water users' associations such as the SRP, several private interest groups--miners, bankers, and particularly the agricultural groups most closely associated with local water users' associations--are also important decision-makers on water policy issues. These groups maximize their influence through a process of cooperation and coalition building among themselves and through a network of cooperation with and representation in public agencies and the legislature. In addition to frequent informal consultations with administrators and legislators, these interest groups often have official positions within public agencies through statutory requirements for group representation (Eiselein, 1969; Null, 1970). The reciprocal relationships between the state and these powerful interests have frequently meant in the past that the state's definition of its interest in water reflects the positions favored and advanced by private groups (Thomas, 1972; Mann, 1963; Null, 1970).

WATER PROBLEM DEFINITION

There are two principal schools of thought concerning the nature of Arizona's water problem and the most appropriate policies to remedy the problem. One school of thought argues that if Arizona's economy and unique lifestyle are to be maintained and enhanced, additional water supplies are required. And, the Central Arizona Project (CAP) is perceived as a crucial component of state efforts to solve the water supply problem (Farris, 1966; Mehren, 1964; Steiner, 1977). This definition of the water problem as predominantly one of supply is the one most widely accepted by elected and appointed decision-makers and major water users. It also complements a basic premise of distributive politics which views investments to acquire new water supplies as the key to economic growth.

Another school of thought criticizes the popularly accepted definition of the state's water problems and questions the need for and feasibility of the CAP. Arguing that economic growth need not be restrained by admittedly scarce water supplies, the problem is defined as basically one of the most economic allocation. For example, it is argued that if water were reallocated from activities such as agriculture, where the net income per unit of water used is very low, to activities such as manufacturing, where net income is high, Arizona could live and prosper within its current water budget (Young and Martin, 1967; Kelso et al., 1973). The CAP is criticized because of doubt whether it can generate sufficient economic benefits to pay construction and operating costs (Young and Martin, 1967). In addition, this school of thought argues, although a high rate of economic growth could be maintained if demand reduction policies were pursued, the focus on supply has largely overshadowed efforts to formulate and implement efficient and conservation-oriented water policies (Finster, 1970; Bruner, 1971).

INACTION ON GROUNDWATER

Although Arizona approved a Groundwater Code in 1948, it has proved so inadequate that in reality no effective management structure for groundwater exists (Clark, 1974). For instance, a major code provision authorizes the State Land Commissioner to designate critical groundwater areas in which no new irrigation wells may be drilled. This apparent restriction on groundwater withdrawal is weakened, however, because new wells for practically all other purposes, including stock watering, industrial use, transportation and domestic water supplies, are exempted. Court decisions have further weakened the code's provisions (Kelso, et al., 1973, p. 64).

In addition, Arizona's groundwater law is criticized because besides promoting maximum overdraft, present water users are not asked to assume their share of the costs that overdraft will incur in the future (McBride, 1972; Porter, 1972). Finally, the law is criticized because it fails to address adequately the problems surrounding the allocation and valuation of the groundwater resources withdrawn from aquifers that extend beneath state trust lands, Indian reservations, and federally controlled lands (Weatherspoon, 1975, Clark, 1974).

To correct these deficiencies, revisions of Arizona's groundwater law are repeatedly urged. Yet, despite the attention devoted to water law reform, actual accomplishments have been meager. In 1963 one observer asserted that "the decisions that should have been made in the 1940s in regard to groundwater still had not been made in the early 1960s" (Mann, 1963, p. 256). They still had not been made in the mid-1970s.

INCHOATE STATUS OF WATER PLANNING

Until recently, Arizona had little interest or capability in the area of water planning. Indeed, from 1929 until 1971 no agency of state government actively assumed responsibility for planning (Steiner, 1975, p. 1). Major state agencies, such as the State Land Department, depended upon clientele groups for the information required to perform regulatory functions (Null, 1970). Except in the area of watershed management, little integrated water research and planning occurred and what was done had only a slight impact upon resource management (Mann, 1963). While the state played a minimal role in planning, federal relationships with local water interests solidified. Subsumed in this federal-local policy system, the state's major function was to muster the political and financial support for the policy arrangements and projects initiated and administered by the federal government and local water users (Thomas, 1972).

Recent developments, however, indicate that the state is beginning to play a more active role in water resources planning. In 1971 the legislature expanded and reorganized the Interstate Stream Commission, restructuring it as the Arizona Water Commission (AWC). Although the State Land Department retained important responsibility for water rights administration, the AWC was provided with extensive planning authority. In addition to the planning studies conducted in relation to the CAP, the AWC has been active in the preparation of a state water plan. It has also made extensive use of the Title III planning grants that the 1965 Water Resources Planning Act makes available to states in order to improve planning capabilities (Ingram et al., 1973). Yet, while some progress is evident, state government as a whole has still not developed the organizational mechanisms for comprehensive and coordinated water planning and management.

THE TRADITIONAL POLITICAL STYLE IN PERSPECTIVE

The traditional style of water politics has resulted in limited state participation in water policy planning, administration and coordination. Local water users' associations and private interest groups have exerted considerable political clout, merging their interests in water development projects with that of the federal government and utilizing their influence over the fragmented and decentralized administrative structure of the state in order to gain public support for their private endeavors. Rather than initiate policy, the state's major role has been to support the policy initiatives of federal, local and private groups. Convinced that this subordinate role was in its best interest (Thomas, 1972), the state has neglected to build the administrative structure in which long-range comprehensive water planning and management, data collection, and policy coordination could occur. Problems go unattended, only to be acted upon when a crisis situation arises (Straayer, 1970). And, the legislature has been more willing to take policy action which will not alter the existing water arrangements than action, such as reorganization or revision of the groundwater code, which would require change and jeopardize the equilibrium which has been so carefully achieved and cultivated (Thomas, 1972). Many of the uncertainties that exist today concerning the scope of the water problem, and many of the legal complexities that surround groundwater management, are a direct result of the state's subordinate position in water policy-making.

NEW POLITICAL DEMANDS AND CONDITIONS

The traditional equilibrium between levels of government and major water interests is currently being challenged by new political demands and conditions. These new conditions make action on items long neglected by state government more imperative and add new problems and demands for action. Discussion of several of these new factors follows.

CONFLICTS AMONG TRADITIONAL WATER USERS

In distributive politics, interest groups reach a working solution through bargaining and compromise; every interest appears to be served and each seems to share in the benefits of the agreed-upon solution. The growing conflicts among traditional water users, however, threaten to disrupt the established political equilibrium. For instance, conflicts among agriculture, mining and municipalities have broken out as a result of legal suits testing what constitutes a reasonable use of water, how much water may be pumped, and where water may be used. In a 1976 suit brought by Farmer's Investment Company (FICO), the Arizona Supreme Court ruled that a mining interest was damaging FICO's interests by pumping water from retired farmland surrounding FICO's holdings to adjacent sites. This ruling placed the mine's water supply in jeopardy since many of the mine's wells provided water which was pumped to other locations. However, the court ruled that municipal interests could continue to pump water to distant sites under the 1970 *Jarvis I* ruling of the Arizona Supreme Court, which specifically allows Tucson to transfer water from retired farmlands. Mining interests in turn petitioned for an injunction preventing Tucson from exporting water from the Santa Cruz Valley, therefore threatening Tucson's water supply (Fleming, 1977). The three conflicting interests have recently reached a compromise which, while serving only as a temporary stopgap solution, does appear to recognize the need to develop statewide strategies for long-term water management. As water becomes more scarce and competition for it grows more intense, it can be predicted that similar and frequent disputes will further upset the status quo. The state will repeatedly be called upon to act as a mediating body in order to accommodate diverse and competing interests. Furthermore, the current body of water law, which will continue to encourage conflicts, requires extensive revision. And in this revision process, the state will need to play an active leadership role.

NEW ENTRANTS INTO THE DECISION-MAKING PROCESS

In addition to the increased potential of conflict among traditional participants, new participants--mainly environmental and citizen groups--have in recent years challenged traditional decision-making arrangements, demanding a greater voice in the policy-making process. These new entrants into the decision-making process are proposing that institutional mechanisms be created which will assure that citizens can express their preferences about water problems and solutions. They are also supportive of policies and procedures which can assure that the environmental impacts of large-scale water projects such as the CAP receive tough environmental scrutiny. Wanting more accountability from decision-makers, they have attacked the strong linkages between the state's principal water users and public agencies. Charges of potential conflicts of interest, for example, have been directed toward members of the Arizona Water Commission who may possibly benefit from the commission's CAP water allocations. As a result of these attacks, one member of the commission has disqualified himself from voting on the allocations (*Arizona Daily Star*, 1977). At the same time, the new entrants are requesting that their groups receive more representation on various water boards and commissions (Stribling, 1976).

Demands for a more open, accountable and environmentally responsive decision-making process, and for greater citizen participation in decision-making, require state sensitivity to citizen participation and environmental quality issues in the water policy arena.

INDIAN CLAIMS

Since the U.S. Supreme Court case of *Winters v. United States* in 1908, Arizona's Indian tribes have been allocated a portion of the surface waters flowing across reservation lands. In addition, Indian proprietary rights to groundwater can be inferred from a 1976 U.S. Supreme Court decision in *United States v. Cappeart* (Fleming, 1977). Basing their claims on these federal judicial precedents, Indian tribes have presented several complaints which have increasingly complicated state water policy.

While there are Indian claims on state water, the question of how much existing and new state water supplies the various tribes may actually claim is unsettled (Fleming, 1977). Several tribes have filed law suits in federal court asserting that other water users are using Indian water reserves, thus causing damage to Indian livelihoods and lands. If these suits are settled in favor of the tribes, there may need to be reallocation of existing and new water supplies in order to comply with the court's rulings. Central Arizona tribes have turned to Congress, trying to force the issue of Indian water rights into the open. For example, in April 1976, Massachusett's Senator Edward Kennedy introduced a bill providing for the purchase of 170,000 acres of Central Arizona farmland in order to assign the water rights to nearby tribes.

While acknowledging that the Indian trustee relationship to the federal government often precludes state action, states can do much to resolve many of the inadequacies and uncertainties in state water policy that relate to Indian claims and water rights. Failure of the state to become more involved will force the tribes to turn to Congress or the federal courts for redress of their grievances. As a result, there could be an enlargement of federal power accompanied by an unnecessary loss of state power.

RISING WATER COSTS

As water becomes more scarce and the expenditures for capital expansion increase, the costs of providing water will consequently rise. These rising costs are certain to generate much public concern. A dramatic example of the political impacts of rising water costs is the recent recall election in Tucson. The 1976 Tucson City Council was faced with the necessity of raising water rates and in doing so, infuriated city residents who subsequently succeeded in recalling the council. New council members were elected on the pledge to roll back water rates, but after studying the water supply predicament, found they could not, and indeed, were eventually forced to increase water rates.

As the above incident illustrates, increasing public dissatisfaction over rising water costs will exert considerable political pressure upon public officials who will seek to avoid rate increases by finding alternative solutions. For the most part, these alternatives will have to be developed within the framework of an essentially finite water supply (Tellman, 1976), and will fall into two categories: water conservation and reallocation of existing water supplies. Reallocation is likely to create further legal and political turmoil. The confusion created by these legal battles and the lifestyle, economic and political impacts of water conservation establish an imperative need for improved policy capabilities. Thus, rising water costs bring the state's water problems to the forefront of public awareness and generate political pressures and demands for action. Rising water costs delineate the need for long-term, comprehensive water planning and management.

ENERGY DEVELOPMENTS

Plentiful amounts of relatively inexpensive energy have provided for rapid population and economic growth in Arizona. Yet, since Arizona is an energy consuming state, importing eighty-five percent of its energy supply, the traditional development and economic expansion philosophy of state government is very vulnerable to changes in its energy supply. Moreover, the water allocations of the Colorado River will provide the majority of the water necessary for energy production in Arizona and its neighboring states. The added water supply projections related to energy production have served to arouse the concern of many. Coming at a time when other sectors of the economy are demanding more, the water demands of energy production may result in significant dislocations in Arizona's historical economic base (Ingram, et al., 1976). As public perception of the urgency concerning Arizona's vulnerable energy supply situation increases, so will the impetus for state government to play an enlarged role in the energy policy arena. While until recently energy has not been a significant factor in governmental decision-making, present conditions demand that the state build an aggressive energy management capability. And, in order to make trade-offs between the state's energy requirements and its available and historical water allocations, a similar state initiated and administered capability in water is needed.

WATER QUALITY

Because of the scarcity of water in Arizona and the entire Colorado River Basin, water quantity, not water quality, has typically been of greater interest. Yet, the quality of the available water supply is now demanding and receiving more governmental attention. As an issue of water quality, salinity is not only a state and regional concern, but an international one as well, since Mexico has sought and received assurances that the United States will improve the quality of Colorado River water flowing into Mexico. To meet new agreed-upon standards for salinity control, improved water use practices will need to be adopted and enforced (Weatherford and Jacoby, 1975; Mann, 1976).

Two other federal water quality programs also are likely to provide an impetus for more state involvement in water planning and administration. The first program is the Federal Water Pollution Control Act of 1972. This Act, and particularly its provisions for statewide water planning and areawide waste water treatment and management plans, encourages state level participation in identifying and prioritizing water quality problems, and in coordinating and integrating the state's planning processes related to water quality. By tying sewage treatment to the planning process, this Act also has implications for state growth management programs (Greenfield, 1977). The second program is the Safe Drinking Water Act. After a state program is developed and approved by the Environmental Protection Agency (the federal administrator of the Act), the state will be eligible for funding to provide additional manpower to implement and enforce its drinking water standards. Both these water quality programs provide legal and financial incentives for state action and necessitate program development and management in the area of water quality.

CONCLUSION

Arizona has traditionally and persistently pursued a style of politics in which state government is a reactor rather than an initiator. Neglecting to build independent policy capabilities, its role has been subordinate to those of the federal government and local and private water users. Yet, as we have argued, a whole new set of political demands and conditions today require greater state participation and decision-making capabilities in water. If the state is to respond adequately to these changing conditions and be an innovative and aggressive policy participant, the conventional style of politics will no longer suffice. A new decision-making agenda which includes the new conditions of decision-making, as well as items such as groundwater law reform and reorganization that have been characterized by inaction for far too long, is required.

There is some evidence that the customary decision-making process is changing. The interest of the state in building an independent water planning capability is one manifestation of that change. Yet, unless and until there is more appreciation of the costs that the prevailing pattern and style of water politics incur, and an even greater positive commitment to policy innovation, state government is likely to continue to lose leadership opportunities in water as well as in other important related natural resource policy areas. The federal government will increasingly encroach upon what could remain state prerogatives. More importantly, inaction is likely to have long-run adverse impacts on Arizona's economy and its environmental and lifestyle amenities.

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AN ECONOMIC ANALYSIS OF THE CENTRAL ARIZONA PROJECT

by

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and

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INTRODUCTION

The Central Arizona Project (CAP) is a multiple-purpose capital investment currently funded by congressional appropriations that are governmental by Reclamation Law. If completed on schedule in 1985 it would provide Colorado River water to central Arizona in accordance with water entitlements that have been established over a 50-year period that dates back to the historic Colorado River Compact (1922). CAP construction was authorized in 1968 as part of the Colorado River Basin Act, and roughly $400 million has been expended to date on project facilities. Further funding of the CAP was halted in January, 1977 by presidential order, pending a review of the project's economic and environmental impacts. More recently that executive decision to discontinue CAP funding has been reaffirmed, placing the completion of the project in further jeopardy. Critics contend that these actions have been taken without sufficient justification and we would agree that little in the way of explanation has emerged since the funding halt was ordered. By the same token, we would argue that insufficient effort has gone toward providing a realistic assessment of the CAP's potential impacts throughout the course of its development, making the average citizen's stance on the project a matter of faith rather than reasoned judgment.

In another paper we have examined many of the CAP's likely impacts,[1] particularly as they would affect central Arizonans. This paper extends that analysis in several ways. First, we develop a simulation model of CAP costs, water operations, and capital repayment alternatives. A variety of experiments are conducted to isolate the features of the CAP that would importantly determine the distribution of financial burdens required to meet the capital costs of the project. Second, we analyze the operating costs of the CAP by comparing its projected operations, maintenance and repair (OM&R) costs to the actual cost experience of the Metropolitan Water District of Southern California (MWD). This comparison provides, in our view, the most realistic picture of what these OM&R costs are likely to be. Finally, we consider some of the indirect benefits and costs that would be created by the CAP and attempt to summarize the overall economic impact of the project.

BACKGROUND

In this section we present some basic facts about the CAP that outline its institutional and economic structure. This descriptive material is necessarily brief;[2] its intended purpose is to motivate the analysis that follows.

CAP CAPITAL COSTS

It has been estimated that CAP construction would require a capital outlay of $1690 million if the land, labor, and materials were all obtained at 1976 prices. Since construction is phased over the period 1972-1985, the realized costs would be considerably larger; we estimate total realized CAP costs at more than $2300 million. Construction funds are to be provided by congressional appropriations, but the bulk of this money is to be repaid according to terms established in a Master Contract signed by the Central Arizona Water Conservation District (CAWCD) and the U.S. Department of Interior in 1972. In effect, the funding consists of a low interest (3.42%) loan for part (41%) of CAP's facilities, an interest free loan for another part (33%), and direct federal financing of the third part (25%). The exact distribution of costs into these broad categories is governed by terms of the Master Contract, and it depends among other things on the availability of CAP water and the allocation of that water to different user classes. The interest bearing portion of the CAWCD loan applies to the (allocated) costs of constructing the CAP's electric power facility and the costs of water delivery facilities for municipal

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1. Barr and Pingry, "The Central Arizona Project: An Inquiry into Its Potential Impacts," Arizona Review, April, 1977.

2. A more complete description is provided in our recent paper, including a detailed bibliography of other source materials.

and industrial (M&I) users. Interest is to accrue on these outlays from the time they are undertaken, so that the CAWCD's total capital obligation would include interest occurring during construction of an additional $116 million. This brief overview of the project's capital costs provides some indication of their relative magnitudes, and reveals the broad financial structure of CAP funding. Table 1 summarizes the CAP cost allocations just described in terms of 1976 ("current cost") input prices and indicates the magnitude of the CAWCD's capital repayment obligation.

Table 1

CAP Costs and the CAWCD Repayment Obligation*
($ Million in terms of 1976 input prices)

Project Function	Allocated Costs	Federal Finance	Non-Interest Bearing Loan	Interest Bearing Loan	Interest Bearing Costs
Irrigation Water Delivery					
Private	556		556		
Indian	189	189			
M&I Water Delivery	581			581	97
Electric Power	122			122	19
Flood Control	130	130			
Recreation	17	16	1		
Fish & Wildlife	49	49			
Other[1]	46	46			
Totals	1,690	430	557	703	116
CAWCD Repayment Obligation			557	819	

[1]Primarily the cost of the Colorado River Division facilities, and the Indian Irrigation Distribution System.

Source: Unpublished data, September, 1976 Arizona Projects Office, Bureau of Reclamation. These cost estimates are based on the bureau's existing estimates of costs, water availability, and the water allocation and are subject to change.

THE CAP POWER SUPPLY

The CAP owns a 24.3% share of the Navajo Power Station which has been operating since 1975. This feature, due to its size and the way its costs and revenues are allocated by the Master Contract, plays a pivotal role in any economic analysis of the CAP. The CAP's share of Navajo power is sufficient to pump water through its acqueducts at their capacity limit (2.17 million acre feet/year). However, the expected water availability for the project is much less than its aqueduct capacity, with current estimates ranging from .8 to 1.2 million acre feet per year (maf/year).[3] Power not used to pump CAP water is to be sold on a wholesale basis to other companies in the southwest power grid. At present CAP's entire share of Navajo power is sold in this fashion; it is expected to return net repayment revenues of $16.3 million in 1977 alone. When CAP water deliveries commence, about half (on average) of the project's power supply would be sold as surplus power.

The capital costs and revenues derived from this Navajo surplus power have been "packaged" into the CAWCD repayment obligation. As can be seen from Table 1, it must repay $122 million as part of its interest bearing obligation, but all surplus power revenues are then to be credited to its account.[4] This financial arrangement has two important consequences. In the first place it provides a substantial subsidy to the financing of the CAWCD's water delivery operations. Second, it acts to protect the CAWCD financially from revenue losses it might experience if less water is available for delivery. For when such shortfalls occur, the CAWCD would receive offsetting revenues from the sale of additional surplus power. It will be seen below in the simulation analysis that the CAWCD water charges needed to meet its capital repayment obligation are rather insensitive to changes in water availability; this is largely a reflection of the offsetting financial impact of surplus power sales.

CAP WATER SUPPLY

One of the major questions surrounding the CAP involves the amount of Colorado River water it would have to deliver. The Bureau of Reclamation has constructed a CAP water supply forecast that is based on a sequential average of recorded virgin flows of the Colorado River during the period 1906-1969, together with estimates of other established rights and priorities already perfected and anticipated. This forecast yields average diversions over the 50-year CAP repayment period of 12.19 maf per year. Our own assessment[5] of the basic data leads to a considerably lower forecast of CAP water availability. This view

3. A recent Bureau of Reclamation study estimates CAP Colorado River diversions at an average of 1.21 maf/year. Our own estimates (op. cit.) are substantially lower than this figure, in the range of .8 to 1.0 maf/year.

4. In addition, "exchange" power revenues derived from Hoover and Parker Dam power generation are to be credited to the CAWCD loan after 1990. They would amount to a total of $133 million by 2035.

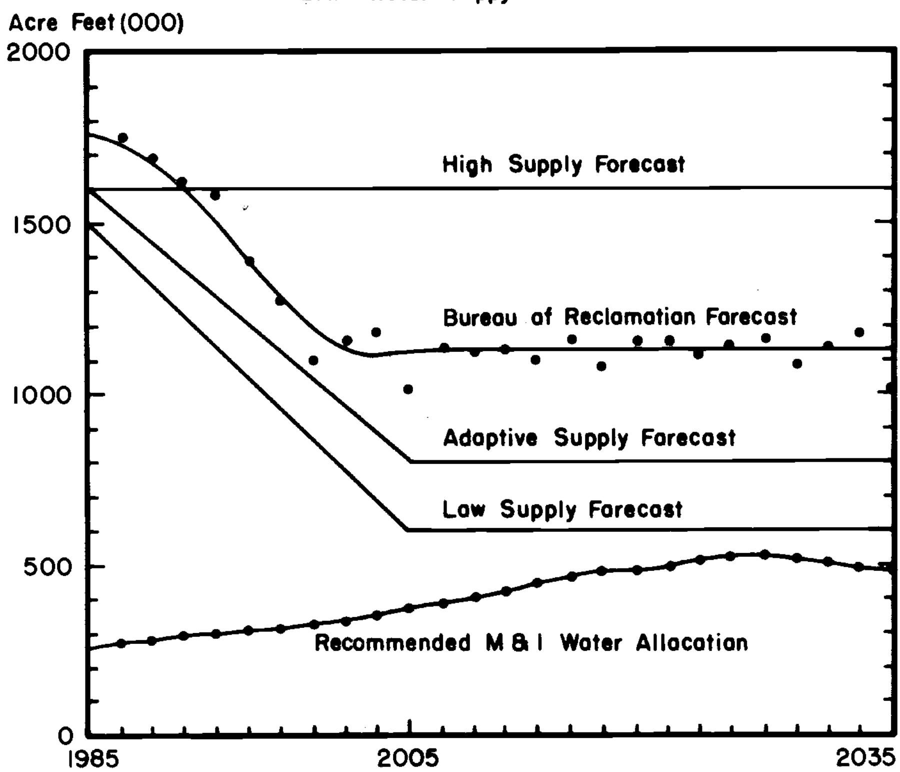
5. See Barr and Pingry, op. cit., pp. 28-33.

stems primarily from the expectation that water users in the upper Colorado basin will exploit their entitlements to a greater extent than the Bureau of Reclamation anticipates. For this reason we have labeled this outcome the Adaptive Supply Forecast. The supply forecast that we endorse in this analysis is in our view conservatively high; it calls for declining water availability over the first 20 years of CAP operations and average diversions of .96 maf/year.

Water supply has been a central issue in the debate over the CAP's social investment value, and to be sure, if there is not going to be much water available there is no point in building the water supply facilities. However, as we have suggested above, the inclusion of a large, profitable power supply in the CAP obscures the real cost of the water delivery system in the event that a low water supply materializes. To be able to demonstrate this point, we will consider two other water supply forecasts in our simulation analysis. The high supply forecast calls for constant Colorado diversions of 1.6 maf/year. The low supply forecast is a more pessimistic version of the adaptive supply forecast, averaging .72 maf/year. The four water supply forecasts used in this study are depicted in Figure 1 for the repayment period, 1985-2034.

Figure I

CAP Water Suppy Forecasts



We have also depicted the currently recommended M&I CAP water allocation[6] on Figure 1. The recommendation calls for the M&I water allocation to increase from 269,000 af to more than 500,000 toward the end of the repayment period (average: 412,000 af/year). These figures will be useful in interpreting the simulation results of Section III.

6. Arizona Water Commission, November 24, 1976.

ANALYTICAL PERSPECTIVE: CAPITAL COST ANALYSIS

The CAP is a well defined contractual entity. About 75% of its total capital cost is to be repaid by the CAWCD, which has broad power to allocate CAP water to private users, set water charges, and levy property taxes in the central Arizona (Maricopa, Pima, and Pinal) counties. These financial instruments, together with the surplus power revenues, comprise the elements of the repayment package that the CAWCD must assemble to meet its federal loan obligation.

The simulation analysis of the next section is concerned exclusively with identifying the capital recovery charges (so-called "canal side" charges) required to meet the repayment obligation under a variety of circumstances. These charges are distinct and separable from the OM&R and distribution costs, treatment costs, and administrative costs that would be incurred in operating the CAP system.[7] The simulation analysis addresses four specific questions regarding capital recovery charges:

A. Water user capital recovery charges: existing contractual arrangement. One obvious question concerns the attractiveness of the CAP as an investment proposition, given the terms of the Master Contract. This analysis will be conducted in terms of the current dollar ($1976) cost of the project so that the capital recovery charges can be compared to current per acre foot capital costs of groundwater retrieval. No tax levies will be permitted in these simulated repayment plans so that the project's (current) capital cost must be recovered entirely by water charges. The resultant canal side charges will indicate what CAP subscribers must be willing to pay for water in current dollar terms for capital recovery only.

B. Water user charges for the incremental capital cost of the water delivery system. The Navajo Power Plant is operating at its designed capacity and the CAP is selling its share of output to the power grid. In a real sense this investment is separable from the CAP water delivery system. The crucial question from a social investment point of view is, "What is the incremental value of the water delivery system?" To answer this question we have purged the current CAP cost estimate of the Navajo investment cost and have simulated CAWCD repayment plans without either the Navajo capital costs or the surplus (and exchange) power revenues. We have retained the other financial terms of the Master Contract, such as the low interest and interest free loan provisions. These simulation experiments provide a partial answer to the incremental cost of CAP's water delivery facilities; the charges required on water deliveries indicate what users must be willing to pay in current terms to recover the capital costs of the water delivery facilities only. This experiment is seen to eliminate the project subsidy provided by the Navajo feature. It is the appropriate test, indeed the compelling test at this juncture, required to judge whether the water supply facilities should be built or not. The Navajo Station is in place; the remaining features of the project must be evaluated on an incremental cost basis.

C. CAP management alternatives: distributing expected realized costs. If CAP construction is completed, the CAWCD will be obligated to repay a portion of the total capital costs that are realized. We estimate that this total would be more than $2.3 billion if the construction work proceeds according to schedule. This simulation experiment retains all terms of the Master Contract and derives the likely options that would be available to the CAWCD. Several trade-offs are established between tax levies and water charges under different assumptions about water availability and its allocation. These results indicate what capital recovery charges would have to be to repay the expected realized capital costs of the project. These estimates differ from those of [A] by the extent realized capital costs would differ from the estimated cost in current dollar terms, and by the extent to which capital costs are financed by tax levies.

D. Water user charges for capital recovery without federal interest subsidy: current cost configuration and incremental water delivery system costs. This experiment inquires further into the question of what the full economic cost of CAP water deliveries would be. Again we are only concerned in this instance with the user charges needed for capital repayment. Here we suppose that federal funding of the CAP is withdrawn and the project is financed by 5% revenue bonds. Two cases are considered: (1) the Navajo Station is retained as an integral part of the project, and (2) the CAP water delivery system is financed separately, with the understanding that power will be supplied to the project at cost. The first case approximates the user cost of capital inclusive of the Navajo subsidy while the second case approximates the incremental user cost of capital for the water delivery facilities alone. This experiment is conducted for both the Bureau of Reclamation water supply forecast and the adaptive supply forecast.

CAPITAL COST REPAYMENT SIMULATIONS

In this section we simulate the capital cost repayment program that would be undertaken by the CAWCD under different financial and water supply conditions. The approach is to combine sets of assumptions about construction costs, water availability and its allocation, repayment methods, etc., and then to simulate the "operation" of the CAP over the repayment period.[8] The appeal of such simulation studies is that they can capture the interaction effects of any assumed conditions and, at the same time, they can isolate the impact of changes in particular conditions. Using this technique, we can assess the sensitivity of the project's economic impacts to two distinctly different kinds of influences: (1) project operating rules over which there is control (e.g., the repayment package) and (2) conditions which are subject to uncertainty (e.g., CAP water availability). By considering

7. These costs will be dealt with in Section IV.
8. Both the Bureau of Reclamation (Arizona Projects Office) and the Arizona Water Commission have conducted similar unpublished studies of CAP operations.

variations in both kinds of influences we can get a "feel" for the range of possible economic outcomes and identify which operating rules and contingencies are particularly influential. Initially we adopt all of the rules stipulated in the Master Contract that govern the CAWCD's capital repayment obligation and other aspects of CAP operations. In addition, we make the following basic assumptions so that we can focus on a manageable set of influences in the simulations:

A1. The main water delivery system will be completed by 1985, and the repayment period will refer to the period 1985-2034.

A2. The user water distribution system will be completed by 1985 so that they can take delivery of CAP water according to schedule.

A3. The current directive on the Indian water allocation will continue to be operative (257,000 af/year until 2005, thereafter 5% of total project deliveries or 10% of agricultural deliveries, whichever is larger in each year).

A4. Repayment revenues derived from other Bureau of Reclamation projects (Hoover, Parker Davis, et al.) will be available according to schedule (these revenues commence around 1990 and will average roughly $2 million per year).

A5. The CAWCD will meet its repayment obligations according to schedule during the repayment period, and further, the package of repayment charges levied is assumed to just meet that obligation.

These assumptions (particularly A1-A3) may not be entirely realistic, but they establish a setting wherein we can analyze factors that importantly affect the CAP's direct payoffs to its constituents. The following influences, or variables, are considered in the simulations:

V1. Total CAP construction costs, including interest charges accruing during the construction period.

V2. CAP water availability (this consists of a 50-year schedule of Colorado River water diversions from Lake Havasu), plus additional water derived from the Salt and Gila Rivers.

V3. The CAP water allocation (this consists of an annual division between agricultural and M&I users of available water (V2) less the Indian allocation (A3) and evaporation losses.

V4. The canal side capital recovery charge for agricultural water, referred to as P_A.

V5. The canal side capital recovery charge for municipal and industrial water, referred to as P_M.

V6. The ad valorem tax rate levied on assessed real property in the central Arizona counties. This taxing authority is limited to a levy of no more than 10 cents per $100 assessed valuation (referred to as t = .01, .02, . . ., etc.).

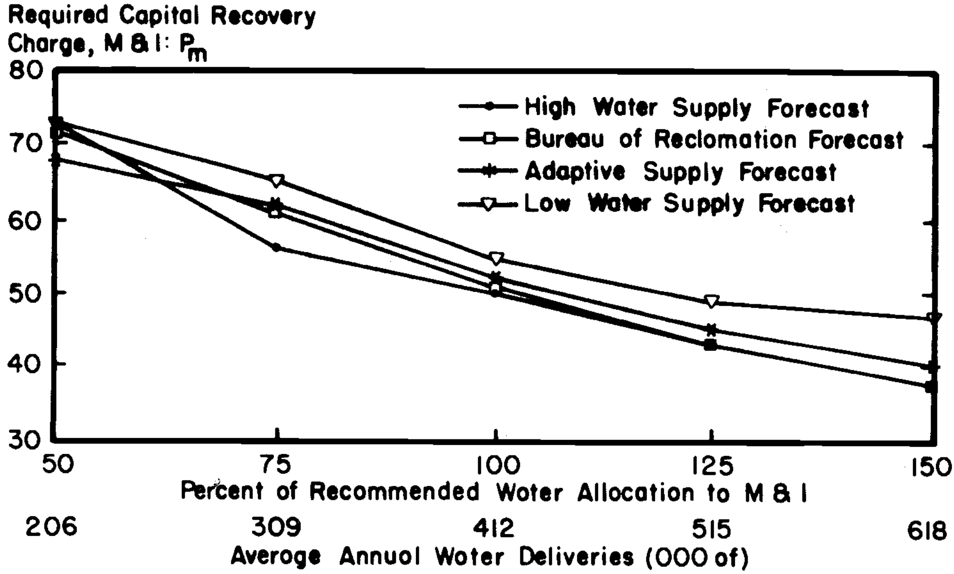
V7. The magnitude of surplus power revenues derived from the CAP interest in the Navajo Station.

All of these variables cannot be predetermined independently if the budget balancing assumption (A5) is to be satisfied. Our basic approach will be to specify conditions for all variables listed except the charge for M&I water, P_M, and then solve for its value in accordance with (A5). This orientation is based on our prior belief that, to the extent possible, the CAP should be financed by (voluntary) water charges. Since the agricultural water charge, P_A, is to be based on ability to pay considerations (and agricultural water is in effect a residual supply), this leaves P_M as the major price instrument available to the CAWCD. This is not to say that the tax instrument is not important; indeed it will be seen to be crucial to the financial viability of CAP. Rather, the taxing authority is construed in the Master Contract as a residual revenue source, and thus it is given secondary importance in the analysis. The first simulation experiment described below reflects this priority in that it determines the M&I water price required to repay the CAWCD's capital obligation on a purely voluntaristic basis (t = 0).

A. Water user capital recovery charges: existing contractual arrangement. This experiment employs the current dollar capital cost estimate ($1690 million), a capital recovery charge for agricultural water deliveries of $2/af and surplus power revenues that are consistent with the alternative water supply conditions of Figure 1. The simulation results are expressed in terms of the capital recovery charge for M&I water required to meet the CAWCD repayment obligation. Figure 2 presents a summary of results for alternative water supply conditions, and alternative water allocations expressed as year by year percent increases or decreases from the currently recommended allocation. It can be seen that the required capital charge P_M is rather insensitive to the assumed water supply condition given the water allocation; this stems from the offsetting effect of surplus power sales and the fact that agricultural water users must be assessed a low capital recovery charge. The required capital recovery charge for expected supply and allocation conditions is $51-52/af; if the M&I water allocation were increased by 50% it would reduce P_M to $37-40/af.

B. Incremental capital recovery user costs. This experiment identifies the user cost of the CAP water delivery facilities in current dollar terms (see Figure 3). When the Navajo subsidy is removed from the repayment package, capital recovery costs increase (vis a vis A) by about 15-30%. For expected water supply conditions and the current allocation, the required capital charge for M&I water would be $64-$67/af. Incremental user costs are seen now to be dependent upon the assumed water supply since surplus power revenues have been eliminated, but the water allocation is still more influential in determining the required capital recovery charge. These user cost estimates reveal that the separable

Figure 2
Required M & I Capital Recovery Charges
Existing CAP Configuration
($ 1976)



cost of the water delivery system is (a) higher on a per acre foot basis and (b) more sensitive to CAP water availability than the overall project cost repayment analysis indicates.

C. Simulated repayment packages for the realized cost obligation. This experiment identifies a set of feasible CAWCD repayment packages while recognizing that realized capital costs ($2300 million) will be considerably more than costs estimated in current dollar terms (see Figure 4). In the main, the analysis reveals that the CAWCD would have a considerable degree of flexibility in setting capital recovery charges while still remaining within the limit of its taxing authority. Put another way, the relatively large tax revenue source would permit the CAWCD to levy very modest capital recovery charges. For the sake of comparison, note that an M&I charge of $67/af would be needed if no taxes are levied. The currently suggested charge of $32.50 could be combined with a 6¢/$100 AV tax levy if the current water allocation were adopted. These results indicate that a range of feasible pricing policies would exist, from the users' willingness to pay standpoint, either if M&I users are allocated more CAP water than is currently recommended or if relatively high tax rates are levied.[9]

D. Unsubsidized user capital costs and incremental capital costs. In this experiment we again express CAP capital costs in current dollar terms but apply a uniform cost of capital of 5% to all borrowed funds. The repayment obligation is first defined to include the Navajo Station costs and revenues and then defined on an incremental cost basis. The required capital recovery charges for M&I water increase dramatically, but do not depend appreciably on whether capital costs are viewed as "packaged" or incremental. This somewhat surprising result stems from the fact that the Navajo Station investment earns an effective rate of return of 5% when its energy is priced according to prevailing policies. As can be seen in Figure 5, the water allocation would importantly affect the magnitude of required capital recovery charges, but for any allocation considered, these user charges are considerably higher than those discussed in experiments A and B. Lastly, note that the per acre foot capital recovery charge is lower for the adaptive water supply forecast than for the Bureau of Reclamation forecast when the M&I water allocation is low. This occurs despite the fact that less water would be available for delivery in the adaptive supply forecast. The result occurs because the Navajo energy is worth more sold as surplus power than it would be worth when used to pump agricultural water at $2/af.

To summarize this analysis, the expected capital costs of delivery M&I water are more dependent on the water allocation than on the amount of the deliverable supply due to the requirement that agricultural users must be subsidized. The current dollar capital charges for expected supply conditions are presented in Table 2. Taken together these estimates indicate the financial importance of the water allocation and the CAP subsidy elements that we have identified.

9. Taxpayers are currently paying 3¢/$100 AV to defray interim administrative expenses.

Figure 3
Required M & I Capital Recovery Charges
Incremental Costs of the CAP Water Delivery System
($ 1976)

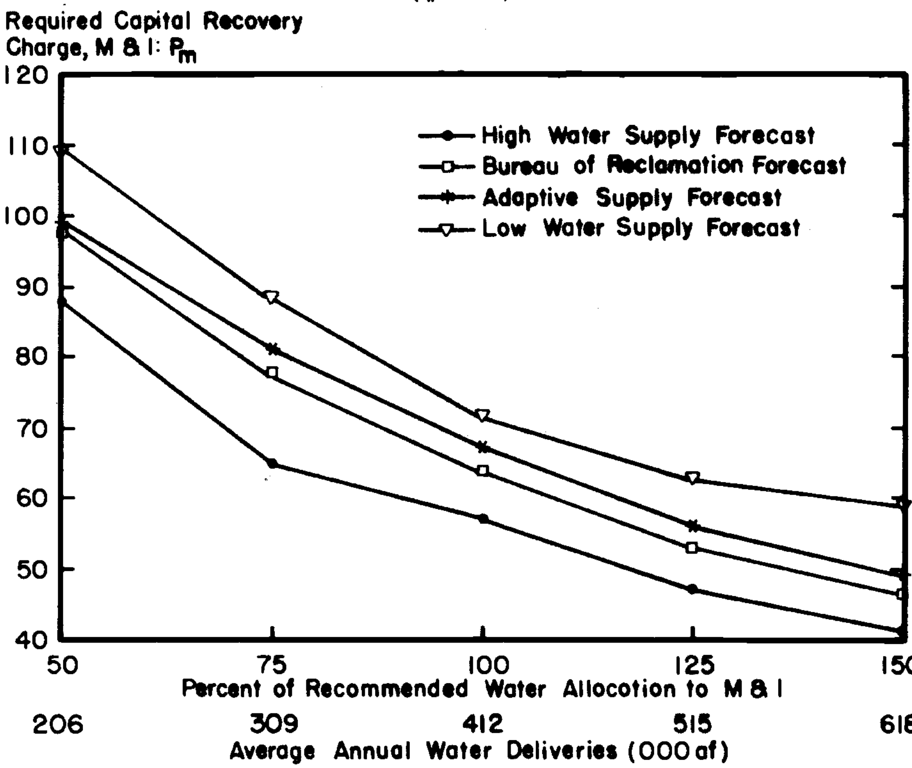


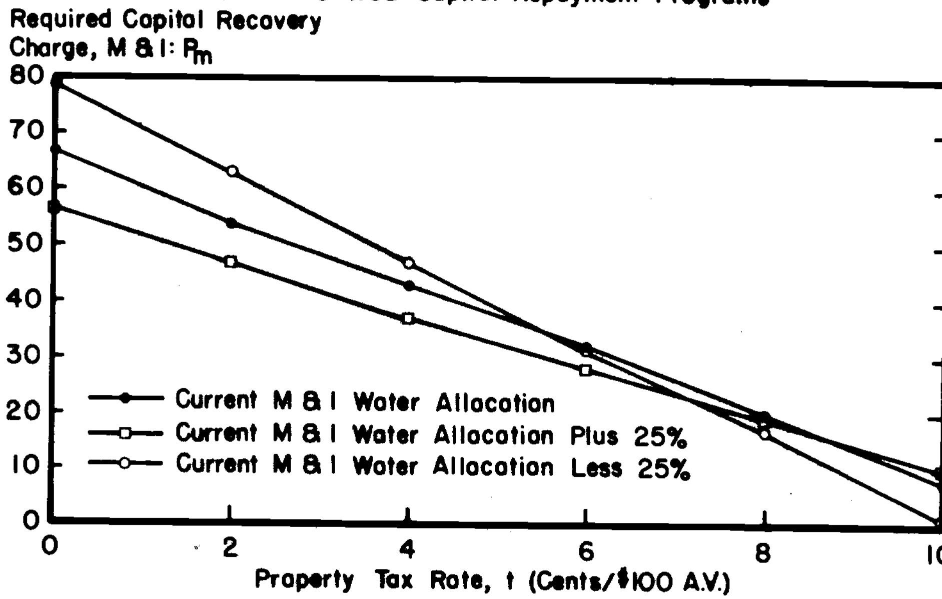
Table 2

Summary: CAP Capital Recovery Charges for M&I Water, ($1976/af)

	I Bureau of Reclamation Water Supply Forecast (a) Current Water Allocation	(b) 50% Increase in M&I Water from (a)	II Adaptive Supply Forecast (a) Current Water Allocation	(b) 50% Increase in M&I Water from (a)
Existing Contractual Arrangement:				
1. Capital Recovery, Inclusive of the Navajo Power Station	51	37	52	40
2. Incremental Capital Recovery Costs	64	46	67	49
5% Revenue Bond Finance:				
3. Capital Recovery, Inclusive of the Navajo Power Station	193	99	186	104
4. Incremental Capital Recovery Costs	194	129	193	129

Figure 4

Feasible CAWCD Capital Repayment Programs



CAP OPERATING COSTS

To estimate the full delivered cost of CAP water we must add OM&R costs and distribution costs to the capital recovery charges just discussed. OM&R costs include the operating costs of the water delivery system and the cost of pumping energy. Distribution costs refer to the per acre foot cost borne by CAP water users in transporting water from the main aqueduct to their use sites. In some cases this might be only a few miles, but in others it might be an appreciable distance. In any event, distribution costs are to be financed separately by users; they must build, maintain, and operate their own facilities. A third cost involves water treatment, but this is only relevant for municipal water deliveries. We will defer discussion of this cost question until the end of this section.

A. OM&R costs. The Bureau of Reclamation[10] has estimated OM&R costs at about $22 per delivered acre foot in terms of 1976 prices. That is, this cost measure is comparable to the current cost estimate discussed earlier. To judge whether the $22 figure is realistic, we must look at the way in which this estimated charge is computed. The cost estimates discussed here are summarized in Table 3. The OM&R estimate consists of three component charges, two of which are derived from the Navajo generating cost.

The $1976 cost of operating the CAP's share of the Navajo station was estimated to be $26.44 million, of which $14.17 million were operations, maintenance and overhead expenses, and $12.27 million were the (delivered) fuel costs. In determining OM&R charges these current dollar annual costs are allocated to M&I water, irrigation water and surplus power on the basis of estimated energy used (net of losses). By this, the pump energy cost included in the CAP OM&R water charges would only cover the variable costs of producing the energy. The estimated energy charges appear to be realistic when compared to the actual budget figures for the Navajo Station. In addition to variable energy costs, the estimated OM&R costs of the conveyance system are allocated (nearly) in proportion to water deliveries. This cost allocation procedure yields per acre foot OM&R charges of $22.16 and $21.30 for M&I and irrigation water deliveries, respectively. The estimation procedure just described indicates that OM&R delivery costs would be determined by proportionally assigning variable energy costs and delivery system costs.

The annual water delivery system OM&R costs of $9.17 million would include expenses for aqueduct maintenance and repair, and CAP administration. We have little feel for the likely magnitude of these costs; one fragmentary piece of information is the annual budgeted costs of the Bureau of Reclamation's Arizona Projects Office for the fiscal years 1976-1977. These costs were $6.7 and $11.2 million, respectively, to plan and administer the CAP construction work and its future operations. The 1976 FY budget for the CAWCD was $245,000. To summarize this cost discussion, the $1976 cost estimate appears to be realistic, barring any abrupt changes in Navajo fuel costs. This eventuality is not expected by the Navajo Station owners, but variable costs are expected to increase over time:

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[10] Arizona Projects Office, preliminary unpublished estimates September, 1976.

Figure 5

User Capital Recovery Costs Versus Incremental Costs of the Water Delivery System

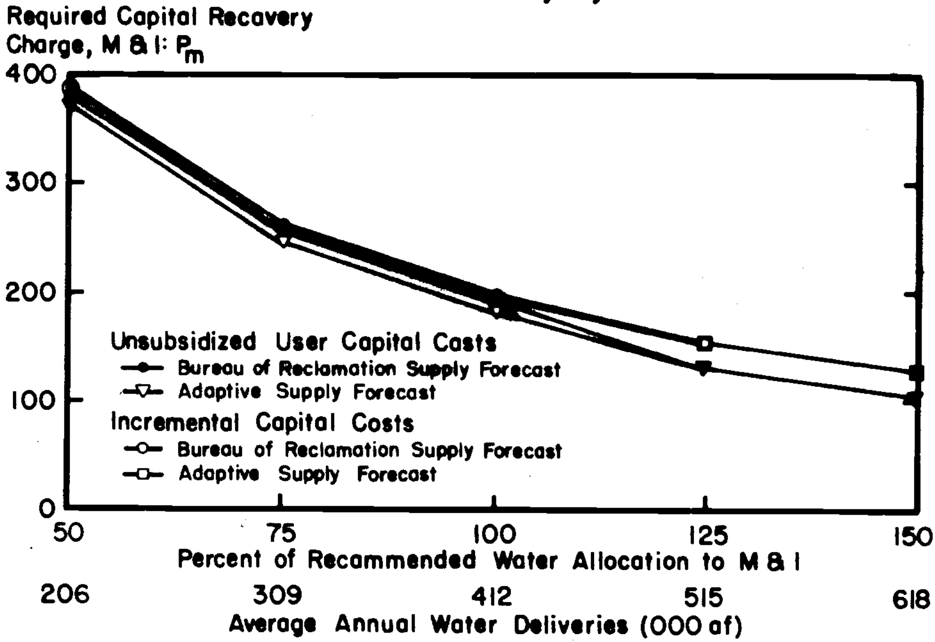

Table 3

Estimated OM&R Water Delivery Costs ($1976) and Navajo Budgeted Costs 1977*

	Estimated[1]				Actual Budget 1977[2]	
	Total	Irrigation	M&I	Surplus Power	Total	Surplus Power
1. Operations, overheads & maintenance ($million)	14.17	5.31	3.71	5.15	11.01	11.01
2. Fuel costs ($million)	12.27	4.59	3.22	4.46	11.62	11.62
3. Total ($million)	26.44	9.90	6.93	9.61	22.63	22.63
4. Kilowatt hours used (million)	3354	1256	879	1219	3334	3334
5. Cost/KWH	7.88	7.88	7.88	7.88	6.79	6.79
6. Water Delivery System OM&R costs ($million)	9.17	5.53	3.64	--		
7. Total OM&R costs (3) + (6)	35.61	15.43	10.57	9.61		
8. Water deliveries (000 af)		732	483			
9. OM&R charge/af[3] ($1976)		$21.30	$22.16			

[1] Data presented here are for a sample year (1997). Estimated water OM&R charges vary from year to year (range: $20.16 to $25.04) according to estimated energy losses and total water deliveries.

[2] The estimated 1977 sale price of surplus energy is 11.68 mills/KWH, comparably less in terms of costs than the sale price of 12.9 mills/KWH used to compute surplus power revenues in the simulation experiments of Section III.

[3] OM&R charge includes a storage charge by Lake Mead authorities of $.285/af.

Sources: Unpublished data, Bureau of Reclamation Arizona Projects Office, September, 1976. These estimates are to be regarded as preliminary and subject to change. The 1977 Navajo Station budget data was obtained through private correspondence, February 11, 1977.

Fuel costs may escalate at a rate somewhat higher than the level of general inflation while other costs should escalate with general price levels. There are no major cost changes anticipated in the future that would cause overall station operating costs to abruptly increase.[11]

Further discussion of the CAP's expected OM&R costs will be presented below in our discussion of the Southern California experience.

B. Distribution costs. As far as we can ascertain, little effort has gone toward estimating the magnitude of these costs. Engineering studies should be conducted by prospective CAP water subscribers to determine these costs. What is certain is that these must be borne on an individual basis at unsubsidized interest rates. Furthermore, these capital costs will be incurred by users prior to the delivery of CAP water. We have suggested previously[12] that average distribution costs per acre foot might be around $15/af, but we are less confident about this estimate than the other cost components of CAP water. Some concrete evidence appears to be available from the historical record of capital costs and recent engineering studies for extending the southern California water distribution system.

C. The Southern California experience. The CAP is not a unique water delivery system. One need only travel to the western shore of Lake Havasu itself to find its older counterpart. The Colorado River Aqueduct, owned and operated by the Metropolitan Water District of Southern California (MWD), delivers water to the Los Angeles area by remarkably similar means to those proposed in the CAP. The physical similarities of the two delivery systems are summarized in Table 4.

Table 4

A Tale of Two Aqueducts

	Colorado River Aqueduct	CAP	
1. Diversion Point	Lake Havasu	Lake Havasu	
2. Average Annual Deliveries	1.039 maf (1960-1975 average)	1.077 maf (Bureau of Reclamation Average Water Conditions)	
3. Energy Required per Diverted Acre Foot	2034 KWH (1974-1975)	1942 KWH (Bureau of Reclamation estimate)	
		Phoenix	Tucson
4. Length	242 miles	190 miles	315 miles
5. Vertical lift	1600 feet	1200 feet	2100 feet
6. Deliveries by User Class			
% M&I	69	36	
% Agriculture	14 (1958-1975)	64	
% Groundwater Replenished	17 averages	--	

The Colorado River Aqueduct (CRA) was built during the 1930's at an approximate capital cost of $220 million. By 1976 the outstanding indebtedness of the project was only $60 million. The MWD has subsequently undertaken other large investments, notably for the State Water Project delivery facilities and treatment facilities, and the overall capital costs of the system are financed jointly by property taxes[13] and uniform water charges. Still, the physical similarities between the two aqueducts indicate that the MWD's operating cost experience with the CRA can provide relevant information on CAP operating costs.

The enacting legislation (MWD Act, 1927) for the CRA clearly establishes the priorities for MWD operations; it is to "first develop, store, and distribute water for domestic and municipal purposes; and then if surplus water is available, it can be sold for other beneficial purposes" such as irrigation and groundwater replenishment. Perhaps more important, both from a managerial standpoint and on economic efficiency grounds, the MWD is resolved (Resolution 5821, September 1960) to price its water uniformly[14] (regardless of point of use or point of supply) and to charge water users all OM&R costs and at least one-half of annualized capital costs. In order to comply with Resolution 5821 it has had to dramatically increase water charges during the last 15 years, and it plans to more than double existing rates over the next decade to reach and maintain full compliance. In what follows we will highlight the MWD cost and water pricing experience where it appears relevant to CAP operations.

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11. Private correspondence, John Daer, Manager of Rates and Taxes, Salt River Project, February 11, 1977.

12. Barr and Pingry, op. cit., p. 47.

13. The current rate levied is 12¢/$100 AV. The rate has varied over the period 1931-1976 from 4¢ to 50¢ and has averaged about 25¢.

14. This has not been interpreted to mean that agricultural users should pay the same costs as municipal users. The adopted pricing policy attempts to charge agricultural water users marginal energy costs plus a modest charge per acre foot as a contribution to capital and other fixed costs. This is similar to the CAP's agricultural water pricing, but since the MWD's marginal energy costs are high and increasing, this will result in rapidly increasing agricultural water prices over the next decade.

1. Power costs. The primary concern of the MWD is the cost of power:[15]

> The most critical factor in the (pricing) study continues to be the future cost of power required for pumping water through the Colorado River Aqueduct and the State Water Project. Such future costs cannot be evaluated accurately, but it is anticipated that costs for pumping State project water will increase very substantially when the rates in the present contract between the Department of Water Resources and the power suppliers expires in 1983 and must be replaced by new rates. As presently anticipated, the resulting power costs could increase by a factor of possibly 10 over costs applicable prior to that time.

Like the CAP, the MWD owns a substantial interest in the Hoover Dam generating facilities and a smaller interest in the Parker Dam facilities. The MWD also purchases energy from Glen Canyon and Southern California Edison at substantially higher cost than that of its own supplies. These energy sources and their respective costs are presented in Table 5. The MWD is understandably concerned about the expiration of its Hoover and Parker Dam contracts since the cost of this energy is 75-80% below that of its alternative sources. By comparison, the transfer price (equal to Navajo variable costs) proposed in the CAP for pumping energy is slightly higher than the 1974-1975 average MWD energy cost for pumping Colorado River water. The average OM&R cost of delivered Colorado River water depends importantly on the extent to which it must use its marginal power source (Edison). The estimated average OM&R cost per acre foot in 1974-1975 was about $22-$24. Inasmuch as average energy costs in this period were comparable to the estimated CAP pumping energy cost, this cost experience serves to validate the estimated OM&R cost discussed previously.

Table 5

MWD Operating Costs and Water Pricing

1. 1974-1975 Energy Costs, Colorado River Aqueduct*

Source	Million KWH	Percent	Unit Cost mills/KWH	Energy Cost/ Diverted Acre Foot
Hoover	1,246	62	2.47	$ 4.99
Parker	234	11	2.47	$ 4.99
Glen Canyon	200	10	12.00	$24.25
California Edison	320	16	17.90	$36.20
	2,000	100%	5.92 (avg.)	$11.84 (avg.)
Estimated CAP Costs (Table 3)	2,135		7.88	$13.52

*Source: 1974-1975 Annual Report, MWD, pp. 4-11.

2. MWD Water Pricing, Untreated Colorado River Water*

	7/1/60	7/1/75 (dollars/acre foot)	7/1/76	Planned 7/1/87
M&I	17	58	62	115
Agriculture	11	25	29	103
Groundwater Replacement	10	32	36	115

*Sources: 1974 Water Pricing Study, Volume 3, MWD Study Report 912 and 1977 Water Pricing Study, MWD.

2. MWD water pricing. In the past decade MWD has been able to charge modest rates for Colorado River water due to a combination of low energy costs and low capital costs, even though the latter includes a share of the capital costs of the State Water Project. Because of the expiration of the Hoover power contract, the MWD is anticipating a dramatic jump in pumping costs after 1987 and is planning to increase its water rates to all users in roughly equal increments during the interim period. Agricultural water rates would be affected the most, since they are to reflect the marginal energy costs of delivery. As the CAP is currently construed, it would not be subject to the same energy cost pressures, although it is quite possible that its energy costs could increase a lot faster than it is currently anticipated. The MWD situation underscores the pivotal role that energy costs play in determining the viability of large-scale water delivery projects. In a contractual sense, the CAP is fortunate to contain a relatively low cost energy source and an additional power supply that can be sold to supplement its water revenues. But in an opportunity cost sense, the Navajo power must be valued in terms of the long run incremental cost of additional power supplies, and this resource cost would be considerably higher than the variable costs reported in Table 4. For this reason it is misleading to claim that CAP water would be low cost water, just as it is misleading to claim that MWD water pumped by Hoover power is inexpensive--the current marginal cost of MWD Colorado River water is considerably higher (Table 5) and the contractual price for Hoover power will be probably comparable in 1983 even though it is turned on the same generators. Proponents of the CAP are correct in their judgment that the project is affordable as it is contractually arranged, but this stance could possibly be altered by a sobering look at Figure 5 and an appreciation of the opportunity cost of Navajo power.

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15. John H. Lanten, General Manager, MWD, "1977 Pricing Study, Proposed 10-Year Program of Water Rate Increases," March 2, 1977.

D. Treatment Costs. The quality of Colorado river water at Lake Havasu is relatively poor. It contained on average in 1975 a concentration of total dissolved solids (TDS)--so called salinity--of 700 ppm. and a concentration of calcium carbonate--so called "hardness"--of 335 ppm. There is no economical means to treat salinity on a large scale basis, while hardness can be reduced by chemical additives. In addition to these dissolved concentrates, Colorado River water contains suspended materials of dubious to negative value that must be removed by filtration before the water is suitable for domestic use.

The MWD has filtered almost half of the Colorado river water it has delivered. Prior to 1975 it also softened (to 185 ppm.) about half of the water that it treated. When the higher quality State Project water became available in sufficient quantities in 1974, the MWD discontinued its water softening operations and switched to blending the two supplies in equal amounts. Blending has reduced hardness to about 220 ppm. and has also reduced salinity appreciably. The MWD currently operates four treatment plants that both filter and blend water. The existence of a second major supply thus permits treatment to be carried out on a large-scale, centralized basis. However, one unavoidable cost of this arrangement is that many agricultural users must subscribe and pay surcharges for unnecessarily filtered and blended water.

When compared to surface and groundwater supplies in central Arizona, CAP water would be significantly harder and probably contain more TDS. (The salinity of existing water supplies in the Phoenix area is comparable to Colorado River water, but groundwater in the Tucson area is significantly better in this respect.) A variety of studies exist[16] that suggest that the differential salinity and hardness of CAP water could impose additional costs on domestic users of about $10-$20 per acre foot if it is not blended or treated otherwise.

Colorado River water filtration costs are better known, since the MWD has just completed the Skinner treatment plant. It has an annual capacity of 240,000 af, a plant size that might be appropriate for Phoenix area users. The per acre foot costs at the Skinner plant have been estimated (in $1976) at slightly more than $25, assuming capacity utilization and 5.085% revenue bond financing.[17] CAP water treatment costs could be expected to vary from user to user, depending on the size and compatibility of existing treatment facilities.

E. Summary. To conclude this comparative analysis, we submit that the operating cost experience of the MWD is directly relevant to the task of forecasting CAP costs. Fortunately, the MWD has conducted thorough cost studies of its operations, and the management principles that it adheres to are worth studying in and of themselves.

SUMMARY

We can now aggregate the cost components just discussed. The user cost estimates in Table 6 are based on the CAWCD's contractual obligation.

Table 6

Estimated User Costs of CAP Water
($1976)

	M&I	Irrigation	Incremental Cost, M&I
Capital Costs[1]	40-55	2	45-65
OM&R	22	22	30
Distribution	15	15	15
Treatment	25	0	25
Quality Associated Costs	10-20	0	10-20
Total User Cost	$112-$127	$39	$125-$145

[1]The cost range reflects the differential charges for 100% and 150% of the current recommended water allocation.

The capital recovery charge for irrigation water was assumed to be $2/af throughout the simulation analysis. In part this value was used because it is the current "suggested" charge, but the other reason is that even at that subsidized rate, irrigation water costs ($37/af) would be equal to or greater than agriculture's (average) ability to pay for water. This restriction that agriculture water deliveries be subsidized acts to increase the required capital recovery charge for M&I water. The uniform capital recovery charge would be around $25/af, but then agricultural users could not afford the uniform price ($62/af).

We have defined incremental user costs to be the per acre foot costs of the CAP water delivery system, assuming that pumping energy would be provided at cost. This would increase the required M&I user cost by about $9-15/af. Finally, the full user capital cost (Figure 5) approach implies even higher CAP water costs.

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16. A number of these studies (some that appear to be in the guesswork stage), have been summarized in the 1974 Water Pricing Study, MWD Study Report No. 912, Volume 2, Appendix G.

17. "Skinner Water Treatment Cost Analysis," unpublished document, MWD, 1976.

Even though the water cost estimates developed in this study are somewhat higher than existing CAP cost estimates, they still may be palatable to a great many Arizonans. Many benefits, both tangible and intangible, have been attached to CAP development. Some of these would include the reduction of current groundwater overdrafts, the increase in the renewable water supply in central Arizona, and the mere satisfaction of obtaining the Colorado water entitlement.

Several kinds of indirect economic benefits would also accrue to CAP constituents. The project's Orme Dam facility would provide flood control and recreation benefits which are in part to be financed by the federal government. To the extent that groundwater use is reduced, the CAP would reduce the threat of ground subsidence. The project will provide employment opportunities during its construction phase, and this temporary stimulus would benefit the construction industry and, indirectly, taxpayers to the extent that derived tax revenues create a net fiscal surplus. The boost in measured personal and corporate income derived from the construction work (and its multiplier effects) would be beneficial to the extent that it reduces the existing unemployment rate. But the sum of these temporary stimulative effects should not be regarded by the CAP as an end in itself.[18]

In any event, we must conclude that there are real cost issues that must be weighed before the CAP's overall merits can be decided. Some of the issues concern contractual costs while others concern equally important opportunity costs. Finally, our analysis points up the importance of who is to receive the water; but then, in central Arizona this has been the issue for some time.

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18. Similarly, it would be difficult to unambiguously measure the welfare gains to Alaskans created by the spurt in measured income derived from the construction of the Trans Alaskan pipeline.

HYDROLOGY AND WATER RESOURCES IN ARIZONA AND THE SOUTHWEST, VOLUME 7, p. 29-31.

Proceedings of the 1977 meetings of the Arizona Section of the American Water Resources Association and the Hydrology Section of the Arizona Academy of Science, held in Las Vegas, Nevada, April 15-16,

THE ARIZONA WATER COMMISSION'S CENTRAL ARIZONA PROJECT WATER ALLOCATION MODEL SYSTEM

by

Philip C. Briggs

The Arizona Water Commission is authorized to plan for development and utilization, by all potential users, of interstate and intrastate waters, surface and ground water, water quantity and water quality - everything concerning water. The Commission is required in its planning to coordinate closely with other State agencies and, although it is authorized to develop integrated comprehensive plans for multi-purpose projects, its authority is not exclusive and in no way infringes upon, for example, the Arizona Game and Fish Department's authority to plan for fish and wildlife impoundments. The Arizona Water Commission, however, is responsible for tying together all State planning efforts in water resources.

In February of 1969, the Governor of Arizona requested that the Commission prepare recommendations for allocations that would maximize the benefit to the State of Arizona from the use of its remaining entitlement in the Colorado River. Expressions of interest in Colorado River water total over five million acre-feet; about five times the project's average delivery. About one hundred entities are interested in contracting. In the spring of that year we contracted for the preparation of a plan of study outlining a means of meeting the Governor's charge. A computerized systems analysis approach was proposed using interlocking optimization and simulation models. The proposal was accepted by the Commission and for the next two years consultants served to develop methodology, develop the models and train our staff in their use. The staff participated in the refinement of the models, collected most of the input data and by July of 1971 were in full command of the system. The first use of the model came in 1974, when then Secretary of the Interior Morton instructed the Bureau of Reclamation to work with the State and the five central Arizona Indian tribes to prepare recommendations as to allocations for the Indian tribes. Each group forwarded recommendations to the Secretary; the Commission's being the most rigorously based - and the lowest. The model has been sitting on the shelf since then awaiting the Secretaries' (three of them) decision on allocations to the tribes so that we would know how much Central Arizona Project water would be left to allocate to non-Indians. The decision was made this last fall, and shortly thereafter, contested by legal action.

Because of the complex interrelationships of the physical, engineering/hydrologic, and the economic and social aspects of the water allocation problem, it was recognized that the analytical system must have the capacity to incorporate and properly account for the many factors which are of vital importance to the allocation problem. At the same time, it was acknowledged that non-quantifiable social and political aspects would also be imposed on the quantitative, i.e., economic and engineering, solution to the allocation problem.

Over the last 30 years, an interdisciplinary science of systems analysis and operations research has evolved for the study and resolution of complex technical-management problems. This interdisciplinary approach to the solution of complex problems often utilizes mathematical and other simulation models which are designed for computer operations to effectively solve such problems, including problems in many areas of our economy and society. The systems analysis approach was consequently a logical avenue to assist in formulating, analyzing and resolving the many problems related to the determination of a recommended allocation of Arizona's remaining entitlement to Colorado River water.

The model is a comprehensive system designed to minimize the cost of distributing water over a large geographic area where sources of water include surface, ground, reuse and import; demands for water are classified as agricultural or municipal/industrial (includes household consumption); and where local demands may vary within a prespecified range to reflect changing patterns in water availability and water procurement costs.

The model is composed of two principal components: (1) a linear program formulated to determine the optimal allocation of all sources of water to all demands

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which assumes per unit procurement costs are fixed; and (2) a hydrology simulator capable of reflecting the impact of distribution alternatives upon per unit cost of delivery. Operating interactively, the two components are programmed to select the least cost delivery plan from the infinite number of possible delivery schemes.

The linear programming (LP) portion of the model is a network flow model designed to determine the least cost way to deliver specified quantities (demands) of water to all applicable nodes within an engineering model area. The demands can be satisfied from any defined, applicable source subject to supply constraints. The LP portion, formulated for solution using IBM's MPSX, simulates the resource flow conditions of each modeled area, and each application of the model is tailored to given, actual conditions.

The model provides a water allocation by source to each demand node which minimizes the summation of the capital, O&M and purchase costs based on specified per unit input cost data. New costs result following an allocation - as determined in the hydrology portion of the model - hence, there is a need to automatically iterate between the two models.

The hydrologic sumulation portion of the model provides a means for analyzing the performance and costs of a combined surface and subsurface water allocation plan selected by the LP. This portion is based on a conceptual representation of the hydraulic system, simulated as a network of storage and transfer elements (nodes and links, respectively).

This portion focuses primarily on the physical effects of an allocation plan upon the ground water basin(s) modeled. Surface flows are included to provide application and transfer data used to compute recharge to the ground water basins as would be experienced under the plan. It does not incorporate a cost analysis.

Given the optimal allocation of the LP, the simulator projects future ground water elevations and corresponding pumping depths under the selected ground water basin management plan. The model output also provides for a detailed accounting of pumping, purchase and distribution costs.

The focus of analysis is on geographic areas called nodes. A node may be of any size or shape but as currently operated, nodes commonly correspond to townships, subsets of irrigation districts, and municipalities. Supply and demand nodes need not be coincident in shape or size. Demand nodes may be classified as either agricultural or municipal-industrial and households. Supply nodes are classified as ground, surface, reuse or import source. Transfer nodes are used for routing and collecting water supplies of various types. A separate set of nodes is defined for each source of water and for each type of demand (use) so that nodal boundaries may be drawn to more readily correspond with conventional data sources and hydrologic and economic boundaries. Once boundaries are defined, nodal connections are specified which allow water to "flow" from node to node along linkages in a manner similar to that seen in reality.

An iterative procedure is established between the LP and the hydrology model wherein revised (updated) data from one is successively input to the other with the goal of obtaining a consistent (least-cost-delivery and hydrologically balanced) allocation plan within the modeled geographic area. The components are concurrently operated with automatic program execution control which proceeds to either a convergent solution or a maximum specified number of iterations. These conditions are determined, *a priori*, by the analyst.

More specifically, an initial LP solution is first derived. Report generator programs of IBM's MPSX are then executed to print user oriented tables summarizing the least cost delivery solution and to create temporary disk storage files specifying demands and ground water pumpage on a node by node basis. Next, the hydrology model is called. The demand and pumpage files are used in conjunction with hydrology input data to calculate recharge, internal ground water flows, dynamic pumping lifts which would result from the LP solution and associated pumpage delivery and purchase costs for each ground water supply link. The resultant cost data is stored on a temporary disk file and execution is returned to the LP where the objective function values are revised according to the cost file. After the objective function is revised, a new solution is obtained and the iterative cycle is repeated until closure is obtained or allowable iterations are exhausted.

Data requirements - Basic data required by the model includes the following:

(1) Nodal boundary and connection definitions.
(2) Magnitude and location of surface, reuse, and import supplies.
(3) Beginning elevations of the water table and the associated pumping depth, by node.
(4) Hydraulic factors which describe the natural behavior of the ground water system (e.g., subsurface flows of ground water), by node.

(5) Hydraulic factors which describe how the ground water system reacts to pumpage and recharge associated with use (e.g., recharge resulting from irrigation), by node.
(6) Per unit costs of distributing surface, reuse, and imported water (including per unit capital cost), by node.
(7) Per unit cost of pumping ground water one foot of lift (including well maintenance and replacement costs), by node.
(8) Reuse water generated per unit of water used for municipal/industrial purposes, by node.
(9) Recharge to the ground water system resulting from one unit of water used, by node.
(10) Upper and lower limits for activity in demand nodes.

When the above data are supplied to the model, the following results may be obtained:

(1) Total cost of meeting the demands for water given the available supplies.
(2) Water utilization and average water cost by node and aggregations of nodes which represent user groups.
(3) Numerous ground water statistics including average ending water table elevations, subsurface flows, recharge, changes in aquifer storage, etc., by node.
(4) Depletions of water supplies by node.
(5) Distribution of water among users, by water type.

The model is currently being utilized by the Water Commission in developing plans for allocating water from the Central Arizona Project. The geographic area being modeled encompasses the Central Arizona Water Conservation District. Results from the model have substantially contributed to the understanding of the role of water in an expanding Arizona economy.

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STUDENT AWARD PAPER

STOCHASTIC PREDICTION OF SEDIMENT YIELDS FROM STRIP MINE SPOILS OF THE ARID SOUTHWEST

by

Mark E. Auernhamer, Martin M. Fogel,
Louis H. Hekman, Jr. and John L. Thames

ABSTRACT

Mathematical simulation of the erosion process is accomplished by using a time series of hydrologic parameters as inputs into a modified form of the Universal Soil Loss Equation. A parameter to account for antecedent moisture conditions was found to improve the predictive success of the Universal Soil Loss Equation. The simulation predicts sediment yield resulting from a stochastic sequence of precipitation events on an experimental watershed. This sediment model will be used as a component in a larger, more complex hydrologic simulation model which can be used to determine optimum reclamation practices for the strip mined areas of the arid Southwest. Data from regraded strip mine spoils at the Black Mesa of Arizona are used in calibrating the model.

INTRODUCTION

Precise quantification of sediment yield from surface mined areas is essential when the current need for increased domestic energy production is coupled with the ever-present concern for environmental quality. The assessment of environmental impacts of a surface mine requires a knowledge of expected sediment yields from the area when the mine is in operation, and years after the reclamation of the land has been completed. Knowledge of the complex sedimentation process is also required to determine reclamation standards and to develop optimum cost-effective reclamation procedures.

The purpose of this paper is to present a method of predicting sediment yields from surface mined lands for individual precipitation events. The Universal Soil Equation is modified to account for antecedent moisture conditions, which directly affect the quantities of surface runoff and the associated sediment yield for a given event. Limited precipitation data from the Black Mesa is used to derive distributions of rainfall characteristics which were combined to simulate sediment yields for an extended period of time. The simulation gives an indication of expected amounts, probabilities of occurrence and return periods of extreme sediment events.

THE STUDY AREA

Strip mining of coal is taking place on the Black Mesa of northeastern Arizona. Peabody Coal Company operates two mines located on lands held in trust by the federal government for the Navajo and Hopi Indians.

Overburden ranging up to 120 feet in thickness is stripped using furrow techniques to expose the coal seams which range from 5 to 30 feet thick. After the coal has been mined, rows of unconsolidated spoil material are recontoured by reclamation crews to slope gradients averaging 8 to 15 percent and ranging up to 300 meters or more in length.

Sediment losses from the strip mine spoils are accelerated by the high erodibility of the soil due to its lack of structure and the absence of organic matter. Vegetation is sparse on freshly regraded spoils, increasing the potential for rainfall and runoff energies to dislodge soil particles and transport them from the surfaces of the spoils into on-site impoundments or into off-site drainages. The semi-arid climate and overgrazing compound the task of reclamation by severely hindering revegetation attempts on the recontoured spoils.

Experimental watersheds on the regraded mine spoil have been instrumented for nearly 4 years by the School of Renewable Natural Resources, University of Arizona, in cooperation with Peabody Coal Company. These study sites are being monitored for precipitation characteristics, surface runoff, infiltration rates, water quality, erosion rates and sediment yield. A 5.5 acre watershed on the reclaimed area is used for parameter values in the prediction model, and expected sediment yields are simulated for this watershed.

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THE PREDICTION METHOD

The Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965) for midwestern agricultural areas, was used as a basis for the prediction model. An additional parameter accounting for antecedent moisture conditions was incorporated into the USLE to improve its predictive accuracy for the study area. The modified equation is given as:

$$A = R\, I_{am}\, K\, (LS)\, C\, P \qquad (1)$$

in which A = the predicted soil loss (tons per acre); R = the rainfall erosion index (foot-ton-inches per acre-hour); I_{am} = the index of antecedent soil moisture; K = the soil erodibility factor; (LS) = the slope length and gradient factor; C = the cropping-management factor; and P = the erosion control practice factor.

The last four parameters of Equation 1 were assumed to remain constant for a particular area of interest over a relatively short period of time. Numerical values of these factors were obtained from previously published nomographs and tables (Wischmeier, Johnson and Cross, 1971; SCS, 1975). Values obtained for the study watershed are K = 0.35; (LS) = 2.72; C = 0.25; and P = 1.0.

The USLE has been most popularly used to predict annual soil loss using an average annual R factor. However, more recently, R values for each event have been used to predict sediment losses for individual storms to obtain greater accuracy (Williams, 1975; Fogel, Hekman and Duckstein, 1976). Renard, Simanton and Osborn (1974) found that a single event on the Walnut Gulch Experimental Watershed in southeastern Arizona accounted for as much as 55 percent of the total annual sediment yield. Therefore, since a few large storms can produce most of the annual sediment yield, it is important to be accurate in predicting the individual storm sediment yields.

Prediction by event also allows for the inclusion of an index of antecedent moisture. Obviously soil moisture directly affects the initiation time and total volume of surface runoff. It is therefore also apparent that the increased energy of larger runoff volumes would yield greater volumes of sediment. A form of a relation proposed by Chow (1964) was used to describe antecedent soil moisture, and is illustrated in Equation 2.

$$I_{am} = 15 \sum_{t=1}^{10} K^t P_t \qquad (2)$$

K is a constant assumed to be equal to 0.85; P is the precipitation amount for a single event in inches; and t is the length of time in days between the day in question, and the day on which the antecedent precipitation occurred. Another assumption made, is that the effect of rain occurring more than 10 days previous to the day in question is negligible. Calculated values of I_{am} for three different events are shown in Table 1.

Table 1. Calculated values for the rainfall factor, R and the antecedent moisture index, I_{am} for 3 individual events

	Date of Event		
	8/11/75	7/26/76	7/30/76
R	1.08	0.92	5.60
I_{am}	1.70	1.01	4.50

The rainfall factor, R is defined to be 1 percent of the erosion-index (EI) units in a single storm or in a year's rainfall. The EI units are a product of the total kinetic energy of a storm and its maximum 30-minute intensity in inches per hour. Equation 3 shows the relationship of Y, the kinetic energy of the rainfall in foot-tons per acre, to X, the rainfall intensity in inches per hour (Wischmeier and Smith, 1958).

$$Y = 916 + 331 \log X \qquad (3)$$

Calculated values of R for the three test events are illustrated in Table 1.

Average values of soil loss per event were obtained from 4 runoff plots on the experimental watershed. Due to the sporadic and infrequent occurrence of rainfall on the Black Mesa, soil loss data was obtained for only 3 events. The modified soil loss equation was applied using the parameters listed in Table 1, and the USLE was also applied using the R factors from Table 1. The values of the four constant parameters mentioned earlier were identical for both equations. Observed soil loss and the predictions of each equation are compared in Figure 1. Note the success of the modified equation for the second and third events. The antecedent moisture factor did not change the near-accurate prediction of the USLE for the second event. However, the prediction of soil loss for the third event by the modified equation was considerably higher than the prediction of the USLE and nearly equal to the observed volume. The prediction of the modified equation for the first storm was quite low, but still an improvement over the USLE.

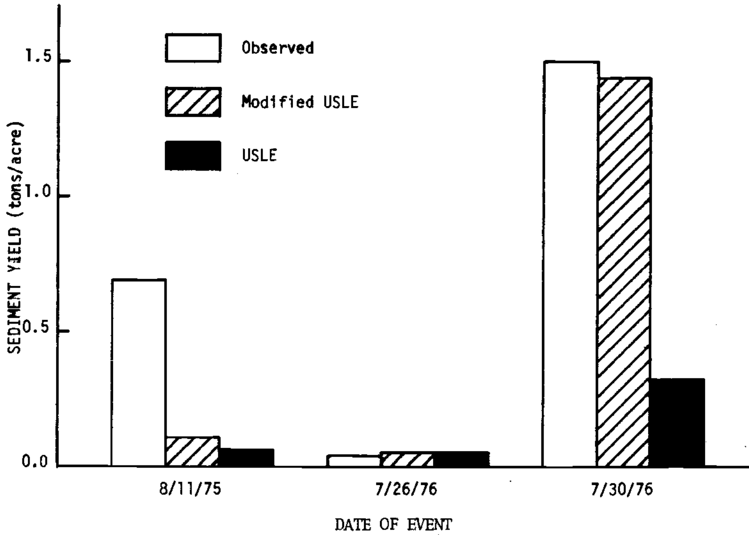

Figure 1. Comparison of observed soil loss to predictions by the modified soil loss equation and the Universal Soil Loss Equation

DEVELOPMENT OF SIMULATION TECHNIQUES

A severe limitation to applying either of the two equations to ungaged watersheds is the difficulty in obtaining the erosion-index units for a storm. Rainfall intensities are needed to calculate values of erosion-index, and it is nearly impossible to estimate intensities without a recording raingage. Attempts have been made to relate readily available precipitation data to the erosion-index units of a given storm. This would eliminate the need for tediously extracting the rainfall intensities from raingage charts, and enable the extrapolation of long-term historical data from one station to a nearby ungaged area.

Ateshian (1974) derived several equations which related the erosion-index of a storm to its precipitation amount and the duration of the event. One equation was found to accurately predict erosion-index units for precipitation characteristics that are representative of Hawaii, Alaska, and the coastal side of the Sierra Nevada and Cascade Mountains in California, Oregon, and Washington. The second equation was said to be representative of the rest of the United States, Puerto Rico, and the Virgin Islands. Upon comparing these equations to precipitation data from the Black Mesa, it was found that the first equation, for the Pacific coast fit the study data significantly better than the second equation. The equation used is:

$$EI = \frac{180\ P^{2.2}}{T_{min}^{\ 0.6065}} \tag{4}$$

where EI = the erosion-index units; P = the precipitation amount per storm in inches; and T_{min} = the duration of the event in minutes. Figure 2 shows a comparison of Black Mesa data to Ateshian's Type I equation.

Using hypothesized distributions of precipitation characteristics and equation 4, a distribution of EI units and subsequent distributions of sediment yield were simulated. Data from 3 years of climatic records taken at the study site were used to derive distributions for precipitation per event, event duration, and event interarrival time. Fogel, Hekman and Duckstein (1976) found that precipitation amount and storm duration are interrelated for summer events. To satisfy this relationship for simulation purposes, a separate distribution of duration was developed for each of 3 precipitation classes (0.0 inch to 0.09 inch; 0.1 inch to 0.25 inch; and greater than 0.25 inch). All five of the characteristics were hypothesized to be exponentially distributed as shown in Figures 3 and 4. Comparison of the observed data to the hypothesized distributions was made using the Kohmogorov-Smirnov goodness-of-fit test. At the significance level, α = 0.10, none of the hypothesized distributions could be rejected.

In addition to assuming that the precipitation characteristics were distributed exponentially for the simulation model, it was also assumed that all of the annual sediment yield was produced in the summer. This was defined to be the period from April 1 to October 31 when the likelihood for high-intensity convective storms is greatest.

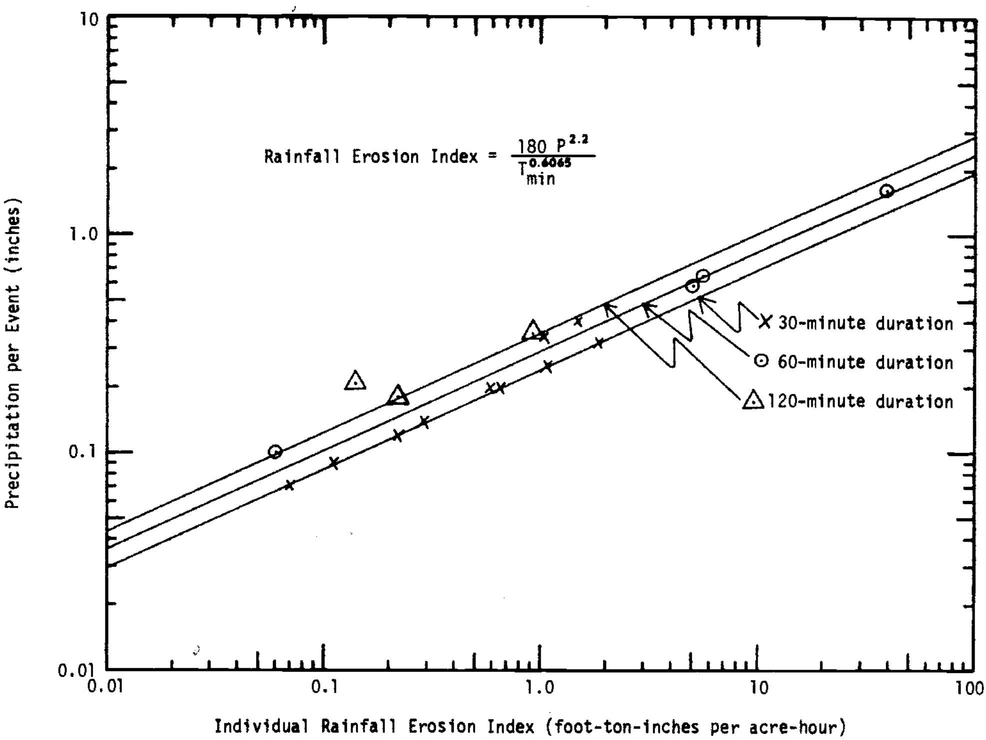

Figure 2. Comparison of Black Mesa data to Ateshian's Type I Equation for determining erosion-index units from durations and precipitation amounts

A computer model was developed to simulate 700 years of hypothetical sediment data using equations 1, 2, and 4. The probability mass functions (PMF) of sediment yield per event and annual sediment yield are shown in Figure 5. As yet, the model does not determine the lag time between the beginning of a rainfall event and the time when surface runoff is initiated. Minute amounts of sediment yield are therefore recorded for very low rainfall amounts that would not actually produce surface runoff. To account for this, the smallest class (0.00 to 0.05 tons/acre) was ignored when calculating the PMF of sediment yield per event. The mean volume of sediment produced in 1352 events was 0.19 ton per acre. A yield of less than 0.1 ton per acre occurred for more than 50 percent of the runoff events. The extreme event in 700 years of simulated data was 5.9 tons per acre from the experimental watershed. A mean annual volume of 0.53 ton per acre was predicted by the model.

CONCLUSIONS

Limited data has shown that the Universal Soil Loss Equation, modified to account for antecedent soil moisture may be used for predicting soil loss from reclaimed mine spoils on the Black Mesa. Additional instrumentation has been installed to measure sediment yield, and the results will be used to further validate and improve the existing model. An advantage of the proposed method is that estimation of the rainfall factor has been extremely simplified by using the relation developed by Ateshian (1974). This allows for use of the model where available rainfall data is limited.

The event-based approach enables simulation techniques to be applied to the modeling procedure. Simulations can provide planners and managers with probable volumes of sediment resulting from various mine reclamation practices and different surface treatments. The expected lifetime of water-holding installations on the reclaimed areas can also be more accurately evaluated using this method.

Incorporation of the sediment model as a separate routine in a comprehensive model to evaluate the hydrologic processes on the regraded mine spoils is being planned. With this model as a decision-making tool, optimum reclamation methods can be determined that will minimize the high cost of reclaiming the land and at the same time, minimize the impact of the mining operation on the surrounding area.

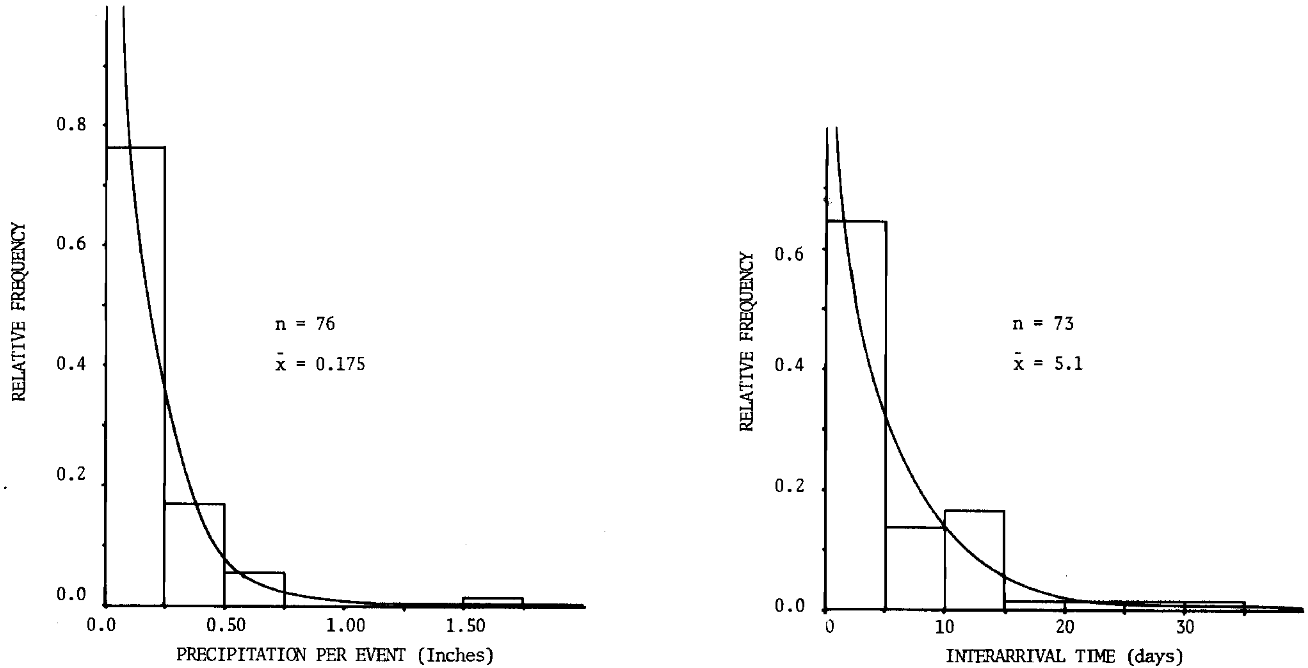

Figure 3. Illustrations of hypothesized exponential distributions compared to probability mass functions of the observed data for precipitation per event and event interarrival time

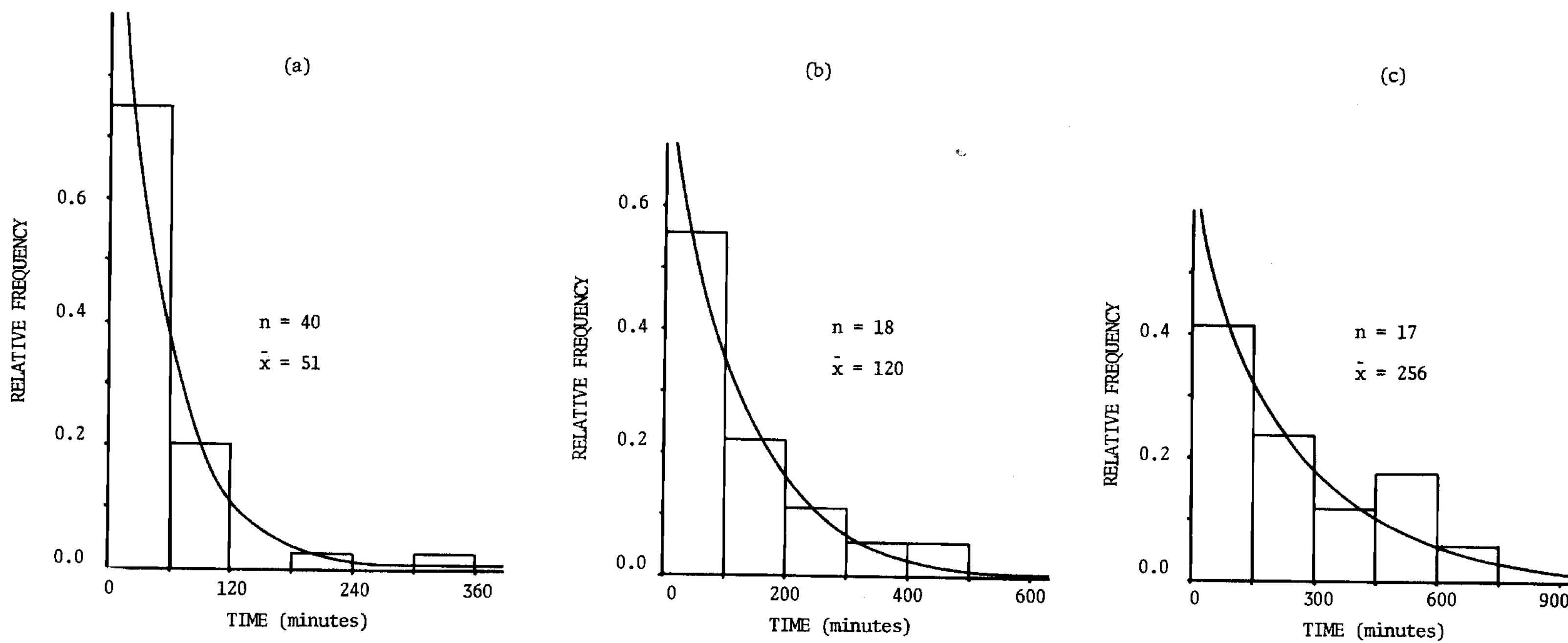

Figure 4. Illustrations comparing hypothesized exponential distributions of event duration to probability mass functions of the observed durations for precipitation events (a) between 0.00" and 0.09"; (b) between 0.10" and 0.25"; and (c) greater than 0.25"

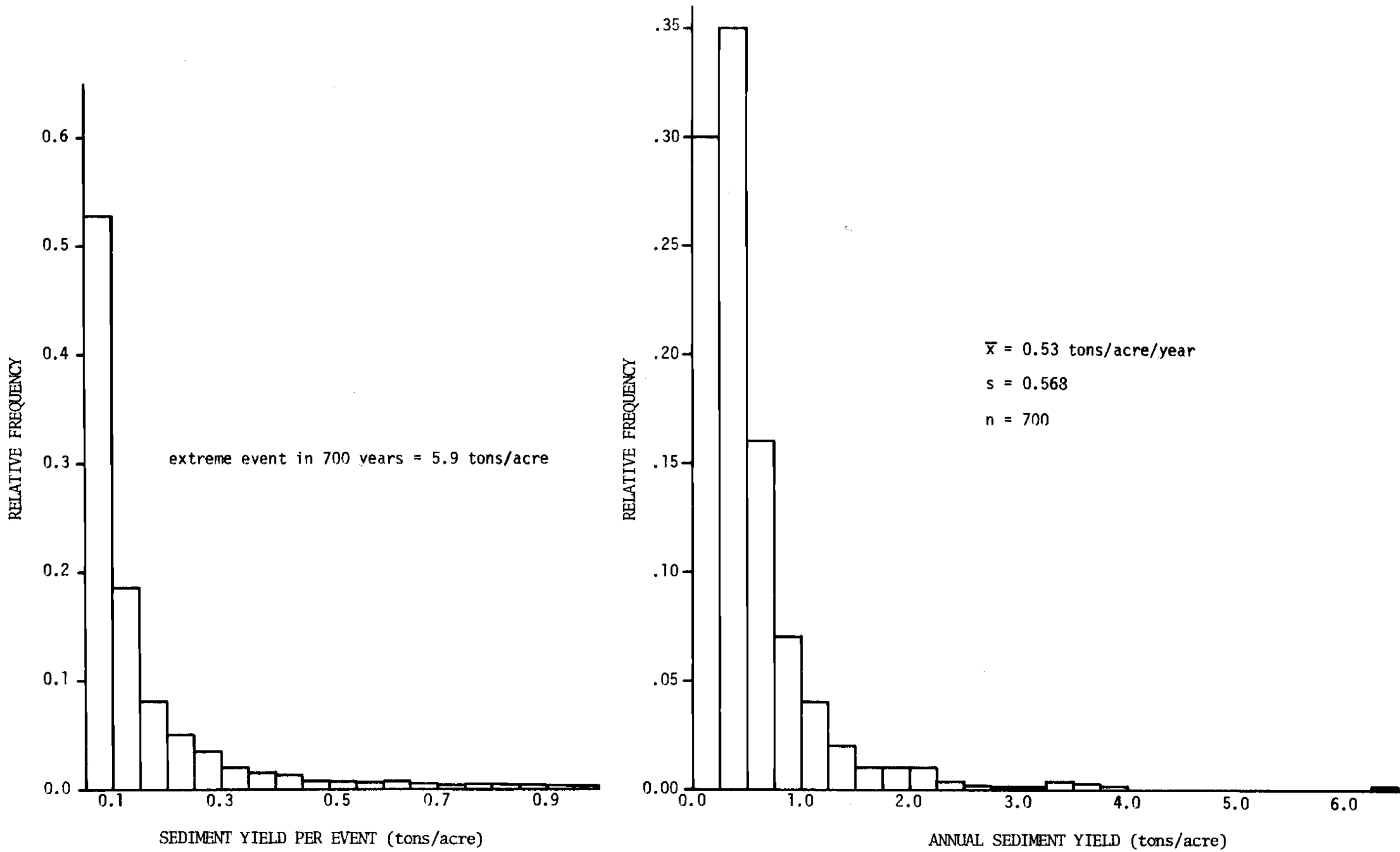

Figure 5. Probability mass functions of sediment yield per event and annual sediment volumes from 700 years of hypothetical data simulated by the model

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SOIL EROSION AND SEDIMENT CONTROL ON THE RECLAIMED COAL MINE LANDS OF SEMI-ARID SOUTHWEST

by

Tika R. Verma, John L. Thames and John E. Mills

ABSTRACT

Extensive disturbances are expected during the remainder of this century due to strip mining in the semi-arid West. Reclamation and revegetation of these disturbed areas is a slow process, primarily due to dry and harsh climatic conditions. Erosion and sediment losses are high. Monitoring of the soil erosion process is a crucial step in planning for a long lasting and stable rehabilitation of these disturbed areas. Erosion plots have been laid out to collect data for the Universal Soil Loss Equation for estimating soil loss from recontoured coal mine spoils. Effectiveness of different cultural and mechanical treatments for erosion control is also being evaluated. Since large-scale coal mining operation has just begun on the Black Mesa, preliminary data could be very effective and useful in Watershed Management planning.

INTRODUCTION

Energy demands are rising at a rapid rate in the United States and energy supplies are rapidly dwindling. As the cost of oil and natural gas continues to rise, coal will be looked to more and more as a major source of energy. The Southwest has approximately 62,000 square miles of coal deposits, about 3000 of which lie in Arizona. Most of this land is on the Black Mesa in the northeast corner of the state. Of the nearly 2.1 million acres comprising the Black Mesa, 14,000 have coal deposits underneath. These deposits are being stripped at the rate of 400 acres per year, a process greatly altering the soil profile and surrounding landscape. To reclaim the overburden strip material successfully, runoff and erosion rates must be accurately predicted. Three erosion plots were laid out on the Mesa for validating the Universal Soil Loss Equation (USLE).

Before the USLE can be used in the West, some factors must be modified to accommodate new environmental settings. The USLE is intended for estimating soil loss on large cultivated fields, and problems could arise when applying the equation to small watersheds. This is a subject which should be studied in more detail.

DESCRIPTION OF STUDY AREA

Black Mesa comprises 2.1 million acres of highlands gently sloping up from the Little Colorado River to an elevation of 8100 feet at its northern rim. The entire area is located on the Navajo and Hopi Indian reservations in northeastern Arizona. The climate is dry and harsh. Precipitation averages twelve inches per year, but is highly variable with long dry spells. Most of the summer precipitation is from convection storms, but with some coming as snowfall in winter. Temperatures range from about 27°F in January to about 80°F in July.

Vegetation on natural sites consists mainly of sagebrush and grasses, with pinyon and juniper at higher elevations. The reclaimed sites have no vegetation or at most, a sparse cover of Russian Thistle (Salsola kali).

Soils on the natural sites are poorly developed and severly eroded. They are generally shallow with an abundance of rock outcrops and are low in plant nutrients and organic matter. Overgrazing and the harsh environment have left the soil surface unprotected and vulnerable to erosional processes.

In an erosion study on the Mesa three 100-ft. plots were laid out on three different watersheds with slopes of 5, 8, and 17 percent. Each of the plots was on a uniform slope. A total of 240 nails were placed in each plot with four centimeters remaining above the soil surface. Three rows, each consisting of 80 nails, were placed in each plot 30, 60, and 90 feet from the top of the slope. Placing of the anils in each row was in four blocks with 1 foot spacing between the nails. Each block was 5 ft. wide and 4 ft. long.

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UNIVERSAL SOIL LOSS EQUATION

The Universal Soil Loss Equation was developed for use in areas east of the Rocky Mountains for considering problems specific to eastern United States. The equation is A = RKLSCP where A = soil loss in tons per acre, R = rainfall factor, K = soil erodibility factor, L = slope length factor, S = slope gradiant factor, C = cropping factor, and P = erosion control factor. The equation is adapted to Arizona by the U.S. Soil Conservation Service (1976).

Rainfall factor (R).

The R factor is the average number of erosion index (EI) units in a year's rainfall. EI values are found by multiplying the total kinetic energy in a storm by its maximum 30 minute intensity and dividing by 100. Kinetic energy for each storm can be calculated with the formula y = 916 +331 log (X) where y is the kinetic energy in foot tons per acre and x is rainfall intensity inches per hour (Wischmeier and Smith 1958). R values have been computed for eastern United States, but have not been for most areas west of the Rocky Mountains. The procedure outlined in Technical Note #32 of the WTSC-Portland (1975) can be used as a guide in computing this factor for the states of Washington, Oregon, California, Montana, Idaho, Wyoming, Colorado, and Arizona.

The states are divided into moisture and temperature zones and the procedure applied to each area. This paper will deal only with northeastern Arizona, which is designated as ustic in moisture regime and mesic or frigid for temperature zone. The term ustic is applied to areas where moisture is limited, but present at times when conditions are suitable for plant growth. Mesic implies annual soil temperatures of 47-59 degrees Farenheit; frigid indicates areas where annual soil temperature is less than 47 degrees. If there is no 0 horizon mean summer soil temperature is greater than 59 degrees, and if there is an 0 horizon mean summer soil temperature is 47 degrees or more.

R factors for Arizona have been calculated from the two year-six hour isopluvial map prepared by the National Weather Service. Values for the R factor can be determined from Figure 1, which was developed by the U.S. Soil Conservation Service.

Using rain gauge data from the Black Mesa for 1976, an R factor of 21 was obtained. This is lower than the 35 obtained from the Soil Conservation Service Planning Note No. 11 (Figure 1). These values are the average of a value which fluctuates with annual rainfall. The below average value obtained for 1976 reflects the low rainfall for that year and will be used for the soil loss estimates in this paper.

Soil erodibility factor (K).

This factor is a function of the physical and chemical properties of the soil. The K factor can be determined experimentally from a "unit plot" 72.6 feet long with a uniform 9% slope which is tilled up and down slope and is continuously fallow. For a given soil K is the erosion ratio per unit of erosion index from "unit" plots on that soil (Wischmeier and Smith 1965).

The overburden material consists mainly of sandstone and shale with smaller amounts of clay. All the reclaimed area has been recontoured to a slope of 20% or less and all precipitation falling on the site is contained within the area. The recontoured area has fine texture and a structure which can be defined as massive. It varies from 30 to 80 feet in depth, and infiltration rates are low because of crusting and puddling caused by its lack of structure and fine particles filling in the spaces between larger particles. This direct result of rain impact will be greatly reduced when vegetation becomes established, but until this is achieved infiltration rate will be quite low.

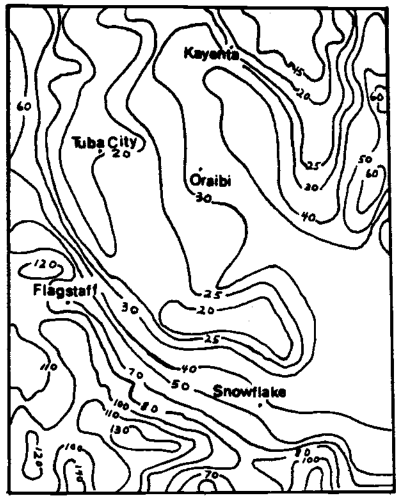
Wischmeier, Johnson, and Cross (1971) developed a nomograph to determine K using the following soil characteristics: percent silt and very fine sand, percent sand, percent organic matter, soil structure, and permeability. The last two are divided into 4 and 6 classes respectively (Figure 2).

The particle size distribution in the recontoured overburden material is 40% sand, 36% silt and very fine sand, and has no organic matter. It has a massive soil structure (Class 2), and slow infiltration rate (Class 5). Using the nomograph (Figure 2), a value of 35 was obtained for K.

Slope length (L) and gradient (S) factors.

Rate of soil loss is greatly affected by slope length and gradient. There two parameters have been studied separately in research, but can be combined as one topographic factor (LS) for field application. This factor is the ratio of soil loss per unit area on a field to the corresponding loss from the "unit plot" defined under the K factor. Values for LS can usually be taken directly from the chart (Figure 3). If there are several slopes on one field, use the value of slope with the greatest erodability. For convex and concave hills, use the steepest slope occurring on the hill.

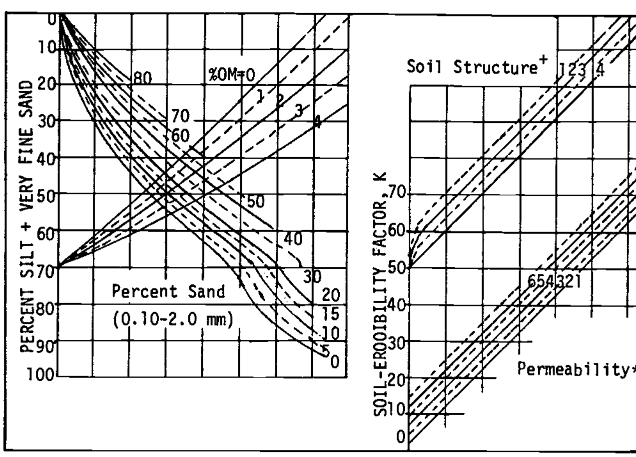
The study site consits of three slopes with uniform conditions except for slope gradient. Site A has a 5% slope, B an 8%, and C a 17%. All are 100 feet long. The LS factors for the plots are: A = .53, B = 1.0, and C = 3.1.



Scale-Statute Miles

0 20 40 60

Figure 1. Average annual values of R in northeastern Arizona. After-USDA, Soil Conservation Service, Phoenix, Arizona, March 1976. (Values on this map include R s where snowmelt is a factor).



+1 very fine granular
2 fine granular
3 med. or coarse granular
4 blocky, platy or massive

*1 rapid
2 mod. to rapid
3 moderate
4 slow to mod.
5 slow
6 very slow

Figure 2. Soil Erodibility Nomograph. After-W. H. Wischmeier(1971).

Table 1. "C" Values for Permanent Pasture, Rangeland, and Idle Land[1/]

Vegetal Canopy			Cover That Contacts the Surface					
Type and Height of Raised Canopy[2/]	Canopy Cover[3/] %	Type[4/]	Percent Ground Cover					
			0	20	40	60	80	95-100
Column No.:	2	3	4	5	6	7	8	9
No appreciable canopy		G	.45	.20	.10	.042	.013	.003
		W	.45	.24	.15	.090	.043	.011
Canopy of tall weeds	25	G	.36	.17	.09	.038	.012	.003
or short brush		W	.36	.20	.13	.082	.041	.011
(0.5 m fall ht.)	50	G	.26	.13	.07	.035	.012	.003
		W	.26	.16	.11	.075	.039	.011
	75	G	.17	.10	.06	.031	.011	.003
Appreciable brush	25	G	.40	.18	.09	.040	.013	.003
or brushes		W	.40	.22	.14	.085	.042	.011
(2 m fall ht.)	50	G	.34	.16	.085	.038	.012	.003
		W	.34	.19	.13	.081	.041	.011
	75	G	.28	.14	.08	.036	.012	.003
		W	.28	.17	.12	.077	.040	.011
Trees but no appre-	25	G	.42	.19	.10	.041	.013	.003
ciable low brush		W	.42	.23	.14	.087	.042	.011
(4 m fall ht.)	50	G	.39	.18	.09	.040	.013	.003
		W	.39	.21	.14	.085	.042	.011
	75	G	.36	.17	.09	.039	.012	.003
		W	.36	.20	.13	.083	.041	.011

1/ All values shown assume: (1) random distribution of mulch or vegetation, and (2) mulch of appreciable depth where it exists. Idle land refers to land with undisturbed profiles for at least a period of three consecutive years.

2/ Average fall height of waterdrops from canopy to soil surface: m = meters.

3/ Portion of total-area surface that would be hidden from view by canopy in a vertical projection, (a bird's-eye view).

4/ G: Cover at surface is grass, grasslike plants, decaying compacted duff, or litter at least 2 inches deep.

W: Cover at surface is mostly broadleaf herbaceous plants (as weeds with little lateral-root network near the surface, and/or undecayed residue.

Plant cover factor (C).

This factor, often called the cropping factor, was defined for agricultural land as the ratio of soil loss from land under specified cropping conditions to loss from tilled, continuously fallow land, all other factors being equal. In extending the C factor to other land uses, two interrelated parameters come into play: (1) vegetative cover on the soil surface and (2) canopy cover (7). C factors have been developed for pastures, range and idle land; woodland; and for cropland and hayland. Table A shows computed C values for pasture, rangeland, and idle land.

Reclaimed land on Black Mesa has no appreciable canopy cover for most of the year. Vegetation grows for about three months in summer consisting of Russian Thistle, with a cover density of about 20%. The plant cover is present when most of the major rains occur which provides some protection from erosion. A plant cover factor of .24 was taken from Table A.

Erosion control factor (P).

If some erosion control has been implemented in an area, it must be taken into account to accurately predict soil erosion. The P factor is the ratio of soil loss with control practices in effect to soil loss on land with straight row cropping up and down slope. P values have been compiled for contouring, contour strip cropping, control irrigated furrows, and terracing (for prediction of contribution to off-field sediment load). If no erosion control is implemented, this factor is equal to 1. Values for slopes of 2 to 24% are listed below.

Land	P Values			
Slope (%)	Contouring	Contour Stripcropping	Contour Irrigated	Terracing
2.0 - 7	0.50	0.25	0.25	0.10
8.0 - 12	0.60	0.30	0.30	0.12
13.0 - 18	0.80	0.40	0.40	0.16
19.0 - 24	0.90	0.45	0.45	0.18

There have been no erosion control practices applied to the study sites on the Black Mesa. After the overburden material was dumped, the only mechanical manipulation was regrading piles to reduce their slope, which has been considered in the slope gradient factor. When tractors (D-9 cats) regraded the slopes they moved only up and down slope so that their tread marks ran perpendicular to the slope direction. This will help reduce erosion while the tracks last, but they are erased after the first major rain. The P factor for the study sites is equal to one.

RESULTS AND CONCLUSIONS

The erosion plots on the Black Mesa had an average of 0.17, 0.49 and 0.57 centimeters of erosion on the 5%, 8%, and 17% slopes respectively. Expressed in tons per acre these figures are 0.04, 0.13, and 0.15.

These values represent nine months of data from July 1976 to March 1977, and can only be considered as preliminary. However, erosion during the rainy season from July to September. The rain from March 1976 to July 1976 amounted to less than one inch and there was no runoff. The same period in 1977 should have a similar rainfall and runoff pattern.

The erosion predicted for the three plots by the USLE is .935, 1.764, and 5.47 tons per acre for the 5%, 8%, and 17% slopes. These values are all much higher than those measured on the study plots.

More data should be collected from the erosion plots for long time averages to compare with the USLE. Runoff sediment plots are presently being installed on the Black Mesa which will provide additional data for comparison studies to the erosion plots and to the Universal Soil Loss Equation estimates.

The major reason for the difference between estimated and actual soil loss may be explained by the soil factor (K) and rainfall factor (R) of the USLE. More extensive studies should be carried out on these factors as they apply to disturbed soils. Modification may be necessary in these factors to apply the USLE to reclaimed strip mined land in the southwest.

While no definite conclusions can be drawn from this preliminary report, it indicates where problems will be encountered and shows the direction that future studies should be directed for accurate estimated of erosion with the Universal Soil Loss Equation.

SLOPE-EFFECT CHART (Topographic Factor, LS)

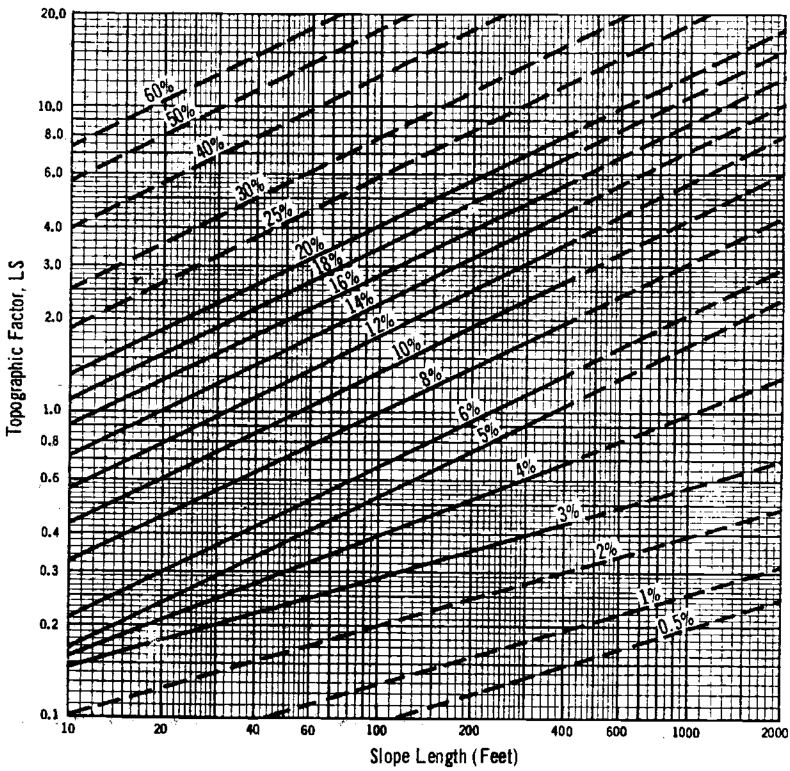


Figure 3. After U.S. Department of Agriculture, Technical Release No. 51 (1975). The curves were derived by the formula:

$$LS = \left(\frac{\lambda}{72.6}\right)^m \left(\frac{430x^2 + 30x + 0.43}{6.57415}\right)$$

where λ = field slope length in feet and $m = 0.5$ if $s = 5\%$ or greater, 0.4 if $s = 4\%$, and 0.3 if $s = 3\%$ or less; and $x = \sin\theta$. θ is the angle of slope in degrees.

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RECLAMATION OF ORPHANED MINE SITES AND THEIR EFFECT ON THE WATER QUALITY OF THE LYNX CREEK WATERSHED

Tika R. Verma and Ernesto N. Felix

ABSTRACT

Lynx Creek Watershed is located eight miles southeast of Prescott, Arizona, on the Prescott National Forest. The watershed consists of 13,600 acres, which are National Forest Lands. Approximately 600 acres in the watershed are patented mining claims. Gold was discovered in Lynx Creek in 1863 and the watershed was extensively mined for gold, silver and copper. The aftermath of the mining has resulted in numerous mine shafts, waste dumps and mill tailing ponds that were abandoned after the ore was played out. Drainage from the orphaned mine sites contribute a certain extent of toxic mineral and sediment pollution into Lynx Creek and eventually into Lynx Lake. Lynx Creek carries runoff which is slightly acidic in nature and has high concentrations of copper, manganese, iron, zinc and sulfates. The mineral pollutants have reduced the recreational and fisheries potential of the Lake. The Sheldon Mine complex consisting of a waste dump and the mill tailing dump were considered the major sources of pollutants into the Lake. The Sheldon Tailings pond was rehabilitated during the summer of 1975 and the waste dump during the summer of 1976 as part of a reclamation study that is being sponsored by SEAM (Surface Environment and Mining). The study is being conducted cooperatively by the School of Renewable Natural Resources, University of Arizona, and the Prescott National Forest. Both sites were culturally treated and dressed with lime and topsoil. Studies are currently being conducted to measure the beneficial effects of the reclamation projects.

INTRODUCTION

History of mining.

Mining in the Lynx Creek Watershed began in 1863 when the Walker party discovered gold in Lynx Creek. Numberous piles of rock along the creek tell the story of early placer operations. Following that period, stamp milling of the oxidized surface ores was carried on during the latter part of the last century. As the ores became base at a depth of 100 to 250 feet, it ceased to be possible to save the gold by amalgamation; shipping concentrates did not pay, the grade also became low and milling ceased. When the Humbolt Smelter was built, it offered opportunity to ship some of the richer base ores. After this, the Sheldon Mill was constructed and operations began in 1924 and continued up to March 1927 when work was stopped to permit enlarging and deepening of the Sheldon Shaft. The mill was again operated in the latter part of 1929 and up to October 1930. The mill treated up to 100,000 tons of ore. The waste from the mill working the ore that came out of the Sheldon was pumped to the Sheldon Tailings Pond located just a short distance away (Figure 1).

A number of underground mines were operated on and off until 1952. These operations are evidenced by the presence of numerous shafts, waste dumps and mill tailing ponds.

The Lynx Creek Watershed is in the Bradshaw Mountains of North Central Arizona. It is located five miles southeast of Prescott, Arizona, on the Prescott National Forest. Lynx Lake is in the watershed that has a drainage area of 13,600 acres. The reservoir, built in 1962 by the Arizona Game and Fish Department, is 55 surface acres in size. The lake is the only cold fisheries water within a 50-mile radius of Prescott, thus making it very valuable for recreation. A recent cost benefit analysis connected with a proposed sediment dam to be built several miles above the lake, placed the 1975 beneficial use value at $328,625. The recreational use numbers were obtained from 1975 USDA Forest Service, Recreation Information Management (RIM) data. Fishermen use data was provided by Region II of the Arizona Game and Fish Department in Flagstaff, Arizona. Monetary value figures (Table 1) for recreational visitor days (R.V.D.'s) for dispersed site use and developed site use are from Resource Protection Act, Supplemental Index and fisheries values from "The Demand for and Value of Hunting, Fishing and General Recreation in Arizona", Technical Bulletin 211.

According to the Arizona Game and Fish Department (A.G.F.), the lake has never been very productive as a trout habitat. Only catchable trout, ranging from 7 to 9 inches, are planted. Fingerling trout of

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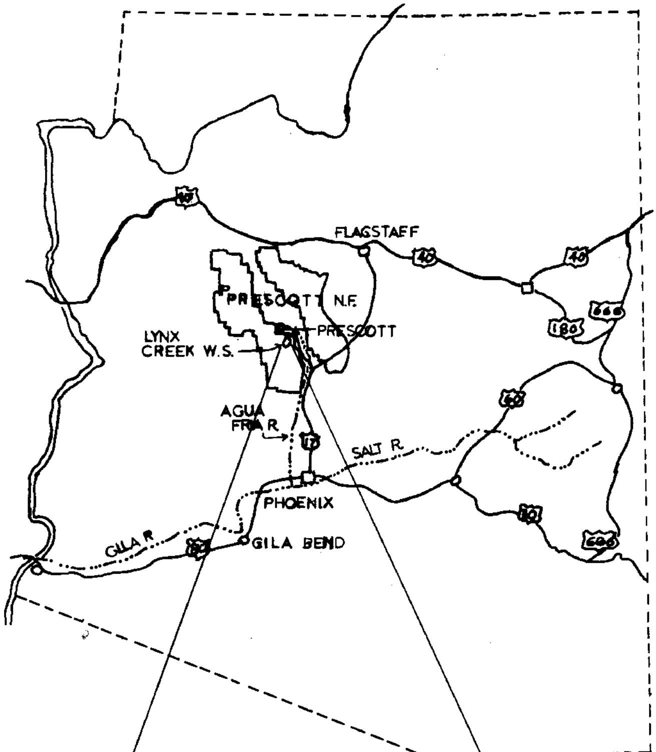

Figure 1. LOCATION OF LYNX CREEK WATERSHED ON THE PRESCOTT NATIONAL FOREST

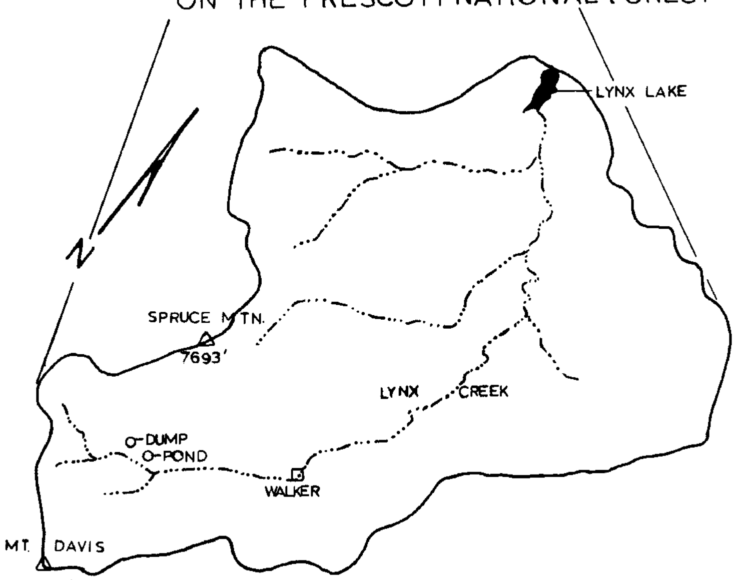

Table 1
1975 Recreational Benefits of Lynx Lake

Type of Use	Amount of Use	Value of Use	Beneficial Use
Developed sites	57,500 R.V.D.	$1.15/R.V.D.	$ 66,125
Dispersed Use	7,400 R.V.D.	$5.00/R.V.D.	37,000
Fishing	15,000 Angler Days	$15.00/A.D.	225,500
		Total	$328,625

3 to 4 inches were stocked in October 1975. They were measured six months later and had grown an average on one inch. Normal growth for trout fingerlings usually averages an inch and a half per month. Fingerling trout are not planted due to the lake's inability to produce a food chain. Also, predation by the warm water fisheries population (sun fish) provides too much competition for survival by the fingerlings. In the 1972 study by the A.G.F. (Rathum) it stated that the growth of zoolplankton, and phytoplankton was inhibited by copper and zinc concentrations in the lake. A 1974 study (February to September) conducted by Arizona State University (Crane) indicated that the heavy metals in solution in the lake are not toxic to phytoplankton algae. The mean phytoplankton standing crop was found to be low (1230 organisms/ml). The study identified a total of 28 species, indicating a low species diversity. The study also suggested that the low standing crop and limited diversity of the phytoplankton is a result of the low nitrogen and phosphorus concentrations and is not due to toxicity of certain trace elements. It is possible, however, that the heavy metals are sediment bound or precipitate at the higher pH levels found in the lake.

Climate.

Lynx Creek Watershed is located in a semi-arid climate of abundant sunshine and low humidities and temperatures. Geographically, the area is situated in an intermediate and comparatively mountainous region between the high forested plateaus of Northern and Eastern Arizona on the one hand, and the low desert floor of Western and Southern Arizona on the other. May is the driest month of the year and August is the wettest (Table 2). Precipitation is light and has two sources; in the winter from Pacific storms and in summer from thunderstorms. As the usual winter storm track is to the north, brief passages of weather fronts account for 30 percent of the precipitation. The worst winter weather is associated with the movement eastward of cold, low pressure systems from the west.

The summer thunderstorm season brings nearly half of the year's rainfall. In this season, thunderstorms occur on the average of every other day. Occasionally, in late August or early September, remnants of dissipated tropical storms invade Southern Arizona from the southwest, bringing several days of low clouds and heavy rains.

Geology.

The surface geology of the watershed is relatively complex with intermixing of Bradshaw granite and Yavapai schist. Steep mountain peaks and ridges border the watershed on three sides. Spruce Mountain, 7693 feet, and Spruce Mountain Ridge border the west. Mount Davis, 7950 feet, borders to the south. Several unnamed ridges and peaks, the highest being 6968 feet, border to the east. Four main formations are found in the watershed (Table 3).

The oldest rocks are the Yavapai Schists that vary in character from thin schists to compact slates. The Bradshaw Granite is later than the schists and intruded into them. Paleozoic sand stones and limestones are present some miles to the northeast of the watershed but none are existent in the watershed. It is speculated that the watershed was probably covered at one time with them. Granodiorite as seen underground is a rather coarse-grained, light gray granitic rock with considerable horn blende and biotite. On the surface, it weathers into darker gray spheroidal boulders where there is little mineralization. Rhyolite occurs as wide aicd rock dikes in the watershed.

Soils and vegetation.

Granitic soils are weakly developed shallow, sandy loams that contain variable amounts of gravel, cobble stone, and rock outcrop on the surface and throughout the profile. Schist soils are chiefly very shallow, weakly developed, gravelly loams that rest directly on bedrock. Vegetative type of the watershed is associated with soil type (Table 4). There are five vegetation types in the watershed, Ponderosa Pine, Chaparral, Pinyon-Juniper, Open-Grassland and Mixed Conifer. The types and their vegetative species are in Table 5.

Hydrology.

Water yields into Lynx Lake are highest during the spring snowmelt and in late summer during the rainy season. Inflow in low precipitation years is estimated at 400 acre-feet. Inflow in a high precipitation year is 2070 acre-feet. Inflow in an average precipitation year is 560 acre-feet.

TABLE 2
Climatological Summary
Station: Groom Creek (1951-1960)
Lat. N. 34 29', Long. W. 112 27', Elevation 6100 ft.

TOTAL PRECIPITATION

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Ann
1951	2.26	1.24	.70	2.80	1.16	00	4.05	7.24	.06	1.32	1.66	5.80	28.29
1952	3.31	.82	5.51	2.28	T	.25	5.11	4.74	1.45	00	1.55	1.00	26.02
1953	.61	.31	.62	1.02	.63	00	9.53	6.25	T	T	.69	.75	20.41
1954	2.90	1.30	6.35	.10	.58	1.52	5.84	2.81	3.10	.33	.31	.32	25.46
1955	3.46	.75	.20	1.61	.10	2.93	5.95	9.58	.03	1.16	1.29	1.76	28.82
1956	.83	.79	.01	.35	00	.53	2.56	2.45	.35	1.32	.00	.17	9.36
1957	5.82	2.17	1.06	1.02	1.45	1.40	2.51	6.96	00	4.43	.60	.96	28.38
1958	.58	4.55	4.55	2.85	.57	1.03	1.06	8.90	6.64	1.66	1.20	T	33.59
1959	.70	3.78	00	.81	.52	.64	3.81	4.73	.55	1.60	.86	6.80	24.80
1960	2.37	1.71	.79	.16	.30	.51	1.92	6.06	1.05	4.45	1.10	.12	20.54
Per	2.28	1.74	1.98	1.39	.53	.88	4.23	5.97	1.32	1.63	.93	1.77	24.56
Yrs	10	10	10	10	10	10	10	10	10	10	10	10	
Per	2.41	2.15	1.91	1.39	.50	.61	3.71	4.45	1.40	1.53	.96	1.97	22.99
Yrs	17	16	16	15	18	18	19	19	19	19	19	18	

MEAN NUMBER OF DAYS WITH PRECIPITATION ≥ 0.10 or ≥ 0.50 inch

0.10	6	5	4	2	2	2	9	10	3	5	2	2	52
Yrs	7	7	7	7	7	7	7	7	7	7	7	7	
0.50	2	1	2	1	+	1	3	4	1	1	1	1	18
Yrs	10	10	10	10	10	10	10	9	10	10	10	10	

MEAN TEMPERATURE

Per	34.2	35.5	39.4	46.5	53.9	63.4	68.2	65.5	62.7	52.8	41.5	35.6	49.9
Yrs	10	10	10	10	10	10	10	10	10	10	10	10	
Per	33.7	36.9	40.5	47.6	54.3	63.0	68.4	66.3	63.0	52.8	42.2	36.3	
Yrs	15	15	15	15	15	15	15	15	15	15	15	15	50.4

MEAN DAILY MAXIMUM TEMPERATURES

Per	48.6	50.8	54.9	63.2	71.2	82.2	84.8	80.6	80.1	69.8	57.7	51.1	66.3
Yrs	10	10	10	10	10	10	10	10	10	10	10	10	
Per	48.1	52.7	56.7	64.8	72.1	82.3	84.8	81.3	80.0	69.3	58.7	51.9	66.9
Yrs	15	15	15	15	15	15	15	15	15	15	15	15	

MEAN DAILY MINIMUM TEMPERATURES

Per	19.7	20.1	23.8	29.6	36.5	44.6	51.6	50.4	45.2	35.7	25.2	20.1	33.5
Yrs	10	10	10	10	10	10	10	10	10	10	10	10	
Per	19.4	21.0	24.1	30.3	36.7	43.5	51.9	50.8	45.9	36.2	25.8	20.6	33.9
Yrs	15	15	15	15	15	15	15	15	15	15	15	15	

HIGHEST TEMPERATURE

Per	71	74	73	87	90	96	98	90	93	87	76	67	98
Yrs	10	10	10	10	10	10	10	10	10	10	10	10	
Per	71	74	85	90	91	101	104	104	98	87	80	71	104
Yrs	15	15	15	15	15	15	15	15	15	15	15	15	

LOWEST TEMPERATURE

Per	-7	-4	4	11	19	24	36	36	20	18	3	1	-7
Yrs	10	10	10	10	10	10	10	10	10	10	10	10	
Per	-7	-4	4	11	19	23	36	32	27	8	3	-6	-7
Yrs	15	15	15	15	15	15	15	15	15	15	15	15	

Table 3
Main Formations in the Lynx Creek Watershed

Material	Period	Era
Soil and gravel Rhyolite	Quaternary Tertiary	Cenezoic or Recent
Granodiorite or Quartz-diorite	Tertiary or Cretaceous	Mesozoic or Intermediate
Sediments now all eroded away	Carboniferous to Cambrium	Paleozoic
Bradshaw granite Yavapai schists	Algonkian or Pre-Cambrian	Archean

Table 4
Vegetative Type and Associated Soils of Lynx Creek Watershed

Pine Type Soils

Mirabal gravelly sandy loam, 20-60% slopes
Mirabal-dandrea gravelly loam, 20-60% slopes
Dandrea gravelly loam, 20-60% Slopes

Chaparral Type Soils

Arp gravelly clay loam 0-20% slopes
Arp gravelly clay loam 20-40% slopes
White House gravelly and cobbly loams, 8-15% slopes
Barkerville very stony, sandy loam, 20-60% slopes
Barkerville very cobbly, sandy loam, 20-60% slopes
Moano gravelly loam, 0-10% slopes
Moano very rocky and gravelly loams, 30-60% slopes

Grassland Soils

Lynx loams, 0-5% slopes
White House gravelly loams, 0-8% slopes

The sedimentation rate of the lake is estimated to be 2.4 acre-feet per year (3872 cubic yards).

Watershed improvement efforts.

Watershed improvement efforts were initiated after it was realized that serious water pollution problems existed in the watershed. Investigative efforts to identify the pollution problems were made by the Arizona Game and Fish Department, Arizona State Department of Health, Environment Health Services Division of Water Pollution Control, U.S. Bureau of Mines, the USDA Forest Service, Prescott National Forest and the Department of Watershed Management, University of Arizona at Tucson (Figure 2). Various State and Federal agencies studied the problem and most studies concluded that mineral pollution was the major cause. The source of pollution was believed to be from old mine tailing ponds and old mine dumps. These mine sites were the main suspected sources of toxic mineral bearing sediment that was being transported into the lake during high runoff periods. The sediment is slightly acidic in nature and has high concentrations of copper, iron, zinc, and sulfates. Rodiek, Verma and Thames (1974) found that water pH increase gradually from upstream, just below the Sheldon mine tailings pond to downstream before the Lynx Creek enters Lynx Lake (Figure 3). Changes in other water qualities were also noted (Table 6).

In 1972, the U.S. Department of Agriculture formed the Surface Environment and Mining Program (SEAM). Its main function was to coordinate Forest Service efforts with other groups involved in mining and reclamation.

SEAM financial support enabled the University of Arizona, in cooperation with the Prescott National Forest, to initiate a reclamation program of the Sheldon Mine complex.

SEAM Sheldon Mine complex reclamation project.

The Sheldon Mine Complex consists of two areas, the Sheldon Mine Tailings pond and the Sheldon Mine waste dump. The former is approximately 2.6 acres in size and the latter approximately 4.5 acres in size.

The material at the pond is mineral refuse that was piped there from the Sheldon Mill. The material is extremely fine textured with a very high moisture holding capacity. Pre-treatment analysis of the

Figure 2. LYNX LAKE WATER QUALITY
DEPTH CHEMICAL SAMPLES AUGUST, 1971

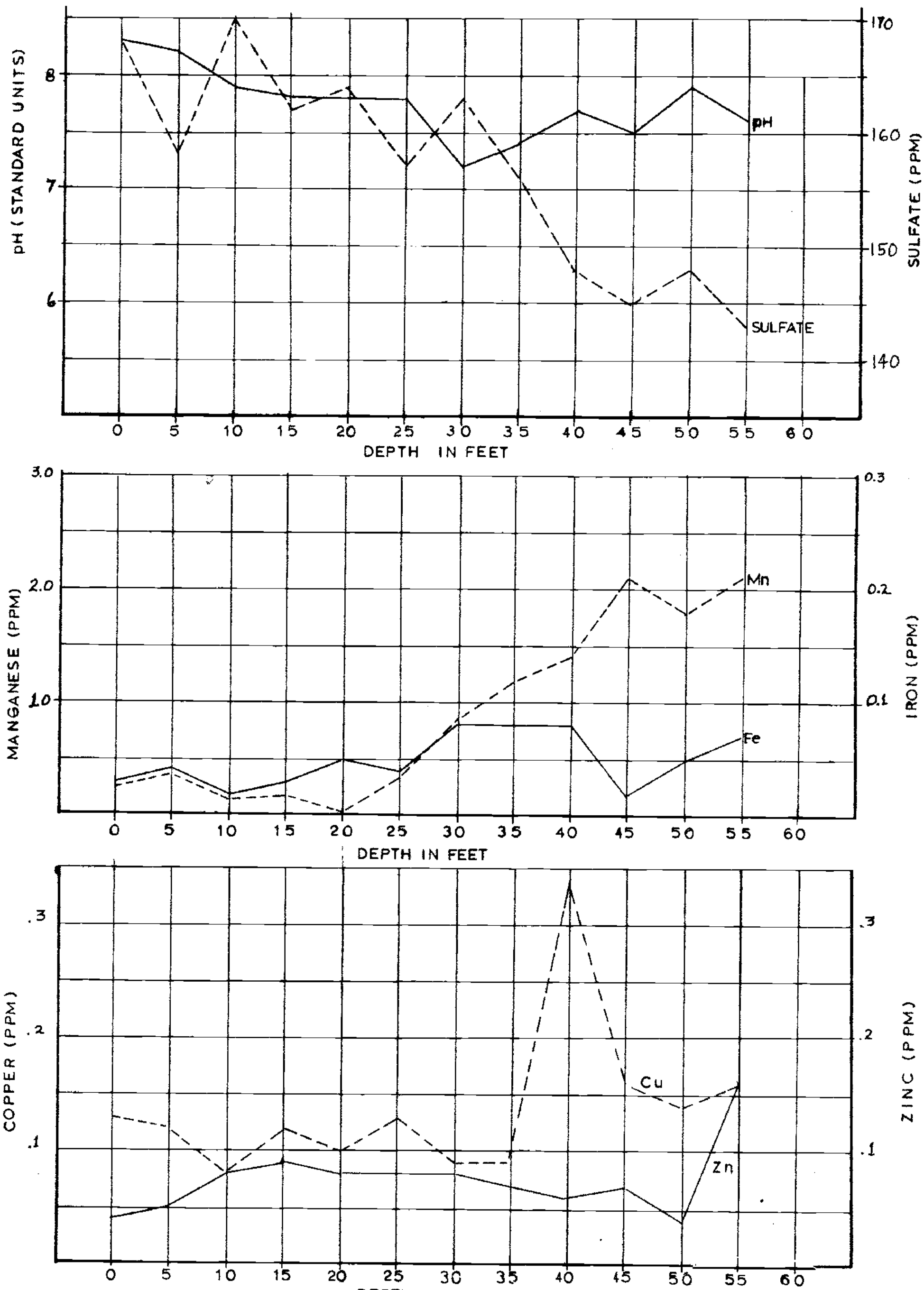

Figure 3. LYNX CREEK WATERSHED WATER QUALITY 1967-75

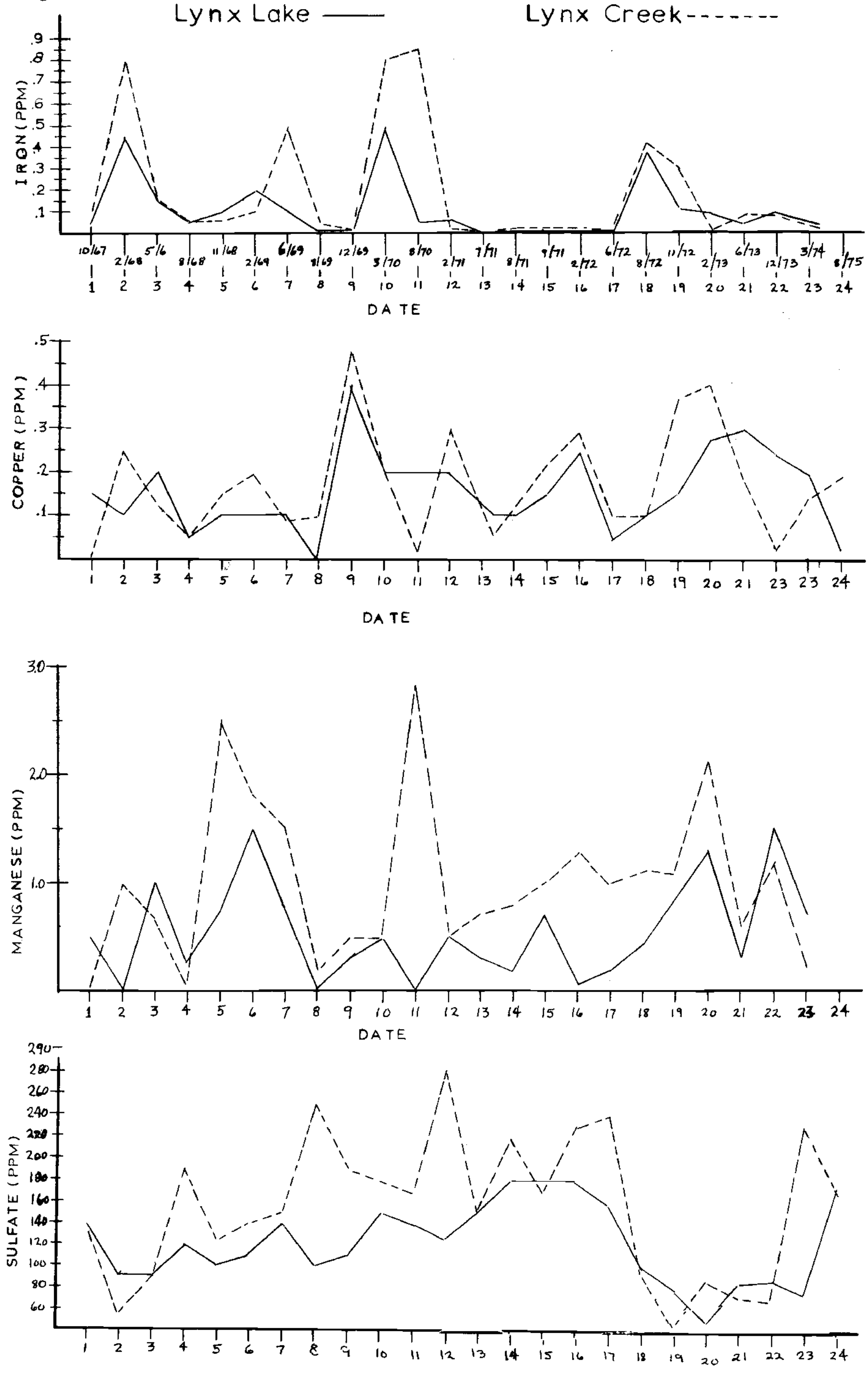

Figure 3. LYNX CREEK WATERSHED WATER QUALITY 1967-75
Lynx Lake ——— Lynx Creek-------

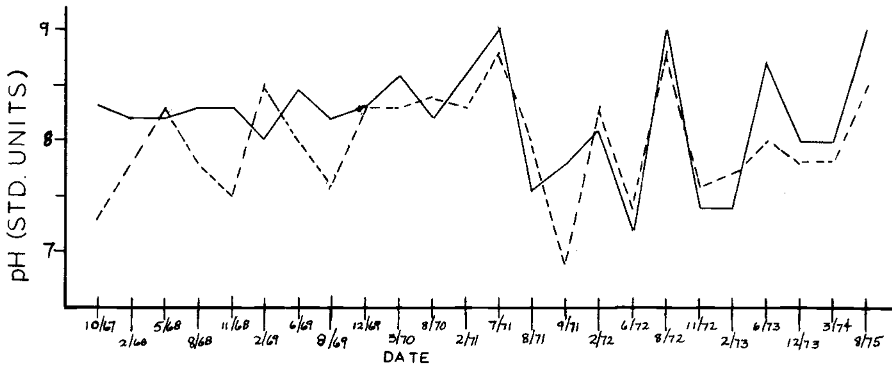

Table 5
Percent Vegetation Type and Vegetative Species

Ponderosa Pine Type (45%)

Pinus ponderosa	Ponderosa Pine
Quercus gambelii	Gambel Oak
Quercus emoryi	Emory Oak
Juniperus species	Juniper
Arctostaphylos pringlei	Pringle Manzanita
A. pungens	Point leaf Manzanita
Bouteloua species	grama grasses

Chaparral Type (33%)

Quercus turbinella	Turbinella or Scrub Oak
Arctostaphylos pringlei and A. Pungens	Manzanita
Rhamnus crocea	Hollyleaf Buckthorn
Cercocarpus betuloides	Birch leaf Mountain Mahogany
Ceanothus fendleri	Spiny Ceanothus
Rhus trilobata	Skunkbush
Juniperus species	Juniper
Pinus monophylla, P. edulis	pinyon

Pinyon-Juniper (9%)

Juniperus species	Juniper
Pinus edulis, P. monophylla	Pinyon
Quercus turbinella	Scrub Live oak
Bouteloua species	grama grasses
Arctostaphlos species	manzanita

Grassland (3%)

Bouteloua gracilis	Blue Grama
B. curtipendula	Side Oats Grama
Sporobolus cryptandrus	Sand Dropseed
Erodium cicutarium	Filaree
Quercus turbinella	Shrub Live oak
Scleropogon brevifolius	Burro Grass
Gutierrezia	Snakeweed
Muhlenbergia torreyi	Ring Muhly
Lycurus phleoides	Wolf tail

Mixed Conifer (10%)

Pseudotsuga menziesii	Douglas Fir
Abies Concolar	White Fir
Pinus Ponderosa	Ponderosa Pine

Table 6
Water Quality Changes with Increased Distance

Station	pH	Cu (ppm)	Fe (ppm)	Zn (ppm)	SO_4 (ppm)
8*	3.0	3.0	5.8	9.0	470
11	2.9	3.7	5.3	9.6	410
14	5.8	0.01	0.25	0.37	55
13*	6.4	0.01	1.4	0.06	43

*Station 8 is immediately below the Sheldon tailings pond and Station 13 is at lake inlet.

tailings solution sample by U.S. Bureau of Mines showed a pH of 2.1 and assayed in grams per liter, 0.28 Cu, 1.0 Zn, 4.86 Fe, 16.1 SO_4 and 0.53 Ca.

The material at the mine dump is a mixture of shaft rock waste and reject material discarded from the Sheldon Mill. Pre-treatment material analysis for pH at the dump at 16 plots ranged from 2.5 to 8.0 with an average of 5.3.

Landscape design considerations.

Primary consideration was given to aesthetics in designing the landscape plans for both sites. The final configuration plans were made to blend in with the surrounding topographical and vegetative site characteristics. Land shaping of the spoil material was designed so that water could be conserved and a stable vegetative cover established. Proper drainage was incorporated into the designs by minimizing the degree of slope in order to minimize surface runoff, decrease sheet and rill erosion and to enhance revegetation success.

After the sites were recontoured, crushed limestone was applied at a rate of 15 tons per acre. After the limestone was added the sites were plated with top soil at depths ranging from 6 to 8 inches. The limestone added was to provide a buffer strip between the top soil and the underlying acidic spoil material.

Revegetation.

Seed was applied at a rate of 16 pounds per acre at the pond and 19 pounds per acre at the dump. Selection of the seed was confined only to those species that are well adapted to the soil, climate and topography of the site. Important climatic factors considered were amount and seasonal pattern of precipitation, frost free period, temperature and wind. Soil considerations were material depth, texture and pH. Topographic features considered were aspect and elevation. Different seed application methods were used at both sites. The flat portions of the pond were broadcast seeded with a cyclone seeder. The seed for the face of the pond was applied in the hydromulch mix. Seed application of the nine seed species at the dump was entirely broadcast with cyclone seeders. In order to obtain equal distribution of the prescribed rate, the species were mixed according to seed size. The sizes were small (Weeping Lovegrass), medium (Hard Fescue, Orchard grass), large (Pubesecent Wheatgrass, Common Vetch, etc.). The three mixtures were then applied separately.

Fertilizer was not used at the pond because the top soil was loam textured and very rich in organic matter. Ammonium phosphate was used at the dump and applied at a rate of 40 pounds per acre. The topsoil in this case was a medium textured soil derived from Granite and Schist with little or no organic matter.

After application of limestone and topsoil and seed, a hydromulch mixture consisting of wood cellulose fiber and a petroleum based soil binder was applied to the pond at a rate of 1,500 to 2,000 pounds per acre. The soil binder was used as an adhesive for the wood fiber hydromulch to prevent the loss of mulch from wind and flowing water. The soil binder was applied in the hydromulch at a rate of 86 gallons per acre. The hydromulch mixture at the dump was the same mixture as at the pond, however, 2000-2500 pounds of mulch per acre were applied and the soil binder was 108 gallons per acre.

Revegetation results.

The face of the pond where the seed was added into the hydromulch solution did not get as successful seed germination as the flat areas did. This is probably due to the lighter seed being suspended in the mulch so that when the seed germinated it did not have contact with the topsoil thus it dried out. The dump seed germination was very uniform throughout the entire site. Several species in the original mixture used at the pond were substituted for use at the dump due to their inability to survive after germination. Perennial Ryegrass was substituted by Intermediate Wheatgrass. Lehman Lovegrass was substituted with Yellow Sweet Clover (Table 7).

Future plans.

It is not feasibility economical to treat all of the abandoned mine spoils in the watershed because of their great numbers and land status. An alternative to consider is the installation of limestone filtering structures along Lynx Creek to help neutralize some of the toxic metals before they reach Lynx Creek.

An in-depth chemical analysis of Lynx Lake is planned during the summer of 1977 to determine whether there has been any change in the water quality of Lynx Lake as a result of the Sheldon Mine Reclamation project.

The final product of the projects will be a mine reclamation manual that will be applicable to orphaned mine sites that are located in the pine type in the Southwest.

Table 7
Seed Species and Rate Application
at the Sheldon Mining Complex

Sheldon Pond

Common Name	Scientific Name	Pounds per Acre
Ranger Alfalfa	Medicago sativa	.80
Black Medic	Medicago lupulina	.4
Pubescent Wheatgrass	Agropyron trichophorum	.40
Perennial Ryegrass	Lolium perenne	.40
Common Vetch	Vicia sativa	5.20
Weeping Lovegrass	Eragrostic curvula	2.00
Hard Fescue	Festuca ovina duriuscula	.4
Lehman Lovegrass	Eragrostis lehmanniana	.4
Orchard Grass	Dactylis glomerata	.4
Range Alfalfa	Medicago sativa	2.5
Smooth Brome	Bromus inermis	2.0
Pubescent Wheatgrass	Agropyron trichophorum	4.0
Intermediate Wheatgrass	Agropyron intermedium	3.0
Common Vetch	Vicia sativa	2.5
Weeping lovegrass	Eragrostis curvula	0.5
Hard Fescue	Festuca ovina duriuscula	1.0
Yellow Sweet Clover	Melitotus officianalis	1.5
Orchard grass	Datylis glomerata	2.0
	Total	35.0

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REHABILITATION OF COPPER MINE TAILING SLOPES USING MUNICIPAL SEWAGE EFFLUENT

Tika R. Verma, Kenneth L. Ludeke, and A. D. Day

ABSTRACT

The suitability of treated municipal sewage effluent for the irrigation of deep-rooting plant material for the rehabilitation of copper mine tailings was studied at the Cyprus Pima Mining Company. The effectiveness of treated sewage effluent was compared with well water on the growth and survival of trees, legumes and grasses. The species studied were eucalyptus (Eucalyptus rostrata), native mesquite (Prosopis juliflora), palo verde (Cercidium floridum), desert tobacco (Nicotiana glauca), barley (Hordeum vulgare), perennial rye grass (Lolium perenne), alfalfa (Medicago sativa), and blue lupine (Lupinus augustifolius). Sprinkler and tree-well irrigation methods were used to apply the treated sewage effluent and well water to steep tailing slopes. The treated municipal sewage effluent was found to be a practical irrigation substitute for well water and a good source of plant nutrients such as nitrogen and phosphorous. Effluent produced better survival and growth than did well water with or without augmentation.

The state of Arizona produces about fifty-four percent of the total domestic production of copper. However, copper production consumes large amounts of water in the processing of the ore and in ecological control of mining wastes. In arid regions such as Arizona, heavy use of precious water by the mines conflicts with domestic and agricultural needs. Therefore, it is desirable to locate additional water resources. We contend that sewage effluent constitutes such a resource.

Most of the copper ore mined in the southwestern United States is extracted from open-pit mines. Ore from the mines is loaded into 200-ton trucks (Figure 1) and hauled to the primary crusher where it is reduced to three inch rock in a series of procedures. The crushed ore is then transported to the grinding circuits for further reduction. The ground ore is subsequently pumped into large open containers called flotation cells where chemical treatment and agitation float the copper mineral to the surface. The copper is then removed, concentrated and transported to the smelter for final processing.

Hundreds of acres of land adjacent to copper mines throughout the West are used to store copper mining wastes. This waste material from the milling of copper ore, composed largely of finely ground silica sand, is called tailing. The tailings are transported as a liquid slurry in thirty-six inch concrete lines from the copper mills to disposal ponds. The tailing ponds have steep slopes (Figure 2) that require some form of immediate stabilization for the establishment of vegetation. In order, to effectively establish vegetation on tailing slopes, irrigation is of extreme importance. In the arid southwest where water is a scarce commodity, all sources of available moisture have a potential for use in irrigation. Municipal sewage wastes offer a possible source of supplemental irrigation water (4).

Modern sewage processing plants can produce a clear effluent that is safe for many agricultural uses. If properly handled, sewage effluent can contribute significantly to our total water supply (1). The effluent produced by cities in or near mining regions could annually provide billions of gallons of additional water. This supplemental water resources will become increasingly valuable in the future as our population and water requirements continue to grow (3).

With intensified domestic and industrial demands for fresh water, agricultural interests may be forced to relinquish some of their "riparian" rights to this natural resource. Forced reductions in water use by particular segments of an economic system are not a new idea. The ancient Babylonians established a priority system for water use known as the code of Hammuralii: the highest priority was given to man and beast; household use received second priority and agricultural applications were considered to be of tertiary importance (2). In our own society, agriculture and industry may soon face a similar obligation to seek alternative sources of water such as sewage effluent.

Treated sewage water looks very much like ordinary water; the clear effluent is the liquid product of bacterial action on raw sewage. Effluents vary in composition and frequently contains more plant nutrients and soluble salts than fresh-well water; detergent is also usually present. Treated effluent has several advantages which serve to increase its value for agricultural purposes. It has no

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Figure 1. Copper ore is loaded into 200-ton trucks from open-pit mine at Cyprus Pima Mining Company.

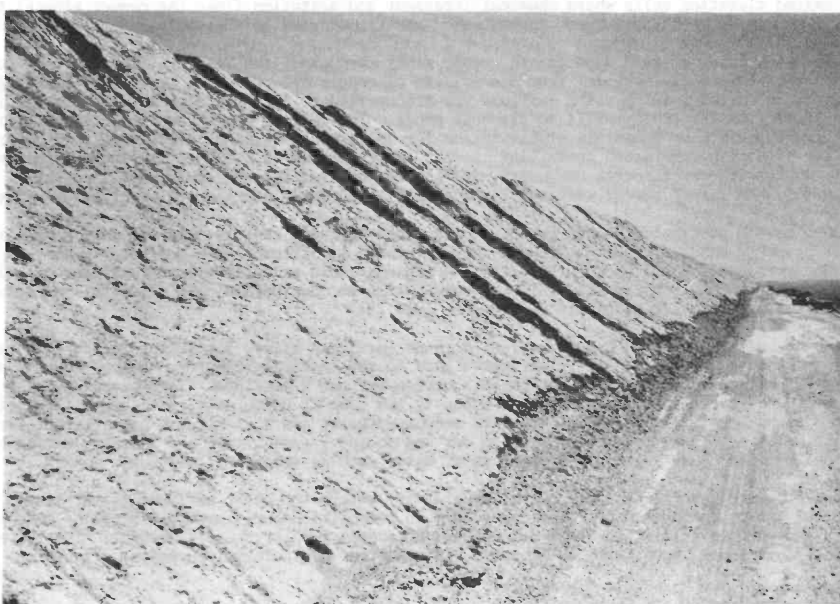

Figure 2. Tailing pond slope seeded without the use of sewage effluent -- poor germination, and severe erosion due to wind and water reducing seeding emergence.

objectionable odor, a high fertilizer value and can be consumed by livestock without harmful effects. Studies conducted at the Arizona Agricultural Experiment Station (2) show that sewage effluent can provide an inexpensive source of irrigation water for production of small grains.

The feasibility of rehabilitating copper mine tailing slopes with several species of trees, legumes and grasses irrigated with municipal sewage effluent was examined at Cyprus Pima Mining Company south of Tucson, Arizona. Various sprinkler and tree-well irrigation methods were tested and a system was developed for the irrigation of one-acre test plots on a 1.5:1 tailing slope with sewage effluent. Using duplicate test plots, the effects of fresh well water were compared with treated sewage effluent in the two-year study (Figure 3). Effluent was substituted for fresh well water and fertilizer in the study of survival and growth rates of trees, legumes and grasses. Tree species studied were eucalyptus, (Eucalyptus rostrata), native mesquite (Prosopis juliflora), palo verde (Cercidium floridum), and desert tobacco (Nicotiana glauca) (Figures 4 and 5). The trees were evaluated with regard to their suitability for establishment of deep-rooting plant growth on steep tailing slopes. The grass and legume studies utilized barley (Hordeum vulgare), annual rye grass (Lolium mutiflorum), alfalfa (Medicago sativa), and blue lupine (Lupinus augustifolius). The studies consumed approximately three acre-feet of fresh-well water or effluent.

Both the effluent and the well water were applied at the rate of two to four inches per irrigation. The irrigation sequence began in October and terminated in May for the small grains while the tree and legume experiments ran through September. The three separate treatments tested were as follows: (1) Fresh-well water with no fertilizer (control). (2) Fresh-well water with 200 pounds of nitrogen, sixty-five pounds of phosphorus (150 pounds of P_2O_5), and eighty-three pounds of potassuim (100 pounds of K_2O) per acre. This was equivalent to the approximate amount of N, P and K contained in three acre-feet of sewage effluent (Table 1). (3) Sewage effluent. Both the sewage effluent and the fresh-well water were applied by means of sprinkler and tree-well irrigation systems.

An analysis of the sewage effluent used (Table 1) indicated that it contained sixty-six pounds of nitrogen per acre-foot, twenty-three pounds of phosphorus (52 pounds of P_2O_5), and twenty-seven pounds of potassium (33 pounds of K_2O). The fresh-well water used in the experiment contained approximately twelve pounds of N, 0.4 pounds of P and thirteen pounds of K.

The small grains,barley and rye grass were planted in November at the rate of 100 and 50 pounds of seed per acre respectively using a hydroseeder. The legumes, alfalfa and lupine were hydroseeded in November at fifty and twenty-five pounds of seed per acre respectively. All tree plantings were done in October from one-gallon containers at a density of 335 plants per acre.

The legumes and small grains were harvested at maturity. In general, effluent irrigation resulted in higher yields, even though additional fertilizer was not used. The survival rates and crown growth of the trees planted were also higher when irrigated with sewage effluent. Barley, when grown with effluent, produced fifty percent more forage than barley grown with fresh-well water without fertilizer (Table 2). Irrigation with sewage effluent had similar effects (45 percent more forage) on rye grass. Alfalfa and lupine grown with sewage effluent produced fifty percent higher forage as compared to the same plants grown with fresh-well water. The survival rate and crown growth of eucalyptus, and desert tobacco were higher when irrigated with sewage effluent than those receiving fresh-well water without supplemental fertilization.

Crown growth was evaluated for all of the test trees (Table 3). Growth was enhanced when sewage effluent was used as a primary source of irrigation water. The survival rates of mesquite and palo verde trees were increased by approximately fifty percent and crown growth was increased approximately forty-five percent when irrigated with sewage effluent. The same proved to be true for the desert tobacco and eucalyptus trees when irrigated with sewage effluent, yielding an increase of approximately sixty percent in plant survival and a fifty percent increase in crown growth.

These experiments indicate that sewage effluent can be used to successfully grow trees, grasses, and legumes producing better survival and growth of plants than well water with or without augmentation. The mining industry in critical water areas is currently examining the possibility of using sewage effluent for both irrigation of tailing dumps and for copper milling and mineral flotation. Sewage effluent contains a built-in agricultural potential that can be tapped for better food and feed production from crops like barley and alfalfa which can be grown on copper-milling wastes. Intelligent utilization of sewage effluent by both mining and agricultural interests can significantly reduce the utilization pressure on dwindling water supplies in arid regions. This study indicates that such utilization is a biologically viable possibility.

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Figure 3. Tailing pond treated with sewage effluent and seeded with new strain of barley -- tailing slope is protected from erosion.

Figure 4. Transplanting of one-gallon size trees to steep tailing pond slopes.

Table 1. Chemical Composition of Sewage Effluent From the Tucson, Arizona Sewage System.*

Name of Constituent	Parts per Million
Total Soluble salts	800
Calcium (Ca)	30
Magnesium (Mg)	15
Potassium (K)	10
Total Nitrogen (N)	20
Sodium (Na)	150
Nitrate (NO_3)	2
Phosphorus (P)	6
Bicarbonate (HCO_3)	300
Sulfate (SO_4)	100
Chloride (Cl)	90

*Composition of a representative sample obtained on September 2, 1974.

Table 2

Sewage Effluent Effects on Plant Growth on tailing soil material.

Small Grains & Legumes	Fresh Well Water		Sewage Effluent
	No Fertilizer	Water & Fertilizer	No Fertilizer
Barley* (forage)	3,116 pounds	6,685 pounds	9,875 pounds
Ryegrass* (forage)	1,062 pounds	2,243 pounds	4,697 pounds
Alfalfa* (cut as hay)	2,241 pounds	4,621 pounds	8,062 pounds
Lupin* (cut at Maturity)	308 pounds	621 pounds	810 pounds

*(All yields are reported on an acre basis)

Table 3

Sewage Effluent effects on survival rate and Crown Growth of Trees Grown on Tailing Soil Material.

Trees	Fresh Well Water		Sewage Effluent
	No Fertilizer	Water & Fertilizer	No Fertilizer
Eucalyptus (Survival)*	15%	45%	95%
(Crown Growth)*	5%	10%	30%
Paloverde (Survival)	20%	35%	88%
(Crown Growth)	10%	25%	85%
Desert Tobacco (Survival)	10%	50%	90%
(Crown Growth)	15%	45%	95%

(*All data are reported on observed and calculated percentages respectively.)

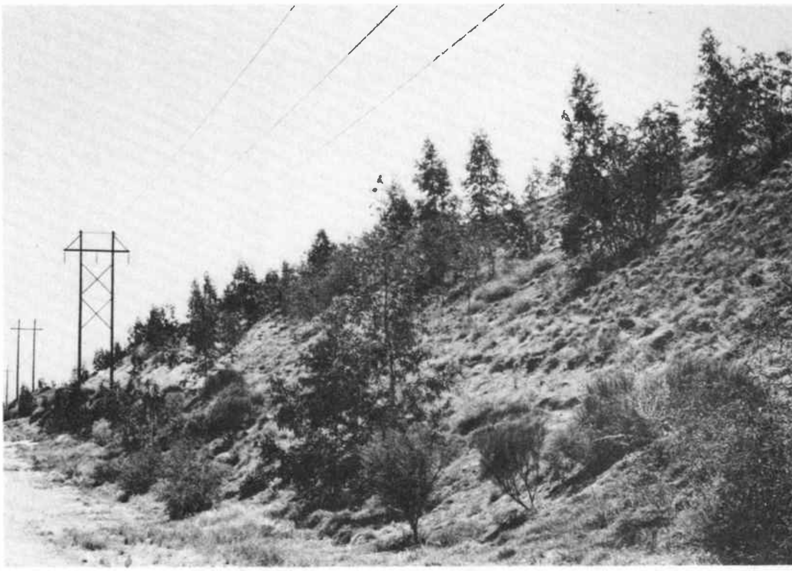

Figure 5. Tailing pond slopes with vegetation -- complete protection against wind and water erosion.

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DECISION MAKING IN A MULTIPLE-USE APPROACH TO THE RECLAMATION OF STRIP-MINED LANDS

by

Ambrose Goicoechea[1], Lucien Duckstein[2] and Martin Fogel[3]

ABSTRACT

With the advent of ever-increasing energy needs, large-scale surface mining has gained new impetus, and there is much concern about reclaiming the mine spoils to bring about beneficial land uses. This paper presents a decision making algorithm labeled PROTRADE, and a case study of the Black Mesa region in Northern Arizona. PROTRADE considers a set of objective functions, a set of physical constraints, articulates the preferences of the decision maker in a progressive manner, and generates a set of alternative solutions. The decision maker is then able to trade level of achievement, for each objective function, against the probability of achieving that level.

INTRODUCTION

Can the mine spoils created by large-scale surface mining be reclaimed so as to lead to beneficial land uses? This is a crucial question in many areas in the southwest where the potential for surface mining exists. In the Black Mesa region in Northern Arizona, on the lands of the Navajo Nation, an area of some 5,700 hectares will eventually be turned upside-down to strip-mine for coal over the next 30 years.

This paper considers a multiple-use approach to the reclamation and management of the Black Mesa region and, toward that end, applies PROTRADE, a Probabilistic Tradeoff Development Method (Goicoechea et al. 1976a). Once a set of objective functions and a set of physical constraints for the problem have been identified, this method allows the decision maker (DM) to articulate his preferences in a progressive manner and generates a set of alternative solutions. In the process, the DM is able to calculate and trade off, for each objective function, the level of achievement against the probability of achieving that level; there are four steps in the method, whose description is illustrated throughout by the case study of the Black Mesa region.

THE PROBLEM

This semiarid area, shown in Figure 1, has been and is still being used as rangeland, a practice which has been abused and has resulted in heavy overgrazing with detrimental consequences (Verma and Thames, 1975). Considering the poor range conditions of the Black Mesa region, surface mining and subsequent reclamation programs offer to the appropriate managing agency an opportunity to design and implement multiple land uses, once the decision to mine for coal has been made. Current coal mining activities in the area are being conducted by the Peabody Coal Company.

Five objectives are considered: 1) livestock production, 2) augmentation of water runoff, 3) farming of selected crops, 4) control of sedimentation rates, and 5) fish pond-harvesting. Verma and Thames (1975) and Brinck et al. (1976) have reported preliminary findings to the effect that reclaimed watersheds in the area have a potential for use as rangeland, in harmony with the preferences of the Navajo Nation. Opportunities for water yield augmentation through vegetation and soil treatments exist; results obtained on experimental watersheds have been reported by Cluff (1971). Some of these treatments also have the potential to decrease sedimentation rates. Current research on fish pond-harvesting by Kynard and Tash (1975) is also used in this study to ascertain the feasibility of fish production and its extent. Also competing for the use of water made available through runoff practices and rainfall will be the farming of selected crops in the area; again, this is an activity in harmony with the preferences of the Navajo Nation.

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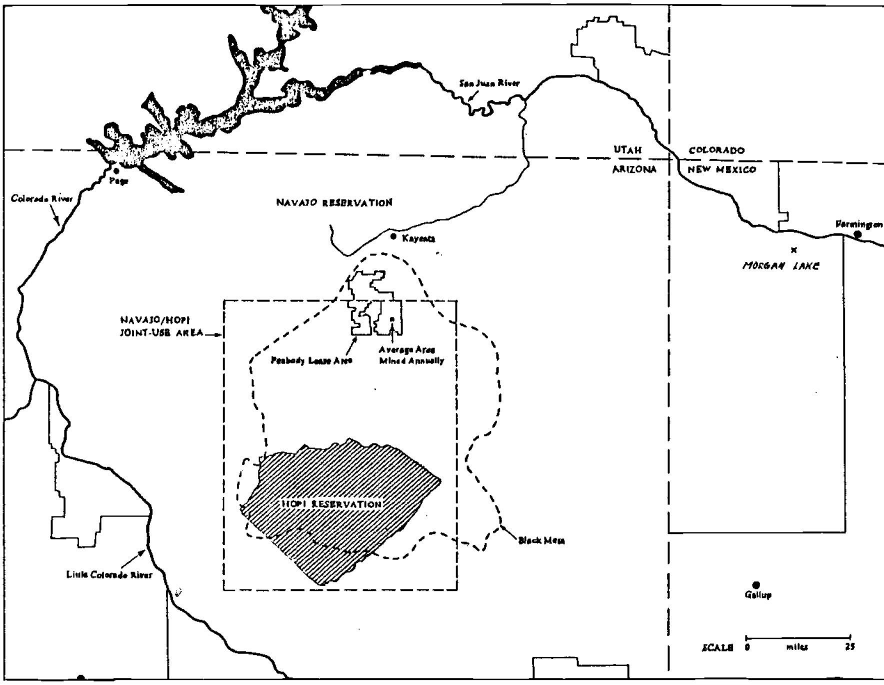

Figure 1 The Black Mesa Region in northern Arizona.

METHODOLOGY

FORMULATION OF POLICY VARIABLES, OBJECTIVE FUNCTIONS AND CONSTRAINTS

Policies or practices. In the first part of the methodology, policy variables (or practices) are defined, objective functions and constraints are modeled and formulated; in the second part, the step-by-step algorithm for solution is presented along with numbers from the case study. In reference to our study area, the managing agency must decide on the extent of new practices which would contribute to achieving the five objectives outlined above.

The practices considered in this study are represented by the following decision variables in hectares of mined land:

x_1 = area with *current management practices* (no land reclamation program),

x_2 = area with *contoured-furrowing and good range conditions*,

x_3 = area with *contoured-furrowing and poor range conditions*,

x_4 = area with *compacted earth (CE) treatment* to increase water runoff,

x_5 = area with *compaction and salt treatment* to increase water runoff,

x_6 = area treated with *plastic cover and gravel* to increase water runoff,

x_7 = area farmed for *wheat production*,

x_8 = area farmed for *corn production*,

x_9 = area farmed for *alfalfa production*,

x_{10} = area farmed for *barley production*,

x_{11} = area farmed for *sorghum production*,

x_{12} = area to be allocated for *fish ponds*.

The above practices are of current interest in the case study but any others could be brought into the analysis as additional needs and concerns materialize.

Objective functions. With these practices in mind, the five objectives have been cast into the form of linear functions of such practices as follows:

livestock production: $f_1(x) = \sum_{i=1}^{12} \ell_i x_i$, animal units [over a two-year period] (1)

water runoff: $f_2(x) = \sum_{i=1}^{12} r_i x_i$, cubic meters (2)

selected crops: $f_3(x) = \sum_{i=1}^{12} c_i x_i$, kgms. (3)

sediment: $f_4(x) = \sum_{i=1}^{12} s_i x_i$, cubic meters (4)

fish yield: $f_5(x) = \sum_{i=1}^{12} f_i x_i k$ kgms. (5)

In the above functions, ℓ_i represents the number of lifestock heads (e.g., animal units) (AU) per hectare of land with practice or treatment i, r_i is the water runoff yield in cubic meters/ha., c_i is the crop yield in kgs/ha., s_i is the sediment yield in cubic meters/ha. Of these noncommensurate objective functions, the one corresponding to sediment, (4), is to be minimized and the others are to be maximized subject to land, water, and capital constraints to be specified later.

The time horizon of 30 years which has been chosen for the case study is intended to reflect the effective lifetime of the mechanical soil treatments and seeding to be implemented (Cluff, 1971; Bartlett, 1974), and of the mining program presently envisioned. The division of this 30-year period into fifteen two-year subperiods is deemed necessary because water runoff rates, sedimentation rates, operating costs, and so forth, are not expected to remain constant during the entire period.

A brief explanation of the formulation of the five objective functions (Equations 1 to 5) follows.

Rationale for objective functions. *Livestock Production (Equation 1).* The livestock production model used herein is the one previously developed by Brinck et al., (1975). It is an event-based model which accounts for precipitation, infiltration, runoff, and sedimentation to describe discrete storm events and their effects. The storm events occur in a sequence throughout the years of program lifetime separated by random time intervals. For each storm event, a pair of dependent drawings of rainfall depth and event duration are made from their joint distribution. The runoff and peak flow, if any, are computed with the Soil Conservation Service (SCS) formulas for each event for furrowed and for unfurrowed slopes, respectively.

Water Runoff Augmentation (Equation 2). Existing water supplies for livestock production and irrigation in the Black Mesa area are not sufficient to satisfy requirements. The use of runoff farming techniques offers an economic alternative to these lands which, otherwise, might revert back to desert when the groundwater supplies are exhausted or can no longer be exploited economically. Opportunities for water yield augmentation through mechanical treatment of the mine spoils are considered, and a program of soil treatments and maintenance requirements is suggested. Performance and cost parameters for this program have been made available through the water harvesting studies at the University of Arizona (Cluff et al., 1971) which were initiated in 1963. Table 2 lists the three catchment methods used in the analysis.

Farming of Selected Crops (Equation 3). Another activity which is in harmony with the preferences of the Navajo Nation is the farming of crops that require relatively small amounts of water. To compete for the water made available through rainfall and runoff augmentation practices, the farming of some selected crops is suggested, such as wheat, corn, barley and sorghum.

Control of Sedimentation Rates (Equation 4). An undesirable by-product of the runoff augmentation treatments suggested to increase water availability is the production of large amounts of sediment. Runoff from rangelands and strip-mined lands, particularly, is the primary force in initiating soil movement and transporting sediments to nearby reservoirs and rivers. This sediment adversely affects water quality and operational costs (Smith et al., 1977).

Fish Pond Harvesting (Equation 5). Fish production in reclaimed spoils catchments would provide a protein source, job opportunities, and would help develop the recreational potential of the area. However, for fish to survive and grow normally in these catchments, the necessary physico-chemical conditions must be present. To determine the feasibility of fish production, a cooperative research effort was conducted during the summer of 1975 in the Black Mesa region by the University of Arizona School of Natural Resources and the Peabody Coal Company (Kynard and Tash, 1975).

Tables 1 through 4 in the appendix present the parameters used in the analysis for the various objective functions and associated physical models.

Set of constraints. For each two-year subperiod, the five objective functions are satisfied subject to specified constraints on land, capital, and water, e.g.:

land: $x_1 + x_2 + \ldots + x_{12} = b_\ell$ (6)

capital: $q_1x_1 + q_2x_2 + \ldots + q_{12}x_{12} = b_q$ (7)

water: $w_1x_1 + w_2x_2 + \ldots + w_{12}x_{12} = b_w$ (8)

where the parameter q_i represents the cost of implementing the ith practice (e.g. treatment), w_i the water comsumption of the ith practice, b_ℓ = 380 ha., b_q = \$35,000, and b_w is the water available for that two-year subperiod through runoff practices and rainfall.

IMPLEMENTATION OF THE *PROTRADE* ALGORITHM

The steps of the algorithm are described along with the case study.

Step 1. The objective functions, (1) through (5), have been formulated in the preceeding section. Here, they are slightly rearranged so that the optimization process will involve maximization, only. Let

$$z_i(x) = f_i(x) \quad \text{for } i = 1,2,3,5,$$

$$z_4(x) = -f_4(x).$$

Next, maximization and minimization of each individual objective function, subject to constraints (6), (7) and (8) (constraint set D_1) yields vectors $\underline{U}_1$ and $\underline{M}$:, respectively

$$\underline{U}_1 = \begin{bmatrix} 52.00 \times 10^0 \\ 541.91 \times 10^3 \\ 331.97 \times 10^3 \\ -58.14 \times 10^0 \\ 14.78 \times 10^3 \end{bmatrix} \quad \underline{M} = \begin{bmatrix} 0.00 \\ 30.00 \times 10^3 \\ 0.00 \\ -7549.08 \\ 0.00 \end{bmatrix} \quad \begin{matrix} \text{AU} & \text{livestock,} \\ \text{cu. m.} & \text{runoff,} \\ \text{kgs.} & \text{crops,} \\ \text{cu. m.} & \text{sediment,} \\ \text{kgs.} & \text{fish.} \end{matrix}$$

An initial surrogate objective function (SOF) is formulated as follows:

$$F(x) = \sum_{i=1}^{5} \frac{Z_i(x) - Z_{imin}}{Z_i(x_i^*) - Z_{imin}} = \sum_{i=1}^{5} G_i(x)$$

Maximization of $F(x)$ subject to $x \in D_1$ yields an initial solution x_1, and goal vector G_1,

x_1^T = [157.37, 69.06, .00, 69.06, 69.06, .00, .00, .00, 13.75, .00, .00, 1.70], G_1^T = [0.183, 0.401, 0.306, 0.585, 0.431];

from G_1 we observe that the level of achievement of livestock production, for instance, is only 18.3% of the maximum possible value, and that the other levels fall quite short also. These levels, however, conform with the physical realities of the problem. We would like, at this point, to have the DM express his preference structure or set of "worth values" to search for another solution, if necessary. In this case study, John Thames[1] was asked to assume the role of the DM.

Step 2. To assist the DM in articulating his preferences for this particular problem, the following multiattribute utility function (Fishburn, 1970; Keeney, 1974) is suggested:

$$1 + ku(G) = \prod_{i=1}^{5} [1 + k\, k_i\, u_i(G_i)].$$

To evaluate the parameters k, k_i, and the form of the single-attribute utility function $u_i(G_i)$, the DM was asked a series of questions:

a) The DM was asked to rank the five objectives in order of importance or worth to him, and the following ranking was determined: G_3, crops > G_1, livestock > G_4, sediment > G_2, runoff > G_5, fish, e.g., G_3 is more important than G_1, and so on;

b) Considering two objectives at a time, the DM was asked to assign a relative worth to each objective, with the following response:

$$\frac{G_1}{G_3} = 0.6, \quad \frac{G_4}{G_1} = 0.8, \quad \frac{G_2}{G_1} = 0.9, \quad \frac{G_5}{G_2} = 0.5$$

e.g., the DM is indifferent between 60% of the crops and 100% of the maximum livestock possible; additional questions and answers from the DM led to the evaluation of parameters shown below:

$$k_3 = 0.519,\ k_1 = 0.260,\ k_4 = 0.223,\ k_2 = 0.201,\ k_5 = 0.081,\ k = -.534.$$

1. Dr. John Thames is a Professor in the School of Renewable Natural Resources at the University of Arizona. He is currently supervising a research program in the Balck Mesa region and has been instrumental in procuring field data.

The surrogate objective functions is now redefined as follows:

$$S_1(x) = \sum_{i=1}^{5} w_i G_i(x), \text{ where } w_i = 1.0 + \frac{r}{G_i(x_1)} \left. \frac{\partial u(G)}{\partial u G_i} \right|_{\underline{G}_i} ;$$

accordingly,

a) Compute $u(G_1)$ to yield 0.493.
b) Ask the DM to decide on an incremental utility $\Delta u(G)$; a value of 0.20 was elicited by the DM.
c) The elements (weights) w_i were then found to be:

$$w_1 = 1.807,\ w_2 = 1.205,\ w_3 = 2.067,\ w_4 = 1.178,\ w_5 = 1.073.$$

Each w_i value can be thought of as the relative "weight" that the DM places on the ith objective. For instance, G_3 is weighted more heavily than G_1, G_1 is weighted more heavily than G_4, and so forth. We notice that whereas initially the DM ranked the objectives in order of importance, here the DM has actually quantified the relative worth of the objectives.

Step 3. An alternative solution is generated this time reflecting the preferences of the DM,

$$\max \quad S_1(x) = 1.807\ G_1(x) + 1.205\ G_2(x) + 2.067\ G_3(x) + 1.178\ G_4(x) + 1.073\ G_5(x)$$

subject to $x \in D_1$. The optimal solution x_2 is given below and was used to generate the vectors x_2^T = [.00, 140.00, .00, 100.73, 118.05, .00, 8.82, .00, 12.32, .00, .00, .06], G_2^T = [0.370, 0.480, 0.354, 0.998, 0.016], U_2^T = [19.25×10^3, 275.75×10^3, 117.71×10^3, -63.73, $.24 \times 10^3$].

Several iterations were required to match the amount of water used (mainly for crops) and the amount of runoff (plus rainfall) needed, approximately 300×10^3 cu. meters.

Goal values and their respective probabilities of achievement are then given by vector V_1,

$$V_1 = \begin{matrix} (0.370, & 0.500) \\ (0.480, & 0.500) \\ (0.354, & 0.500) \\ (0.998, & 0.500) \\ (0.016, & 0.500) \end{matrix}$$

i.e., Prob $[\tilde{G}_1 \geq 0.370] \geq 0.500$.

At this point in the analysis, the DM has been able to state his *preferences* for the various goals (which may generally be in conflict with the *"realities"* of the problem, e.g., the constraints of the problem are not satisfied), and Step 3 has now reconciled these preferences and realities. Assume that the vector $\underline{U}_2$ is not satisfactory to the DM, and continue.

Step 4. The DM is asked to select the objective function $z_k(x)$ with the least satisfactory pair $(G_k(x_2), 1 - \alpha_k)$. The DM specifies that he would like to have G_3, crops, increased from 0.354 to 0.450 *and* with a probability of 65% or better,

$$\text{Prob}[z_3'(x) \geq (0.450)(331.97 \times 10^3)] \geq 0.650.$$

A new solution space, D_2, is now defined to include the DM's requirement;

D_2:

$$x_1 + x_2 + \ldots + x_{12} = 380, \quad \text{Land,}$$

$$q_1 x_1 + q_2 x_2 + \ldots + q_{12} x_{12} \leq 35, \quad \text{Capital,}$$

$$w_1 x_1 + w_2 x_2 + \ldots + w_{12} x_{12} \leq W, \quad \text{Water,}$$

$$\sum_{j=1}^{12} E(c_j)x_j + K_{\alpha 3}[x^T A x]^{1/2} \geq (0.450)(331.97 \times 10^3),$$

where the variance-covariance matrix A is given by

$$A = \begin{bmatrix} \text{var}(c_j) & \ldots \text{cov}(c_1, c_{12}) \\ \text{cov}(c_{12}, c_1) & \ldots \text{var}(c_{12}) \end{bmatrix}$$

For our problem, it is reasonable to assume mutual stochastic independence between the random variables c_i, such that $\text{cov}(c_i, c_j) = 0$ for $i \neq j$. Estimates of these variances are presented in Table 4. Also, $k_{\alpha 3}$ is such that

$$\Phi_{\text{normal}}(K_{\alpha 3}) = 1 - 0.650$$

and from standard normal tables we find $k_{\alpha 3} = 0.385$. The last constraint then becomes,

$$\sum_{j=1}^{12} E(C_j)x_j - 0.385 \left[\sum_{j=1}^{12} \mathrm{var}(C_j)\, x_j^2\right]^{1/2} \geq (0.450)(331.97 \times 10^3),$$

W, in the water constraint, is varied parametrically to match the amount of water made available through rainfall and runoff.

Now maximize $S_1(x)$ subject to $x \in D_2$. This optimization yields vector x_3,

x_3^T =[0.00, 120.10, .00, 120.10, 96.21, .00, 22.76, .00, 13.10, .00, .00, .00] V_2^T =[(0.370, 0.340), (0.480, 0.409), (0.450, 0.650), (0.998, 0.525), (0., 0.)].

With this new vector, x_3, we are able to achieve G_3 = 0.450 with a minimum probability of 0.650, for instance; a cutting-plane method (Goicoechea et al., 1976a, b and c) was used to solve the nonlinear problem above.

The DM has gained knowledge about how the various goals trade off from V_2, and is willing to accept the levels and probability of achievement for the *first four* goals. However, he finds *fish* to have an unacceptable level, G_5 = 0. He would like to have G_5 = .10 with a minimum probability of achievement of 0.70. Now, the optimization problem becomes

$$\max S_2(x) = \sum_{i \neq 3} w_i\, G_i\,(x)$$

subject to:

$$x_1 + x_2 + \ldots + x_{12} = 380.,$$

$$q_1 x_1 + q_2 x_2 + \ldots + q_{12} x_{12} \leq 35.,$$

$$w_1 x_1 + w_2 x_2 + \ldots + w_{12} x_{12} \leq W,$$

$$\sum_{j=1}^{12} E(C_j)x_j - 0.385 \left[\sum_{j=k}^{12} \mathrm{var}(C_j)x_j^2\right]^{1/2} \geq (0.450)(331.97 \times 10^3)$$

$$E(f_{12})x_{12} - 0.525 \left[\mathrm{var}(f_{12})x_{12}^2\right]^{1/2} \geq (0.100)(14.78 \times 10^3)$$

where $\Phi(-0.525) = \alpha_5 = 1 - 0.70$.

The above optimization yields vector X_4,
X_4^T = [0.00, 48.10, .00, 168.00, 122.30, .00, .00, .00, 20.66, .00, .00, .66], V_3^T = [(0.127, 0.500), (0.480, 1.000), (0.450, 0.650), (0.998, 0.511), (0.100, 0.700)].

RESULTS AND DISCUSSION

It is important to realize that in order to provide additional water for fish harvesting, G_5 = 0.100 with a probability of 0.700 or better, the last optimization allocated additional runoff (with a total runoff plus rainfall of 400 x 10^3 cu. meters, approximately). This is the reason why G_2 = 0.480 with a probability of 1.0.

Water availability was critical in most of the preceding optimizations. That is, runoff augmentation practices played an important role in supplying the water needed by the various objectives in the study. Capital availability, on the other hand was not a determining factor.

As shown in vector V_3, the goal values obtained are far from their maximum value of unity, with sediment being the exception. This was to be expected as all the objectives were very much in conflict and competition with each other, particularly in competition for water.

Expressing the objective functions in their respective natural units, rather than in dollars, allowed the DM to bring social, environmental, and aesthetic concerns into the analysis.

The preceding example has attempted to demonstrate the applicability of PROTRADE, a multiobjective algorithm, to realistic problems. The following observations are made:

1) The algorithm allows for a dynamic weighting of the objectives as the preferences of the DM are articulated. Also, once the trade-offs among the objectives are quantified, the DM is able to "change his mind" if he so desires to accommodate his new expectations.

2) Analysis results for each two-year subperiod and the entire 30-year period reflect that particular value structure exhibited by our DM. We can imagine that replacing the single DM with a group of decision makers able to reflect the needs of each constituent, in some manner, and able to cast these into a single vote would alter the choice of an acceptable policy.

3) The randomness of some of the parameters was effectively handled in the analysis, thus making the algorithm applicable to real world situations. The random variables considered were assumed to be normally distributed, for convenience. Current literature (Goicoechea, 1977a, b), however, now makes it possible to consider random variables with any type of distribution, as the problem at hand may dictate.

4) With this uncertainty-handling capability, the DM is no longer limited to considering expected values alone as he trades off the various objectives against one another. The DM can now demand probabilities of goal achievement higher (or lower) than .50 and thus provide for project success and safeguard more effectively his personal reputation, if he so desires.

5) Computational requirements are kept to a minimum since there is no need to resort to Monte Carlo simulations to arrive at or maintain a given probability of achievement.

6) Once an acceptable policy is identified for a two-year subperiod, present values for the various objective functions over the entire 30-year period can be readily obtained by considering the sum of discount rates operating on the appropriate objective, itself a random variable, provided the DM's preferences are time-invariant.

7) The use of the cutting-plane technique to solve this nonlinear problem has been demonstrated to be an effective tool.

8) Now that the DM has been able to see the results above, which adhere to the physical constraints of the problem and reflect his own preferences, he is still able to initiate a second iteration, with new expectations, if he chooses to do so.

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Parameter	expected value	standard deviation	units
ℓ_2	.1375	.0550	AU/ha.
ℓ_3	.0365	.0130	"
ℓ_i, $i \neq 2,3$	0	0	"
r_1	428	223	m^3/ha.
r_2	98	152	"
r_3	79	89	"
r_4	990	223	"
r_5	1,410	223	"
r_6	1,980	223	"
r_i, $i \neq 1[1,6]$	0	0	"
c_7	3,024	505	kgs./ha.
c_8	1,568	249	"
c_9	7,392	1,037	"
c_{10}	3,169	102	"
c_{11}	2,576	249	"

TABLE 1

Parameters for livestock production, runoff and crops

Catchment Methods	Approx. cost per ha.	Efficiency in percent	Estimated life
Compacted Earth*	$ 50.60	30-60	indefinite
Compacted Earth* sodium treated	85.20	40-70	indefinite
Graveled Plastic**	191.60	60-80	20-25 years

* Prices and efficiency are dependent on soil type, cost of clearing and shaping. Maintenance consists of weed removal and recompaction as needed.

** Price of catchment is primarily dependent on the cost of the gravel and to a lesser extent on the cost of clearing and shaping. 10 mil black polyethylene is used.

TABLE 2

Soil treatments for water runoff

Treatment i	K	C	P	LS	$E(s_i)$ m^3/ha.	$[VAR(s_i)]^{1/2}$ m^3/ha.
1	0.40	1.00	1.00	4.50	19.86	20.63
2	0.40	0.10	0.50	0.50	0.11	0.12
3	0.40	0.15	0.50	0.40	0.15	0.17
4	0.30	0.25	0.70	0.40	0.24	0.36
5	0.25	0.20	0.70	0.40	0.16	0.37
6	0	0	0	0	0	0
7	0.40	0.20	0.60	0.40	0.24	0.40
8	0.40	0.30	0.60	0.40	0.33	0.33
9	0.40	0.10	0.60	0.40	0.11	0.12
10	0.40	0.20	0.60	0.40	0.21	0.29
11	0.40	0.30	0.60	0.40	0.35	0.44

K, soil erodibility factor

C, cropping management factor

P, erosion control factor

LS, slope length and gradient factor

TABLE 3

Sediment parameters

Costs and yield estimates:

- $50/cage
- 30 cages/ha. of pond
- pond depth is 1.5 meters
- 0.5 kg. of fish require about 2.0 kg. of food pellets in 1-year term
- 500 fish units/cage, assume an expected mortality rate of 50% over a 1-year term
- $0.374/kg. of food pellets
- $0.05/fish unit, initial cost
- 0.5 kg./unit, market weight

cages		
(30 cages/ha.)($50/cage)		$1,500/ha.
food pellets		
(30 cages/ha.)(250 units/cage)(2.0 kg/unit) ($0.374/kg.)		$5,610/ha.
initial cost of stock		
(30 cages/ha.)(500 units/cage)(2.0 kg/unit)		$ 750/ha.
digging of pond (reclamation program)		---
transportation to and from power plant		
($10.15/man-hour)(100 man-hours/ha)		$1,015/ha.
$E(q_{12})$	Total	$8,875/ha.
$E(f_{12})$, expected yield		
(30 cages/ha.)(250 units/cage)(0.5 kg./unit)		3,741 kg/ha.
$VAR(f_{12})$, yielf variance (assumed)		$(2,000\ kg/ha)^2$

TABLE 4

Fish harvesting parameters

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A LAND IMPRINTER FOR REVEGETATION OF BARREN LAND AREAS THROUGH INFILTRATION CONTROL

by

R. M. Dixon and J. R. Simanton

ABSTRACT

A new minimum tillage implement, "the land imprinter," has been designed and fabricated, and is currently being tested. Its design is based on water infiltration control theory developed during the past decade. The land imprinter was developed primarily for establishing vegetation in barren land areas in semiarid and arid regions of the world. It simultaneously forms interconnected downslope and cross-slope corrugations that shed water and then infiltrate it precisely where vegetative growth is to be encouraged. This controlled short distance routing of water along short waterways into small reservoirs makes more rainwater available for seed germination and seedling establishment, and less water available for loss by surface runoff and evaporation.

The imprinter has only one moving part, in the form of a massive compound roller and central axle which turn together as a rigid assembly during operation. The compound roller consists of two imprint capsules which are linked together on the axle shaft by an axle pulling clamp. The core of the imprint capsule is a hollow steel cylinder (1-m diameter and 1-m long) fabricated from 1.27-cm steel plate. A variety of imprint geometries are formed by welding short lengths of specially-cut steel angles (1.27 cm x 15.24 cm x 15.24 cm) to the outer surface of the cylindrical core. Ten imprint capsules with distinctly different geometric patterns of steel angles have been developed and fabricated. By pairing these capsules in as many ways as possible, 45 different geometric patterns can be imprinted.

The patterns of steel angles perform a number of different tillage functions including (1) brush and soft rock crushing, (2) brush and rock imbedding, (3) runoff inducing and directing, (4) infiltration inducing and directing, (5) biomass concentrating, (6) seedbed forming, (7) surface and vertical mulching, (8) wind and water erosion controlling, (9) surface compacting, and (10) surface trenching and pitting.

Advantages of the land imprinter as compared with alternative tillage methods include (1) greater stability, diversity, complexity, and precision of surface geometric patterns; (2) better control of point infiltration, runoff, erosion, and evaporation; and (3) greater utility in brush-covered, steeply-sloping, deeply gullied, and rocky land. The land imprinter should have widespread utility in both range and croplands because of its unique ability to mold runoff-watered seedbeds that increase the probability of seed germination and seedling establishment.

INTRODUCTION

Vast barren land areas, particularly in semiarid and arid regions of the world, need to be vegetated for environmental protection and efficient use of soil and water resources in the production of food, feed, and fiber. Historically, cropland tillage implements have been modified and redesigned in an attempt to revegetate such land areas. The resulting implements are referred to in the literature as the eccentric disc pitters (Wight, 1973); brushland disc plows (U.S. Forest Service, 1974); root plows (Abernathy and Herbel, 1973); moldboard plows (Rauzi, 1975); land rippers (Dortignac and Hickey, 1963); land furrowers (U.S. Forest Service, 1970); and brush cutters and shredders.

Disc pitters gouge out basins that collect and infiltrate water. Although soil moisture is increased, these basins do not provide adequate sites for vegetation establishment. Soil surface barrenness and looseness is increased, thereby increasing splash erosion. Such erosion contributes to the short life of the basins and the frequent excessive covering of seeds and seedlings with sediment. Ponded water depths are sufficient to cause drowning of seedlings in wet years. Brushland disc plows loosen the soil and give partial control of forbs and shrubs; however, much of the existing plant material is buried, thereby exposing the surface to wind and water erosion. The soil is often too loose and too dry for successful seed germination and seedling establishment. Root plows performs about the same tillage functions as disc plows and have similar disadvantages. They give better control of shrubs than disc plows. Moldboard plows also loosen the soil, bury plant materials, and provide excellent control of forbs; however, operation is unsatisfactory in shrublands. Disadvantages of these plows are

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similar to those noted above for disc plows. Land rippers fracture the soil deeply with a narrow chisel or wedge-shaped tool. This fracture usually increases infiltration until surface sealing occurs, at which time infiltration may fall below the pretreatment level. Bulk density is too variable in the fractured zone to provide an adequate seedbed. Sealing of the ruptured soil surface occurs rapidly because of the high instability of the loosened and exposed soil material. Furrowers or listers produce contour corrugations, but in the process loosen the soil surface and bury plant materials. Advantages and disadvantages of furrowers are similar to those given for disc pitters except that operation is severely hampered by shrubs. Brush cutters and shredders do not directly alter the shape of the soil surface. The additional litter on the soil surface and the tractor tracks will reduce sealing and increase surface ponding, thereby increasing infiltration. The increased litter also reduces surface evaporation following rainfall. Obviously, seedbed soil moisture is improved only where vegetation is available for cutting or shredding.

The seedbed that is produced by any one of the preceding implements is usually not good enough to insure vegetation establishment except under the most favorable climatic conditions. These implements generally require a large amount of energy to perform each tillage function. Tillage functions are often too few in number, inappropriate in kind or intensity, and conflicting in purpose. Consequently, both the longevity and the initial suitability of the seedbed is diminished. Even when these implements are used in combinations, vegetation establishment is highly erratic. All of these implements operate unsatisfactorily in brushy, steeply sloping, deeply gullied, and rocky terrain. Surface geometries that they produce generally may be characterized as irregular, imprecise, and highly unstable. Very little control over point infiltration, runoff, erosion, and surface evaporation is provided by any of these implements, even though such control is basic to revegetation for the better protection and efficient use of soil and water resources.

The need for a better implement prompted the design and fabrication of a device called the land imprinter. This new tillage implement was developed primarily for establishing vegetation in barren land areas in semiarid and arid regions of the world. In this paper, the theoretical basis for the land imprinter is presented; fabrication and operation details are summarized; preliminary testing results and further testing needs are discussed; and some advantages and disadvantages of the imprinter relative to conventional implements are listed.

DESIGN THEORY

Worldwide over-grazing of pasture and rangelands and excessive tillage of croplands, combined with short-term droughts, are causing rapid expansion of the already vast barren land areas. Strip mining and highway construction are also denuding large land areas. Abandoned irrigation lands are often nearly barren. Barren land characteristically possesses relatively low infiltration rates which are often only one-tenth of those for woodlands and grasslands (Dixon, 1966). Consequently, barren soils shed most of the rainwater from intense thunderstorms, whereas litter-covered soils infiltrate most of the water where it falls. Bare soils shed water readily since they possess well-developed surface drainage patterns and are sealed tightly by raindrops impacting on their surfaces. Litter-covered soils absorb water rapidly because their surfaces are hydraulically rough and macroporous. The small amount of water that does infiltrate barren land areas, penetrates the soil so superficially that most of it is lost by surface evaporation soon after the rain ceases. Thus a vicious circle begins that is responsible for desertification and increasing aridity on both a micro- and macroscale (Fig. 1).

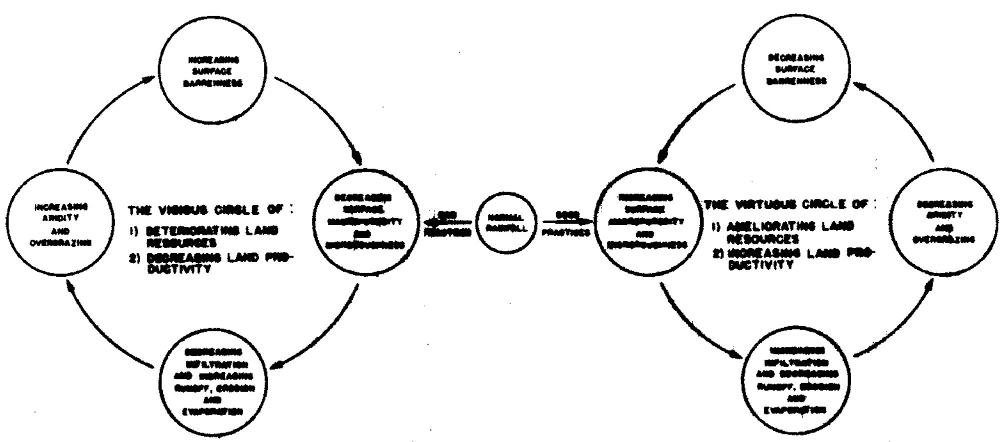

Fig. 1. The land imprinter is designed to break the vicious circle of deteriorating land resources and declining land productivity by molding moist surface soil and vegetal material to precisely shape a stabile runoff-irrigated seedbed and rootbed.

This circle is driven by physical processes such as surface sealing and is accelerated by overgrazing, over-cultivation, and short-term droughts. As the surface becomes increasingly barren, smooth, and sealed, less water infiltrates and less water is available for plant growth, which in turn further increases barrenness. The land imprinter is designed to break this circle by reestablishing the high infiltration rates necessary to replenish the soil-water reservoir required, in turn, to revegetate the soil. This involves converting the smooth closed surface to a rough open one in accordance with the air-earth interface concept - - a recently developed theory setting forth the principles for practical infiltration control through soil surface management (Dixon, 1975a).

The air-earth interface concept postulates that soil surface microroughness and macroporosity control the rates and routes of water infiltration by governing the flow of air and water in underlying macropore and micropore systems. Exchange of soil air and ponded water occurs freely across a rough open surface; consequently, water infiltrates rapidly via the relatively short broad paths of the macropore system. In contrast, exchange of air and water is greatly impeded by a smooth closed surface, and water infiltrates slowly via the relatively long narrow paths of the micropore system. Field testing of this concept under diverse climatic, edaphic and vegetal conditions indicated that rough open surfaces generally infiltrate water about 10 times faster than smooth closed surfaces. In addition, water entering the soil via a rough open surface is less susceptible to loss by evaporation since it is routed deeply into the soil along macroporous paths. Transformation of the smooth closed surface to a rough open one is greatly facilitated by the presence of some plant material that can be used as a mulch. The mulch not only shields the soil against falling raindrops, but also feeds the small soil animals (ants, termites, etc.) which perforate the soil surface and underlying soil with their burrows, thereby creating infiltration-increasing macropore systems.

The soil, water and vegetal resources of arid and semiarid regions, although vast in magnitude, are somewhat sparsely and diffusely distributed. Thus, to insure vegetation establishment the land imprinter is designed specifically to concentrate these resources onto part of the total land area by creating alternating strips of land with runoff enhancing and infiltration enhancing surface geometries. The land imprinter simultaneously forms interconnected downslope and cross-slope corrugations that shed water and then infiltrate it precisely where vegetative growth is to be encouraged. This controlled short-distance routing of water via minute waterways into minute reservoirs makes more rainwater available for seed germination and seedling establishment, and less water available for loss by surface runoff and evaporation.

CONSTRUCTION AND DESCRIPTION

MATERIALS AND SPECIFICATIONS

Excluding the axle bearings, the imprinter has only one moving part in the form of a compound roller and central axle which turn together as a rigid assembly during operation (Fig. 2).

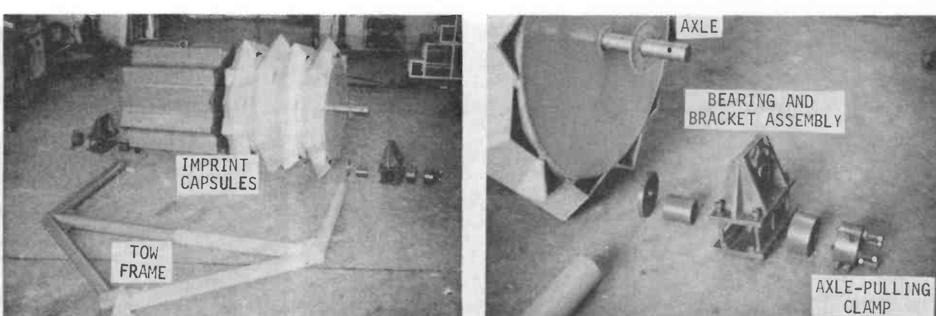

Fig. 2. The land imprinter consists of a compound roller-and-axle assembly in which two imprint capsules are linked rigidly together by means of the axle and a special axle-pulling clamp. The pictured capsules are designed to shape runoff-fed seedbeds by molding moist surface soil and plant materials into complex geometric patterns.

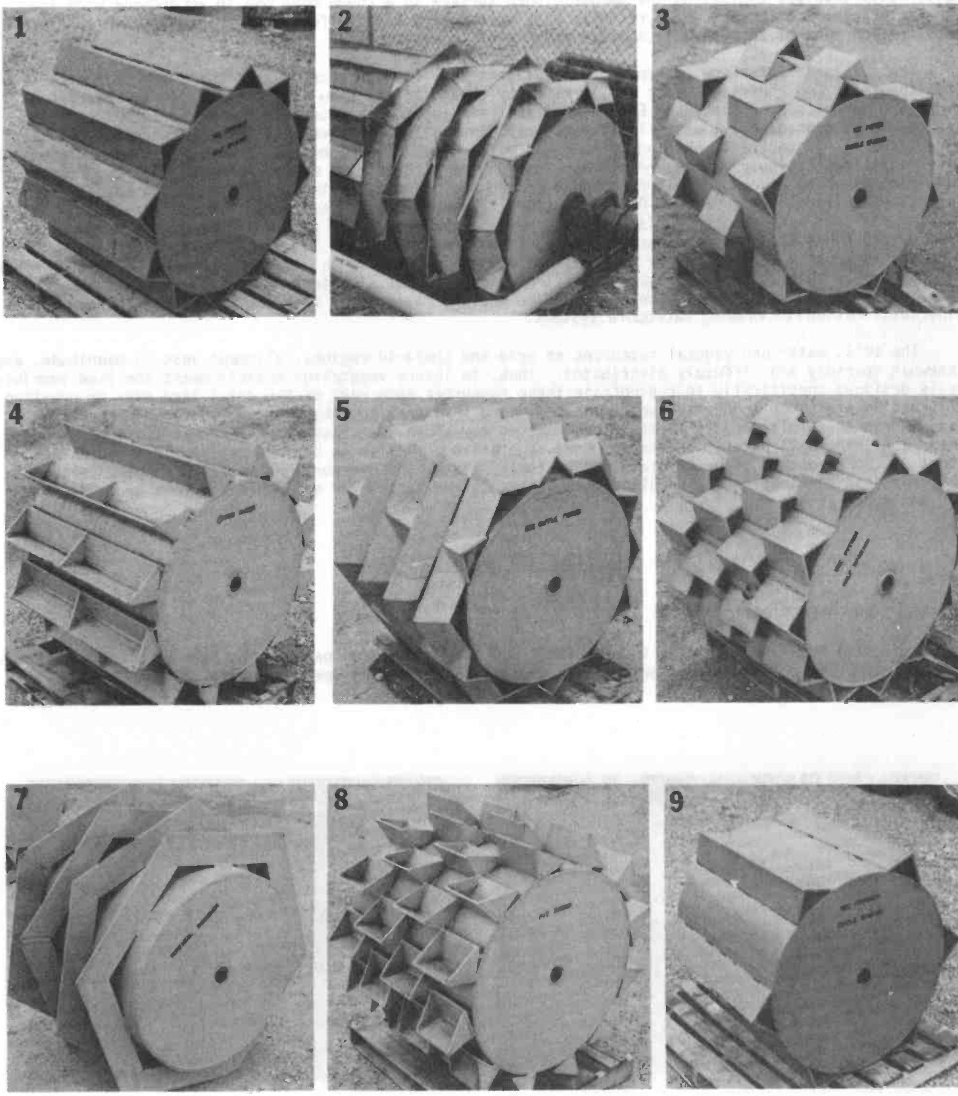

Fig. 3. Forty-five different geometric patterns can be imprinted on land surfaces by pairing ten unique capsules in as many ways as possible. Tillage objectives are achieved by an appropriate mating of two imprint capsules for compatibility with ambient land and climatic conditions.

The compound roller consists of two imprint capsules which are securely linked together on the axle shaft by an axle-pulling clamp. A 0.64-cm thick disc of spring rubber is sandwiched between the two imprint capsules to absorb the shocks of rocky land operation and to maintain the desired alignment between the two capsules. The core of the imprint capsule is a hollow steel cylinder (1-m diameter and 1-m long) fabricated from 1.27-cm steel plate. A variety of imprint geometries are formed by welding short pieces of specially-cut steel angle (1.27-cm thick with 15.24-cm legs) to the surface of the cylindrical core. The outermost edges or corners of the angles are hard-surfaced to resist abrasive wear and to self-sharpen with use. Ten imprint capsules (nine of which are shown in Fig. 3) with distinctly different geometric patterns of steel angles have been designed and fabricated. Imprint capsule No. 1 is fabricated by equally spacing (26.2 cm apart) and welding 12 angle pieces to the cylindrical core with the angle vertex pointed out radially as shown in Fig. 3. Capsule No. 2 is fabricated by welding four hexagonal-shaped angle frames (spaced 25 cm apart) to the core. Angle vertices are oriented radially outward and the corners of the hexagons are staggered as shown in Fig. 3. Capsule No. 3 is fabricated by equally spacing and welding 24 steel angle pieces (25-cm long) to the core with the angle vertex oriented as in Capsule 2. Capsule No. 4 is similar to No. 1 except that an angle leg is oriented outward rather than the vertex. The angle legs are tied together with welded gussets. Capsule No. 5 is similar to No. 2 except that the hexagonal frames are aligned radially. Short angle pieces are welded between the sides of adjacent hexagonal frames to interconnect the vee furrows imprinted by the hexagonal frames, thereby directing rainwater on a zig-zag path through the seeded or vegetal strip. Capsule No. 6 is similar to No. 3 except that twice as many angle pieces are welded to the core at half the spacing. Capsule No. 7 is similar to No. 2 except that the hexagonal frames are fabricated with one angle leg oriented radially outward. As in No. 4, angle legs are reinforced with gussets. Capsule No. 8 is like No. 6 except that an angle leg is pointed outward rather than the vertex. Again, legs are reinforced. Capsule No. 9 is like No. 1 except that half as many angles are welded to the core at twice the spacing. Imprint capsule No. 10, (not shown in Fig. 3) is similar to No. 2 except that dodecagonal (12-sided) frames are substituted for the hexagonal frames.

FUNCTIONS AND OPERATION

By pairing the 10 imprint capsules in as many ways as possible, 45 different geometric patterns can be imprinted. Further variations in imprint geometries and surface water routing can be achieved by radial alignment of the two capsules with respect to each other and orientation of the compound roller with respect to the land slope or grade. The appropriate land slope orientation of the imprinter or the direction of travel with respect to land grade depends on the combination of imprint capsules selected and the tillage objectives or functions. Travel directions include cross-slope (contour), with-slope (contour normal), or diagonal-slope (angle formed by the lines of travel and contour). For instance, if the tillage objective is to increase depression storage, then the direction of travel for imprint capsule No. 1 should be with-slope; but if water harvesting is the desired objective, then travel should be cross-slope.

The patterns of steel angles perform a number of different tillage functions including brush and soft rock chopping and crushing, brush and rock imbedding, runoff inducing and directing, infiltration inducing and directing, biomass concentrating, seedbed forming, surface and vertical mulching, wind and water erosion controlling, soil compacting, and surface trenching and pitting. Each angular pattern performs some or all of these functions with varying degrees of efficiency. Selection of the best pattern and pattern pairs is based on the tillage objective, soil and vegetative conditions, landslope, season, and climatic conditions.

Soil penetration by the imprint angles depends on soil moisture content and the weight or downward force of the imprinter. Downward force is increased by filling the capsules with water or other liquids and by weighting the tow frame with solid steel bars.

Unequal side-to-side weighting can sometimes produce the most desirable penetration depths. Such weighting may be required for uniform penetration, depending on the geometry of the paired capsules. Unequal weighting can also create microslopes in imprinted furrows which would be desirable in nearly level terrain. The maximum weight of the land imprinter is about 5 metric tons, with the water-filled roller-and-axle assembly weighing about 3 metric tons and the weighted tow frame about 2 tons. The land imprinter operates best when the soil is moist, yet dry enough at the surface to prevent sticking of soil to imprint angles. In this respect the imprinter is similar to other tillage implements; however, unlike other implements, the imprinter does not lift and turn the soil over.

Imprint formation involves the shearing and compressing of surface soil material. Since very little soil lifting occurs, less energy is consumed with this type of implement. Also, unlike conventional implements which produce a somewhat haphazard and highly unstable surface geometry, the land imprinter can create a great diversity of precise surface geometries which are relatively stabile. It is possible to form closed surface drainage geometries which can pond considerable water on the surface to enhance infiltration. Much of the plant material remains on, or imbedded in, the soil surface where it can retard surface runoff, surface sealing, erosion and surface evaporation; and enhance surface micro-rougness, surface macroporosity and water infiltration. The plant material mulch also helps to stabilize the imprint geometry by absorbing raindrop impact energy. Through a chopping and crushing action, the imprinter kills the above-ground growth of brittle shrubby species such as creosotebush, thereby conserving the transpiration water long enough to aid in grass seedling establishment. Since this action increases the concentration of biomass near the soil surface, the imprinter should facilitate brush control by burning.

As compared with other minimum tillage implements used in crop and rangelands, the imprinter has a slightly higher initial cost, but has a somewhat lower operation and maintenance cost and is much more versatile. The land imprinter is extremely durable since it is constructed to withstand even the shocks and stresses encountered in rocky hilly land. Cost of imprinting should be less than half that of root plowing. Satisfactory operation requires a 30-hp tractor or larger. Maintenance entails only lubricating axle bearings and oiling imprint angles to inhibit rust formation while the machine is not in use.

MODIFICATIONS, ACCESSORIES AND ALTERNATIVES

The basic imprint capsule design is being modified to permit deeper covering of seed and thus facilitate planting of the small grains, sorghum, corn, cotton, and soybeans. Either a steel rod or a steel bar is welded to the vertex of the steel angle. Rods are 1 cm in diameter, whereas the bars are either 1-cm square or 1 x 2 cm in cross section. This modification forms a 1-cm-wide seed slot in the bottom of the vee furrow. Seed can be covered by rainfall splash erosion, a drag ball or chain, or concave press wheels.

The basic imprint capsule design is also being modified to improve performance of the imprinter on nearly level terrain. Steel angles are altered by removing part of both legs by cutting them diagonally. These altered angles, when welded to the surface of the capsule core, can imprint vee furrows with microslopes to concentrate rainwater.

Other cultural practices can easily be combined with the land-imprinting practice when the expected economic benefit justifies the added cost. Accessories for vegetal shredding, cutting or mulching; seeding grasses, legumes and small grains; spraying herbicides and insecticides; and applying chemical soil amendments are presently being mounted on the A-frame of the land imprinter.

Alternative modifications and designs for the land imprinter include (1) self-propulsion through replacement of wheels of a farm tractor with imprint capsules; (2) fabrication of imprint capsules from reinforced concrete to reduce cost of materials; (3) utilization of imprint capsules single or in combinations of more than two; (4) reduction of imprint capsule diameter for smooth land use and enlargement of diameter for extremely rough land use; (5) utilization of smaller or larger steel angles in the fabrication of imprint patterns; (6) use of more than one angle size on a single capsule to provide minor modification of imprint geometry; (7) modification of number and spacing of steel angle pieces that are welded to the capsule's central core; and (8) replacement of the polygonal angle frames with rings fabricated by welding together two right-angle cone sections.

Other imprint geometries could be created by welding 3- and 4-sided polyhedrons (fabricated from triangular steel plates) to the imprint capsule core in a variety of patterns. For circular geometries, specially-cut pipe sections could be substituted for the steel angles. An infinite number of complex geometries, including sinusoidal waves having a variety of amplitudes and magnitudes, could be created through laminar construction of the imprint capsule. The design geometry would be formed by sandwiching many steel and plyboard discs, each representing a different thin radial section of the imprint capsule.

UTILITY AND TESTING

DESIGN UTILITY

In general, the land imprinter is designed to (1) better protect and more efficiently use soil, water, and vegetal resources in the production of food, feed, and fiber; (2) increase and stabilize range and cropland productivity; (3) reduce land management costs and consumption of fossil fuels per unit of product; (4) reverse the trend toward desertification of vast crop and rangeland areas; and (5) extend agriculture into rocky hilly lands not otherwise arable. To achieve these design objectives, the land imprinter is uniquely capable of providing wide-range control of point infiltration, runoff, erosion, and evaporation; creating precise and stabile surface geometries that can be easily described mathematically; forming a minimum of 45 complex imprint patterns or soil surface configurations for a good fit to ambient land conditions and management objectives; simultaneously creating an efficient surface water routing system (at a microscale level) and seedbed so that rainwater is concentrated and infiltrated at the point where vegetal growth is to be encouraged; performing several complementary tillage functions simultaneously with a relatively small consumption of fossil fuel per function; crushing, chopping and imbedding plant material and rocks in the compacted soil surface to stabilize the geometric imprint pattern against the erosive forces of wind and water; and operating satisfactorily in shrub-covered, steeply sloping, deeply dissected, and rocky terrain.

The land imprinter is expected to be particularly useful in the revegetation of barren land areas produced by short term droughts, overgrazing of rangelands, overcultivation of croplands, overcutting of woodlands, abandoning of croplands, expanding deserts (desertification), strip mining, road construction and urban development. The land imprinter should prove useful in solving land management problems which are aggravated by uncontrolled infiltration including excessive upland runoff and flash flooding; excessive soil erosion and sedimentation of upland waterways and reservoirs; shallow penetration of rainwater into the soil and excessive evaporation losses; pollution of surface and groundwaters; inefficient water harvesting for off-site precipitation uses; and inefficient on-site use of precipitation for food, feed, and fiber production.

Although developed primarily for revegetation of rugged barren land, the imprinter may well find widespread use in croplands either as a secondary or primary tillage implement for preparing efficient seedbeds. The precise control of rainwater movement (at the microscale level) on the soil surface and into the soil could lead to increased and stabler dryland yields of major crops like corn, soybeans, grain sorghum and wheat. The imprinter could eliminate the need for bare fallow as practiced in wheatland areas of the Northern Great Plains. It could also be useful in second cropping, where lack of moisture is the major factor limiting success of this practice.

The imprinter can be used to compact and corrugate land surfaces for furrow irrigation while simultaneously forming an efficient seedbed. Such a practice could increase irrigation efficiency of soils normally having excessive infiltration rates. The imprint made by capsule No. 1 serves as a linear gear, in which this capsule becomes enmeshed on successive passes (return trips) if there is a small amount of overlap. This feature could be useful for forming continuous downslope furrows for irrigation or water harvesting. Capsules Nos. 2 and 10 would also be well suited for creating furrows.

The land imprinter may be used to stabilize abandoned irrigation lands that are highly susceptible to wind erosion. Eroding soil pollutes the air and causes visibility problems along major highways in semiarid regions. The microroughness produced by the imprinter has suitable dimensions for effective wind erosion control (Woodruff and Siddoway, 1973). The imprint would be expected to perform somewhat better than soil clods in wind erosion control because of the lower wind turbulence associated with the imprint and the absence of loose soil. Compressing the soil to form a stable microroughness would seem, therefore, to be a sounder approach to wind erosion control than the traditional approach of loosening the soil to form clods.

The land imprinter could replace conventional wheatland drills for molding a wind-stable seedbed in the stubble of the previous year's wheat crop. This substitution would be particularly advantageous during dry years when wind-eroding wheat fields often pose severe land management problems in the Great Plains.

Soils of the Great Basin in Nevada commonly exhibit a vesicular surface horizon, which severely impedes penetration of rainwater. This horizon could easily be disrupted with the land imprinter to facilitate revegetation. The imprinter should also be effective in mulching the sagebrush of this region.

The imprint produced by capsule No. 1 is expected to be appropriate for vegetating rocky, deeply dissected, hill lands. Two of these capsules could be coupled together with the imprint angles staggered to produce discontinuities in the resulting vee furrows. The imprinter would then be operated up-and-downlope to mold discontinuous furrows on the contour. A dozer blade mounted in front of the tow tractor would be useful for roughing out a path across steep-walled gullies and channels.

Presently, the land imprinter is being applied to increasing rangeland forage production in Arizona through the concentration of sparsely and diffusely distributed soil, water, and vegetal resources onto part of the total land area. Use of the imprinter to create alternate contour strips of land with high and low infiltration geometries, can greatly increase the probability of grass seed germination and establishment. The land imprinter with an appropriate capsule combination forms and firms the soil to produce a precise microdrainage pattern that directs rainwater downslope to the desired point for ponding and subsequent infiltration.

PRELIMINARY TESTING

Seedbed imprint. The imprint capsules with the hexagonal and dodecagonal frames create a variety of favorable seedbed environments, thereby increasing the probability of an adequate stand establishment for a given plant species and set of climatic conditions. The polygonal frames produce vee furrows of variable depth, ranging from a minimum to a maximum depth as the frame rolls from the mid-side to the corner position. Thus, water concentration and depth of seed covering are greatest where the corners deeply indent the soil, and are least midway between these indentations. It is expected that on relatively dry years the corner seedbed sites would be the best. Obviously, the furrow depth variability is less with the dodecagonal imprint frame than with the hexagonal frame.

The initial test of the land imprinter conducted during the summer of 1976 succeeded in revegetating two small experimental areas on the Santa Rita Experimental Range near Tucson, Arizona. Hand broadcast sideoats grama (Bouteloua curtipendula) seed quickly germinated in a seedbed prepared with the imprinter. Most of the seedlings subsequently became well established. By pairing capsules Nos. 1 and 2, an imprint was formed that directed runoff from upslope microwatersheds to the lines and points of seed placement (Fig. 4). A many-fold concentration of rainwater thereby infiltrated the seedbed soil and penetrated deeply beneath the seeds. Additionally, the seedbed firming produced by the imprinter probably enhanced moisture flow to the seeds - - particularly the duration of such flow.

Seed broadcasted over the imprint blew, settled, and washed into the vee furrow bottoms and thus germinated and became established in rows (Fig. 5). Consequently, aerial seeding of imprinted land could probably achieve the results of rangeland drilling.

The most successful imprint sites for grass seedling establishment were where the points of the hexagonal steel frames indented the bottom of the V-shaped furrow. Grass establishment was the highest where such indentations contained mulch to suppress sealing and subsequent evaporation (Fig. 5).

Splash erosion seems to be a suitable means for covering grass seeds in the vee furrows produced by capsules Nos. 2 and 10. Depth of seed covering by splash erosion depends on several factors, including imprint capsule loading (depth of imprint), plant residue cover, rainfall intensity and duration, antecedent soil moisture, capsule design, and soil texture and structure.

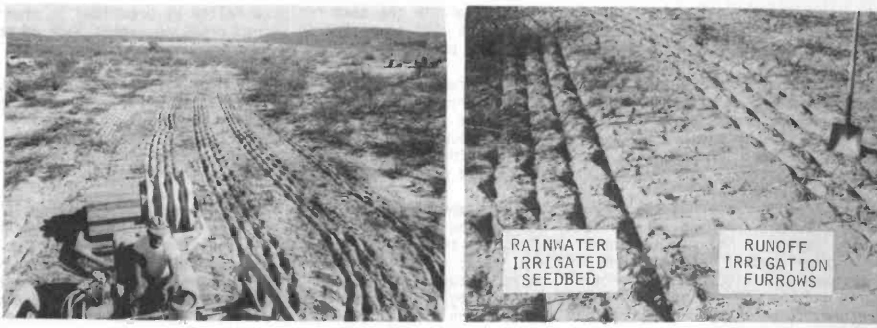

Fig. 4. A rainwater-irrigated seedbed can be molded at the soil surface by the land imprinter to assure adequate water for seed germination and seedling establishment.

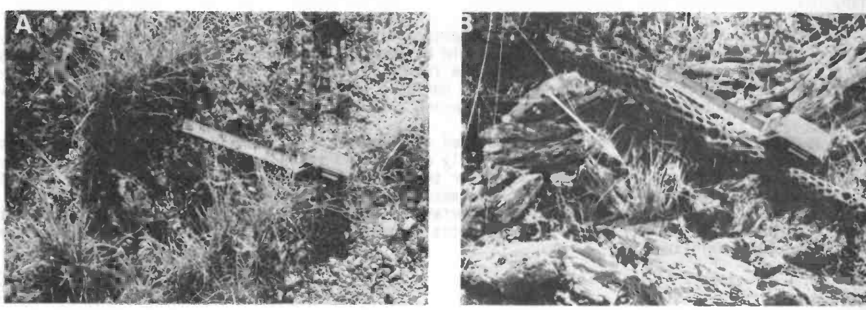

Fig. 5. A. Grass seed broadcasted over the V-shaped imprints germinated and became established in distinct rows giving the appearance of having been drilled.

Fig. 5. B. Mulch-filled indentations produced by the land imprinter were favorable sites for grass seed establishment.

Imprint stability. The imprinter can be operated at soil moisture contents below the sticky point, or when the soil dries enough after rainfall to prevent soil from adhering to and building up on imprint angles. The imprinter produces soil-deforming stresses which compress and sheer the soil to produce the imprint pattern. The resulting compaction or densification increases the soil volumetric moisture content and correspondingly decreases the soil air volume and moisture tension.

In humid and subhumid regions, selecting the optimal soil moisture for imprinting would involve a compromise between the need for soil surface stability (strength) and soil looseness (aeration), since stability increases with compaction. Maximum imprint stability and strength would be expected with an initial moisture content near the lower end of the plasticity range and a final moisture content in the upper end of this range, but just below the sticky point (Baver et al., 1972). If excessive soil compaction is a critical land management problem, then the imprinter should be operated at final moisture contents below the lower plastic limit.

In arid and semiarid regions, the compromise between soil stability and looseness is often unnecessary since land can often be imprinted when the surface 10 to 15 cm of soil has a plastic consistency, and the underlying soil has a hard or harsh consistency. This combination of a wet surface layer overlying a dry layer facilitates molding of a stable imprint without compacting the root zone. In southern Arizona, these soil moisture conditions are prevalent after the first large rain of the July-August monsoon season. This depth distribution of soil moisture could be easily created in irrigated lands by allowing the soil to dry and then irrigating lightly before imprinting. However, moderate compaction of the seedbed is usually desirable, especially in coarse-textured soils. The optimal initial soil moisture for operating the land imprinter will usually be somewhat greater than it is for conventional tillage implements, since the principle purpose of the imprinter is to produce a stabile (strong) imprint geometry rather than a layer of loose friable soil.

Uniformly high imprint stability results in efficient routing of rainwater to the vegetal site, uniform covering of seeds by splash-eroded soil, rapid development of a stabile surface macroporosity in the bottoms of cross-slope furrows, and a long effective life of the imprint geometry. The soil moisture contents for maximum traction, tractor tire life, and imprint stability would probably be nearly identical. Preliminary results suggested that imprint stability (under the erosional forces of wind, water and gravity) could be maximized by operating the imprinter at a final moisture content just below the sticky point. Maximum soil compaction and bulk density also occur at this moisture content. Consequently, sandy and gravelly soils should be imprinted as soon as possible after ponded surface water infiltrates following a large rain, whereas clayey soils should be allowed to dry for several days or until soil no longer sticks to imprint angles. Additional imprint stability and longevity can be achieved by shredding all existing plant materials and depositing them on the seedbed strip, imprinting during a low-intensity rainfall season, and seeding a variety of plant species, including some that will provide a quick vegetative cover.

It is important to establish vegetative cover as soon as possible to protect the imprint geometry from raindrop impact. Even where the imprint has no protective mulch, its life is sufficient to insure seed germination and establishment, after which time the vegetative growth can create and maintain the surface hydraulic roughness and macroporosity which are essential for high infiltration rates (Dixon, 1975a). By placing a variety of adapted seeds in a variety of suitable seedbeds, the likelihood of achieving an adequate stand of plants under prevailing climatic conditions is greatly enhanced. In southwestern United States, vegetation established during the gentle winter rains would protect the imprint from the beating raindrops of the intense summer thunderstorms. Ideally, the seeding mixture should contain both legumes and grasses, because of their contrasting rooting depths and the ability of legumes to fix nitrogen for possible use by the grass. Annual, perennial, warm-season, and cool-season grasses should be included.

<u>Runoff and erosion</u>. Rainwater is concentrated at the points or lines of seed placement and seedlings are established by two different transport modes acting during three time periods. During the initial period, water is transported by raindrop splash alone; during the intermediate period, by a combination of splash and rill flow; and during the final period, after rainfall ceases, by rill flow alone. If rainfall is of very short duration or of very low intensity, only splash concentration will occur.

Although splash erosion shortens the life of the imprint, some possible advantages were observed. Splash erosion (1) rapidly seals the bottoms of the downslope furrows, thus increasing runoff delivery to the cross-slope furrows; (2) rapidly covers seeds in the cross-slope furrows; (3) hills and braces plants in the bottom of the furrows with the transported soil; (4) concentrates top soil and plant litter in the cross-slope furrows; and (5) smooths the soil surface for cropland harvesting equipment.

<u>Imprinting speed and depth</u>. The imprinter has been operated at velocities up to 6 km/hr to determine the effect of surface molding rates on the resulting geometry. Preliminary tests indicated that the effect of velocity is minor. Some loose soil particles settled into the bottom of the vee furrow at the higher speeds, especially when soil moisture was below the plastic range. As expected, penetration depth of the imprint angles is a function of imprinter loading, soil texture, initial bulk density, and initial soil moisture, with the depth increasing with increasing imprinter weight, initial soil moisture, and texture coarseness up to certain limits; and with decreasing bulk density. With the imprint capsules filled with water and the tow frame fully loaded, the land imprinter can penetrate even a dry, compact clayey soil.

<u>Imprint macroporosity</u>. Contrary to Darcy-based infiltration theory, the air-earth interface theory (Dixon, 1975a) indicates that high infiltration rates and high bulk densities are not mutually exclusive conditions. Soils with relatively high bulk densities will have relatively high infiltration rates, if their surfaces are microrough (hydraulically) and macroporous. In contrast, soils with relatively low bulk densities will have relatively low infiltration rates if their surfaces are smooth and microporous.

The imprinter initially increases surface bulk density, microroughness, depression storage, and litter; and decreases surface macroporosity. However, the increases in microroughness and surface litter cause rapid development of surface macroporosity in the cross-slope furrows. This microroughness, combined with intense rainfall, produces a hydraulic head that favors macropore formation through a micropiping process whereas the mulch stabilizes the microroughness and the developing macroporosity. The mulch directly promotes macropore formation by feeding the small animals that burrow in the surface soil. Additionally, the imprinted geometry favors the germination and establishment of newly seeded vegetation with consequent formation of root-void macropores. Wetting and drying of the cross-slope furrows also creates macropores in the form of shrinkage cracks, which commonly can be observed in the furrow bottom. Thus, the range in infiltration control is expected to widen rapidly after the downslope and cross-slope corrugations are imprinted (Dixon, 1975a). The widest infiltration range is expected to develop in fine-textured soils, imprinted at a moisture content favoring maximal densification, with available plant materials forming a complete mulch cover for the cross-slope furrows.

<u>Imprint modeling</u>. The land imprinter produces geometries that are sufficiently stabile to justify describing them mathematically. The vee furrow can be described by the general equation:

$$y = a|x - b\lambda| + c$$

where the variables x and y represent horizontal and vertical distances, respectively; and the constants a, b, c and λ represent, respectively, the furrow side slope y/x, the number of furrows from the origin, the y-intercept of the furrow bottom, and the furrow wave length or spacing.

Sinusoidal imprint patterns could be modeled by the equation

$$y = A \sin Bx$$

where the constant A is the furrow amplitude (half the furrow depth) and the constant B is $2\pi/\lambda$. Splash erosion of the vee configuration may cause it to approach a sine wave shape. Fourier series analyses may provide a quasi-quantitative method for describing progressive changes in the vee and sinusoidal geometries resulting from splash erosion. Such an approach could provide a convenient way for estimating depression storage and the depth and distribution of ponded surface water as it is affected by splash erosion.

Further testing. Testing is still needed to determine how well and under what conditions the land imprinter can achieve its broad design objectives as listed previously. Basic to achieving these objectives is the land imprinter's ability to control point water infiltration rates and soil penetration routes. Sprinkling (Dixon and Peterson, 1964) and closed-top infiltrometers (Dixon, 1975b) will be used before and after imprinting to evaluate the immediate and long-term infiltration effects of land imprinting under diverse edaphic, climatic and vegetal conditions. Specifically, the initial infiltration control range, rate of range change, and the final (equilibrium) range will be determined.

Numerous seeding trials must be conducted with success of vegetation establishment treated as a function of several variables including imprint geometry, seeding mixture, and soil and climatic conditions.

Initially, the land imprinter will be tested relative to its use in revegetation of barren land areas; however, some exploratory studies will be directed to related potential uses of the imprinter, including brush control and wind and water erosion control.

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NONPOINT-SOURCE POLLUTANTS TO DETERMINE RUNOFF SOURCE AREAS[1/]

by

L. J. Lane, H. L. Morton, D. E. Wallace, R. E. Wilson, and R. D. Martin[2/]

ABSTRACT

Hydrologic information is needed to understand and control water pollution from semiarid rangelands. However, the hydrologic systems under any given conditions must be understood and the effects of various land uses predicted.

Based on the concept of partial area response, a runoff tracer study was conducted on two small watersheds. The watersheds were partitioned into four geomorphic subzones or hydrologic response units. Each of the four zones on both watersheds was treated with about 1 kg/ha of an individual water soluble herbicide. Runoff volumes and sources estimated using the tracers were consistent with results from simulation studies. Also, the principle of corresponding runoff and pollutant discharge rates was used to develop two methods of runoff hydrograph estimation from each of the geomorphic subzones. Method 1 matched the mean total concentration and total runoff volume. Method 2 matched the instantaneous total concentration and the instantaneous runoff rate from the entire watershed. Results from the two methods suggested that, although they may be equivalent with respect to runoff volume, Method 2 may be more consistent with respect to peak discharge.

INTRODUCTION

BACKGROUND

Basic requirements under Public Law 92-500, "The Federal Water Pollution Control Act Amendments of 1972", are "to restore and maintain our water quality." This charge requires two major efforts: 1) to understand the present conditions in order to maintain the present status or to have a base for restoring the quality and 2) to predict the consequences of rehabilitative measures or future land uses. Thus, we must understand the hydrologic systems under any given conditions and be able to predict the effects of various land uses including agricultural practices and conservation measures.

As specified in the legislation, nonpoint pollution sources are characterized by the following: 1) the runoff is not controlled or produced at a single point or source; and 2) runoff, as the transport medium, gathers the pollutants over an area and not from a single point. Thus, one of our research objectives is to provide hydrologic information needed for understanding and controlling water pollution from rangelands.

BASIC CONCEPTS

Partial Area Response (variable source area response) is a term used to designate the response of a watershed when only a portion of the total drainage area is contributing runoff at the watershed outlet or point of interest.

Geomorphic Subzones (or hydrologic response units) are zones within a watershed where specified geomorphic features are relatively homogeneous.

Kinematic Cascade Model is a mathematical model wherein watershed topography is represented by a cascade of planes and channels in a logical flow sequence. Water flow routing is accomplished using the kinematic wave equations as approximations to the full continuity of mass and momentum equations (Kibler and Woolhiser, 1970). Planes and channels in this model are chosen to correspond closely with the geomorphic subzones. Thus, to an extent measured by statistics of goodness-of-fit, the watershed topography (geomorphic character) is preserved in the mathematical model.

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1. Contribution of the United States Department of Agriculture, Agricultural Research Service, in cooperation with the United States Forest Service.

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Principle of Corresponding Runoff and Pollutant Discharge Rates states that, for a given geomorphic subzone, if a pollutant is available for transport in surface runoff, then for each runoff rate there is a corresponding pollutant discharge rate.

WATERSHED AND DATA

The Santa Rita Experimental Range is a 200-sq-km range located some 50 km south of Tucson, Arizona. It was established in 1903 and is maintained by the Forest Service, USDA, for studying the interrelationships of organisms, attributes, and processes of semidesert ecosystems (Martin and Cable, 1975). In 1975, eight small experimental watersheds were established and instrumented to investigate the effects of various grazing and vegetation controls on the hydrologic and erosion response of semiarid watersheds.

Generally, surface runoff results from short duration thunderstorms during the summer months. Continuous records of rainfall and runoff are obtained by the recording equipment. Also, water quality/sediment samples are obtained at 3 min intervals throughout the runoff events (Renard, Simanton, and Donica, 1976). Sediment data consist of concentration values throughout the hydrograph. Water quality data consist of the sediment concentration data and concentrations of up to four different herbicides throughout the recorded hydrographs. Infiltrometer data (Dixon and Peterson, 1968) were taken at eight plot sites within the experimental watersheds. Vegetation transects were established at several sites in each watershed (Martin, Morton, and Renard, 1974). Soil samples and plant samples were taken to determine soil concentrations and plant uptake rates of the various herbicides. In a previous experiment, Velvet Mesquite (Prosopis juliflora var. velutina) was killed on Watershed 76.002. Watershed 76.001 was not treated before this experiment.

PROCEDURE AND EXPERIMENTAL DESIGN

Two watersheds were divided into four geomorphic zones as shown in Figs. 1 and 2 (Lane and Wallace, 1976). Watershed 76.001 has a drainage area of 1.64 ha, whereas Watershed 76.002 drains 1.77 ha. Water soluble herbicides were applied to the zones at about 1 kg/ha (Table 1) on July 9, 1976 in anticipation of minimizing the time between application and the start of the runoff season. In actual brush control programs, the herbicides would be applied earlier to minimize, rather than maximize, the likelihood of their transport in runoff. Soil surface herbicide concentration data through time are shown in Table 2 for Watershed 76.001 and Table 3 for Watershed 76.002. Smooth curves were fitted to means of these data as shown in Figure 3. These curves were then used to show qualitative trends in the concentrations of herbicides available for transport throughout the runoff season. For comparison, data from White, et al. (1976) are shown in Figure 3. Since precision in the soil concentration data was poor, they were not used to normalize concentration in the water samples.

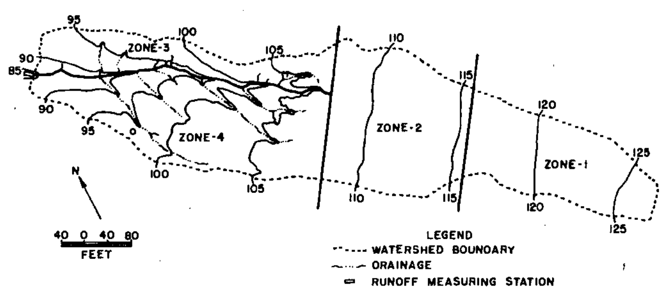

Figure - 1. Map of Watershed 76.001 showing drainage pattern and division of the watershed into geomorphic zones.

Herbicide concentrations in the water and soil samples were determined using a gas-chromatograph technique (Merkle, M. G. et al. 1966). Any herbicides that may have traveled with the sediment were extracted and combined with the water samples. Water and soil samples were refrigerated after collection until analysis to minimize herbicide degradation. Concentration and runoff data were combined to determine sediment and herbicide yield rates from all zones in each watershed.

RESULTS

OBSERVED DATA

Runoff and corresponding herbicide yield data are summarized in Table 4 for storms in 1976.

Essentially, there was no difference in runoff yield between the two watersheds (Watershed 76.001 had more small storms), but Watershed 76.002 had nearly 3 times as much herbicide yield in the runoff. Although the reasons for this difference were not determined, our speculation is that part of the differences may be due to differences in watershed topography (Figs. 1 and 2) and to differences in vegetation due to previous experiments.

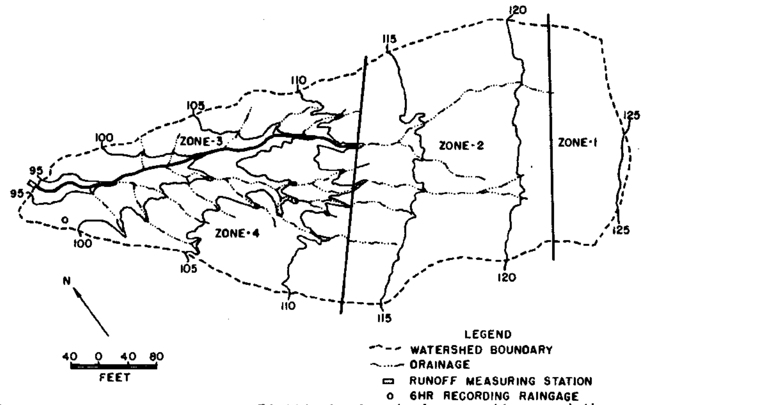

Figure - 2. Map of Watershed 76.002 showing drainage pattern and the division of the watershed into geomorphic zones.

TABLE 1.

Amount of herbicides applied to each zone in Watersheds 76.001 and 76.002 for the 1976 tracer study.

ZONE	AREA (ha)	AMOUNT OF HERBICIDES APPLIED (g) Design	Actual	ACTUAL APPLICATION RATE (kg/ha)
		Watershed 76.001		
1 (2, 4-D)	0.38	426.	393.	1.03
2 (2,4,5-T)	0.45	504.	483.	1.07
3 (Picloram)	0.26	291.	272.	1.05
4 (Dicamba)	0.55	616.	605.	1.10
TOTAL	1.64	1837.	1753.	
		Watershed 76.002		
1 (2, 4-D)	0.21	235.	181.	0.86
2 (2,4,5-T)	0.78	874.	914.	1.17
3 (Picloram)	0.24	269.	242.	1.01
4 (Dicamba)	0.54	605.	544.	1.01
TOTAL	1.77	1983.	1881.	

RELATION BETWEEN RUNOFF AND HERBICIDE YIELDS

Although the data were limited, they suggested that there is no simple relation between runoff volume and herbicide yield for individual events (Figs. 4(A) and 5(A)). Points labeled 7/17/76 are for the first runoff event after treatment and the points labeled 7/27/76 are for the largest event observed during 1976. These figures illustrate the importance of storm sequencing and size. For Watershed 76.001, the first storm (7/17/76) produced the greatest herbicide yield while on Watershed 76.002, the largest storm (7/27/76) produced the greatest herbicide yield. For Watershed 76.001, about 0.21% of the applied herbicide was washed off with the summer runoff. About 0.56% of the applied herbicide was washed off in runoff from Watershed 76.002. Figures 4(B) and 5(B) show the cumulative runoff and herbicide yields. Data from White et al. (1976) are shown for comparison in Figures 4 and 5. Their data produced nearly 2% of the applied herbicides in runoff from simulated rainfall for a time period of 35 days for herbicides applied at the rate of 0.56 kg/ha (White et al. 1976, Table 2, p. 489).

RELATIONS BETWEEN RUNOFF RATES AND CONCENTRATION

Relations between runoff rate and sediment concentration for two storms on Watershed 76.001 are shown in Figures 6(A) and 7(A). Apparently, there may be a relationship for the data from the storm on 7/17/76, but not from the storm on 7/27/76. Similar data for herbicide concentrations are shown in Figures 6(B) and 7(B). The linear relationships between concentrations and runoff rate for the first

TABLE 2.

Summary of herbicide concentrations in the surface soil, Watershed 76.001.

Type and Time of Samples	Zone-1 2, 4-D	Zone-2 2, 4, 5-T	Zone-3 Picloram	Zone-4 Dicamba	Mean of All Zones
	Herbicide Concentrations in µg/g				
7/9/76[1]					
GLC[2]	1.78	1.56	.51	.96	1.2
BIO[3]	- - -	- - -	- - -	- - -	- - -
7/15/76					
GLC	.20	.66	.04	.73	.41
BIO	.04	.12	≥.01	≥1.0	≥.29
7/22/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	.006	.08	≥.01	.14	≥.06
8/6/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	1.37	.004	≥.01	.14	≥.38
9/2/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	.09	.004	≥.01	.78	≥.22

1. Date of application.
2. Gas liquid chromatograph.
3. Bio-assay

TABLE 3.

Summary of herbicide concentrations in the surface soil, Watershed 76.002.

Type and Time of Samples	Zone-1 2, 4-D	Zone-2 2, 4, 5-T	Zone-3 Picloram	Zone-4 Dicamba	Mean of All Zones
	Herbicide Concentrations in µg/g				
7/9/76[1]					
GLC[2]	.39	.51	.22	.89	.50
BIO[3]	- - -	- - -	- - -	- - -	- - -
7/15/76					
GLC	.44	.68	.06	.19	.34
BIO	.04	1.08	≥.01	≥1.	≥.53
7/22/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	≥2.	.004	≥.01	.14	≥.53
8/6/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	≥2.	.06	≥.01	.14	≥.55
9/2/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	.0001	.001	≥.01	.007	≥.005

1. Date of application.
2. Gas liquid chromatograph.
3. Bio assay.

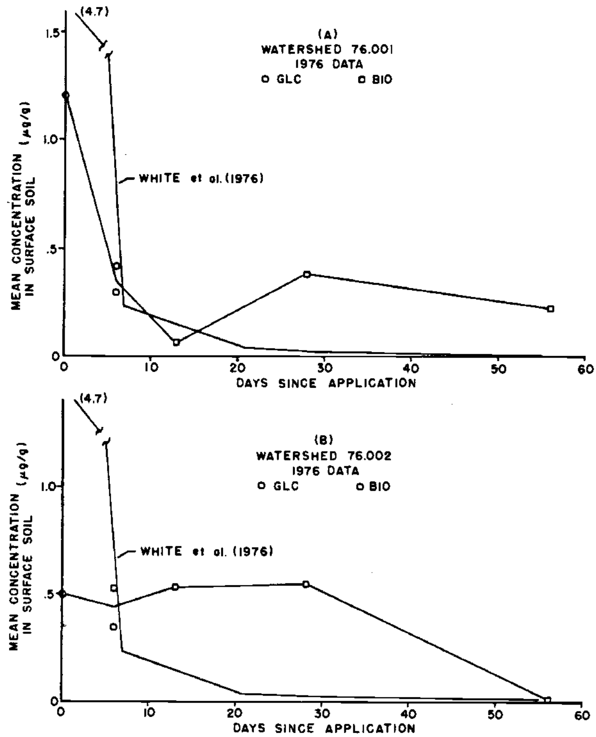

Figure - 3. Herbicide concentrations in surface soil. Initial application rate of 1.0 kg/ha. GLC represents concentrations by gas chromotography and BIO is the bia-assay method.

TABLE 4.

Summary of runoff and herbicide yields from Watershed 76.001 and 76.002 during the 1976 study.

DATE OF EVENT	DAYS SINCE TREATMENT	VOLUME OF RUNOFF (liters x 10^4)		YIELD OF HERBICIDES (g)[1/]	
		EVENT	CUMULATIVE	EVENT	CUMULATIVE
		Watershed 76.001			
7/17/76	8	1.99	1.99	2.04	2.04
7/21/76	12	.65	2.64	.13	2.17
7/27/76	18	7.06	9.70	.69	2.86
7/28/76	19	.07	9.77	.01	2.87
8/10/76	32	.42	10.19	.06	2.93
8/26/76	48	3.19	13.38	.19	3.12
9/1/76	54	.61	13.99	.05	3.17
9/22/76	75	.07	14.06	.01	3.18
9/25/76	78	2.81	16.87	.46	3.64
		Watershed 76.002			
7/17/76	8	.69	.69	.95	.95
7/21/76	12	.03	.72	.05	1.00
7/27/76	18	7.36	8.08	8.41	9.41
8/26/76	48	5.49	13.57	.53	9.94
9/25/76	78	2.40	15.97	.64	10.58

1. No 2, 4-D from Zone 1 was found in any of the water quality samples.

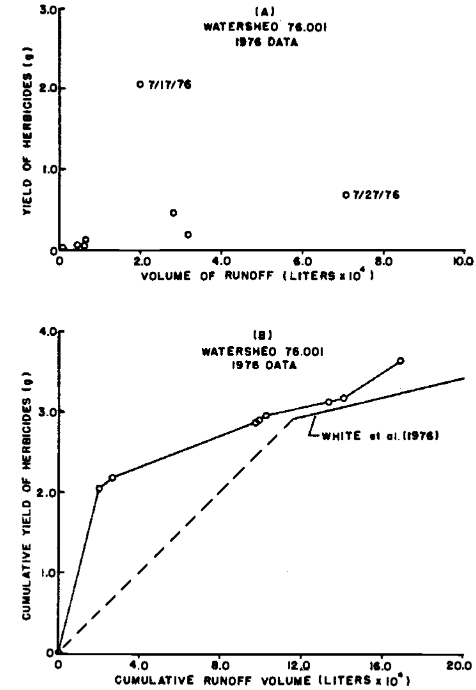

Figure - 4. Relation between runoff volume and herbicide yields.

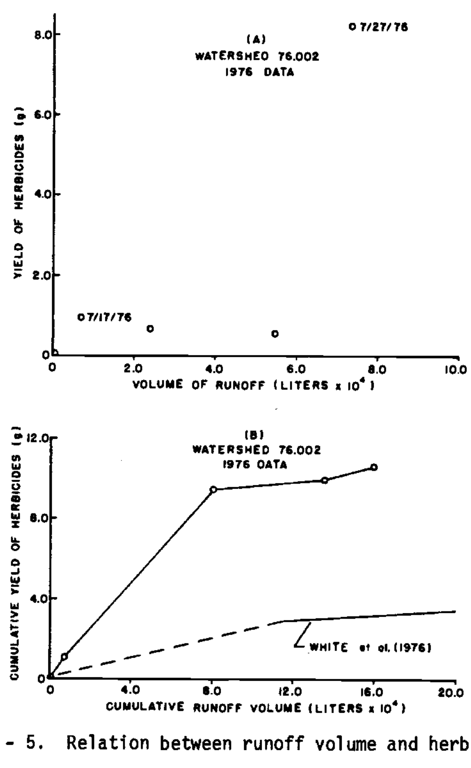

Figure - 5. Relation between runoff volume and herbicide yields.

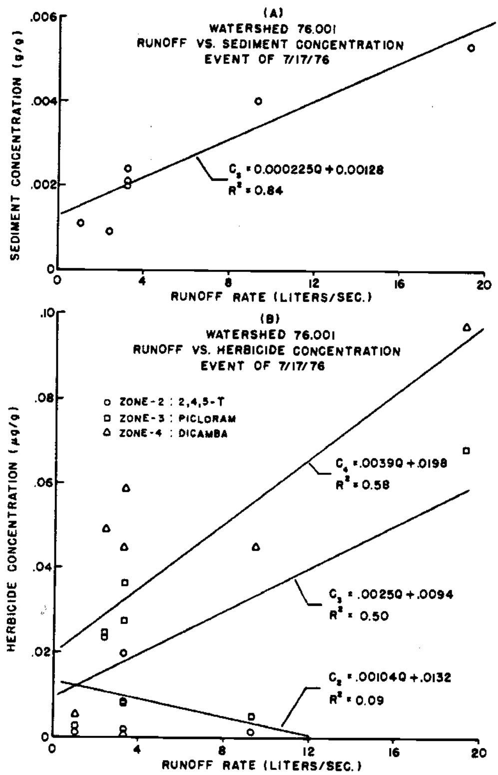

Figure - 6. Relations between runoff rate and concentration.

storm (7/17/76) can be partly explained from the time distributions of the water quality samples. Relations between runoff rate, sediment concentration and time for the two storms are shown in Figure 8. For the event of 7/17/76, both runoff and concentration decreased with time, although no sample was collected on the hydrograph rise. This was not true for the second event (Fig. 8(B)). Therefore, the existence of a linear relationship between concentration and runoff rate was due to the simple hydrograph shape and the small number of samples for the event on 7/17/76. Similar results are seen in plots of herbicide concentration (Fig. 9) where there appeared to be no linear relation between runoff rate and herbicide concentration.

APPLICATION: A TRACER STUDY

PARTIAL AREA CONCEPT

The partial area concept (variable runoff source area concept) was developed in humid regions (e.g., Hewlett, 1961, and Dunne and Black, 1970). An exception, developed for semiarid watersheds, is the average loss rate procedure of Arteaga and Rantz (1973). Lane et al. (1976) developed four analytical procedures to simulate partial area response on small semiarid watersheds. From these studies and observations, we concluded that the mechanism for surface runoff generation on small semiarid watersheds, like those discussed here, is generation of overland flow on portions of the watersheds. The four analytic procedures used suggested that for the 1.64 ha watershed, 40 to 100% of the total area was contributing runoff. These results are from analysis and not observation. Therefore, a tracer study was conducted for field testing the simulation results.

GEOMORPHIC SUBZONES

Watersheds 76.001 and 76.002 were both divided into four zones (Figures 1 and 2) These zones were selected to be relatively homogeneous within each zone with respect to average slope, drainage density, and mean length of first order streams. These criteria were more nearly met in Watershed 76.001 than in Watershed 76.002. Figure 10 shows a simplified kinematic cascade model corresponding to the four zones on Watershed 76.001. Each of the four zones is modeled as a plane and the channel network is modeled as a single channel corresponding to the main channel of the watershed.

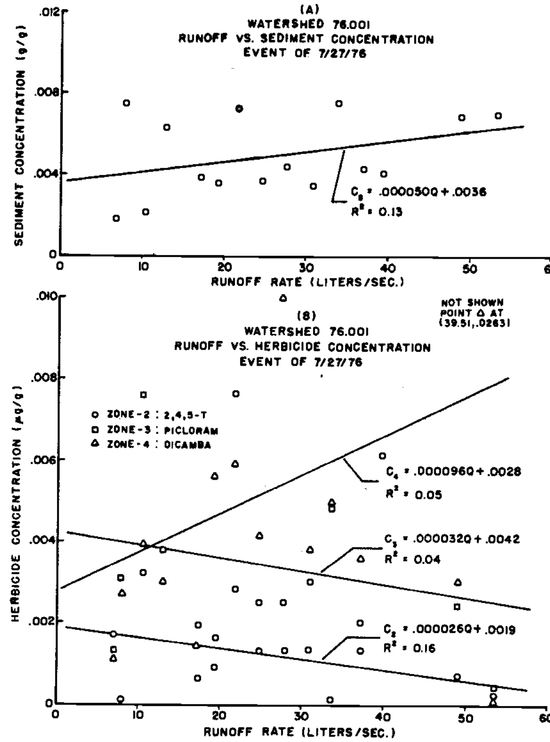

Figure - 7. Relations between runoff rate and concentration.

Using the kinematic cascade model described above and the SCS (1971) curve number procedure, runoff rates and amounts were estimated for each zone for various storm sizes. These estimates were used to determine the amounts of herbicide to be applied to each zone so that detectable and safe concentrations of herbicides could be sampled (Table 1).

EXPERIMENTAL DESIGN FOR TRACER STUDY

Infiltrometer data (Dixon, 1976) suggested a variation of infiltration rates in the ratio 2:1 between the upper and lower zones on Watershed 76.001. The optimal curve number in the SCS runoff estimation procedure (SCS, 1971) for the entire watershed is 89. Therefore, zones 1 and 2 were assigned a value of 84, and zones 3 and 4 were assigned a value of 94. With these values, a rainfall depth of 3 mm (0.12 in) would cause runoff on zones 3 and 4. A rainfall depth of 8.9 mm (0.35 in) would produce runoff on zones 1 and 2. From these values of rainfall and runoff, it was determined that rainfall depths of 8.9 mm (0.35 in) or more would produce runoff and detectable concentrations of the herbicides, if they were applied at the rate of 1 kg/ha.

PROCEDURES FOR DETERMINING RUNOFF FROM EACH ZONE

Total runoff and concentration data were used with the principle of corresponding runoff and pollutant discharge rates to estimate runoff rates and amounts for each zone. The technique involving matching runoff volumes is Method -1 and that based on matching rates is Method -2.

RUNOFF VOLUMES

Let Q_i be the volume of runoff from zone i during a particular runoff event. Let Q_T be the total volume of runoff from the entire watershed. Thus

$$Q_T = \sum_{i=1}^{N} Q_i \tag{1}$$

where N is the number of zones. Let Y_i be the total yield of herbicide i from zone i, and Y_T be the total yield of herbicides from all zones so that

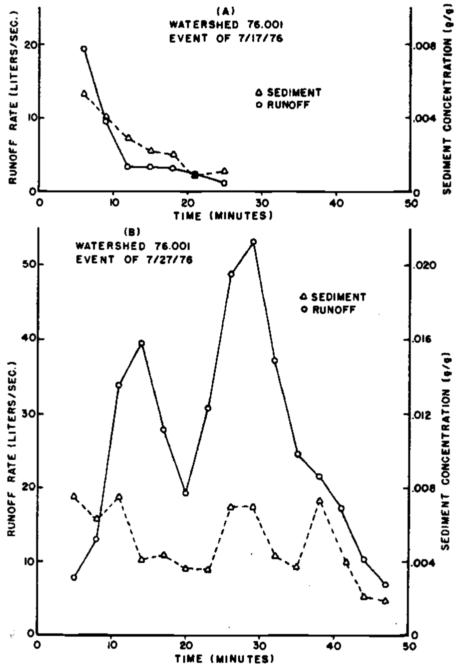

Figure - 8. Relation between runoff rate and sediment concentration.

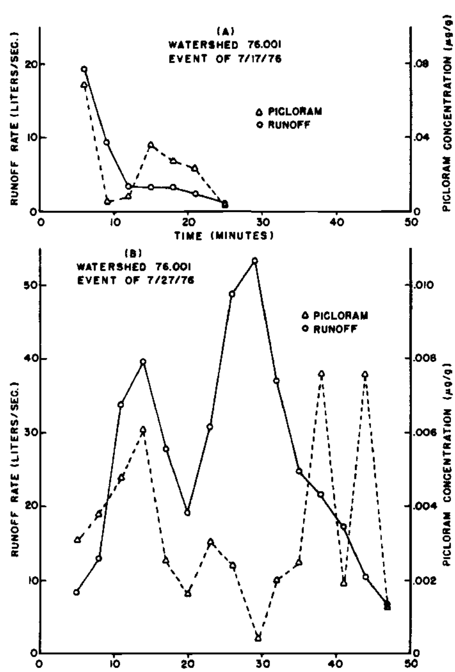

Figure - 9. Relation between runoff rate and herbicide concentration.

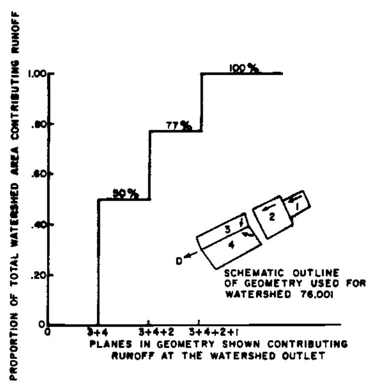

Figure - 10. Relation between number of planes and proportion of watershed area contributing runoff.

$$Y_T = \sum_{i=1}^{N} Y_i \tag{2}$$

as in Eq. 1. If the volumes of runoff are proportional to the mass yields of corresponding herbicides,

$$\frac{Q_i}{Q_T} = \frac{Y_i}{Y_T} \tag{3}$$

which can be solved for Q_i as

$$Q_i = \frac{Q_T}{Y_T} Y_i \tag{4}$$

where the variables are as described above. Equation 4 is used to estimate the volumes of runoff from each zone.

RUNOFF RATES

As in Eq. 4, if $q_i(t)$ is the runoff rate from zone i, $q_T(t)$ is the runoff rate from the entire watershed; $y_i(t)$ is the yield rate of herbicide i from zone i, and $Y_T(t)$ is the total yield of all herbicides, then

$$q_i(t) = \frac{Q_T}{Y_T} y_i(t) \tag{5}$$

is a means to estimate the runoff rate from zone i. This procedure was called Method -1. Following the form of Eq. 5, but in terms of rates (following a similar suggestion by E. D. Shirley), the second method of estimating the runoff rate is

$$q_i(t) = \frac{q_T(t)}{y_T(t)} y_i(t) \tag{6}$$

called Method -2. The sum of runoff volumes from Eq. 4 equals the total observed runoff volume since summing both sides of Eq. 4 produces

$$\sum_{i=1}^{N} Q_i = \frac{Q_T}{Y_T} \sum_{i=1}^{N} Y_i \tag{7}$$

which simplifies to $Q_T = Q_T$. With this, Eq. 4 matches the observed runoff flow volume. If both sides of Eq. 5 are integrated up to time T, the duration of flow,

$$\int_0^T q_i(t) = \frac{Q_T}{Y_T} \int_0^T y_i(t)\, dt \tag{8}$$

and,

$$Q_i = \frac{Q_T}{Y_T} Y_i \tag{9}$$

which is the same as Eq. 4. Therefore, Method -1 also matches the observed runoff volume. With the same logic, if both sides of Eq. 6 are summed,

$$\sum_{i=1}^{N} q_i(t) = \frac{q_T(t)}{y_T(t)} \sum_{i=1}^{N} y_i(t) \tag{10}$$

which becomes $q_T(t) = q_T(t)$ since

$$\sum_{i=1}^{N} q_i(t) = q_T(t) \tag{11}$$

and

$$\sum_{i=1}^{N} y_i(t) = y_T(t) \tag{12}$$

by definition. Also

$$\int_0^T q_T(t)\, dt = Q_T \tag{13}$$

so that Eq. 6 matches total rate and total volume of runoff.

Examples of runoff predictions by Method -1 and Method -2 are shown in Figures 11 and 12. There was no herbicide detected from Zone -1, and Method -2 exactly matches the total runoff hydrograph from the entire watershed. Also, Method -2 seemed less prone to overestimate peak discharge rates.

Volumes of runoff from each zone, as estimated by the two methods, are shown in Figure 13. There is nearly a one-to-one relation in estimated volumes, which suggests that, with respect to volumes, the two methods are equivalent.

SUMMARY OF TRACER STUDY RESULTS

To determine diffuse pollutant source areas, runoff and sediment source areas must be determined. Analytic procedures suggested that for the small watershed studied, 40 to 100% of the watershed contributed runoff. Results of a tracer study in 1976 supported the partial area or variable source area concept.

The principle of corresponding runoff and pollutant discharge rates was used to develop two methods of runoff hydrograph estimation from each of the geomorphic subzones. Results from the two methods suggested that they may be equivalent with respect to runoff volume but that Method -2 may be more consistent with respect to peak discharge.

Finally, Method -1 uses the inverse of the mean total concentration as the coefficient in Eq. 5. Therefore, Method -1 matches the mean of the observed concentration data at the sampling times. Method -2 uses the inverse of the instantaneous total concentration as the coefficient in Eq. 6. Therefore, Method -2 matches the total instantaneous concentration data at the sampling times.

SUMMARY

Based on the concept of a partial area response, a tracer study was conducted on two small semiarid watersheds that were partitioned into geomorphic subzones or hydrologic response units. Each of four zones on both watersheds was treated with about 1 kg/ha of four individual water-soluble herbicides.

Herbicide yields in surface runoff during the 1976 summer season amounted to 0.21% and 0.56% of the total amounts applied. For individual runoff events, herbicide yields were not related to runoff volume alone, but were influenced by storm sequence.

Runoff volumes for each zone of the watershed (as estimated from the tracer study data) agreed with analytical results indicating a partial area response. These results were consistent in identifying runoff and pollutant source areas on these small watersheds.

Based on the corresponding rates principle, two methods were developed to relate runoff rate and herbicide (pollutant) discharge rates. Method -1 matches the mean total concentration and total runoff volume. Method -2 matches the instantaneous total concentration and the instantaneous runoff rate from the entire watershed.

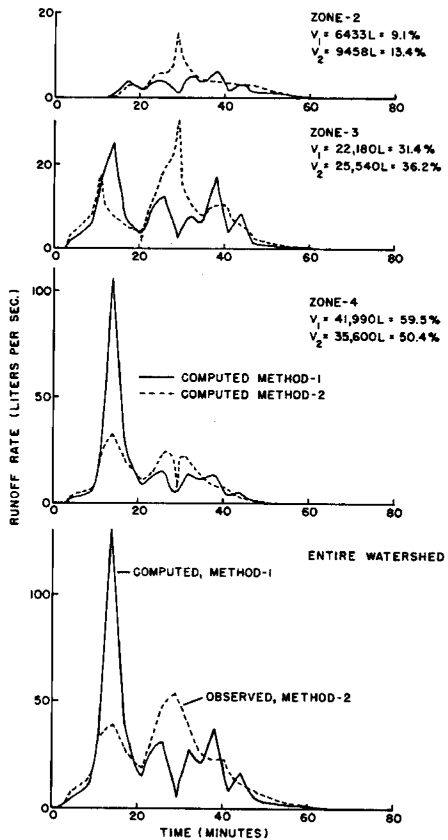

Figure - 11. Computed runoff hydrographs for event of 7/27/76 on Watershed 76.001.

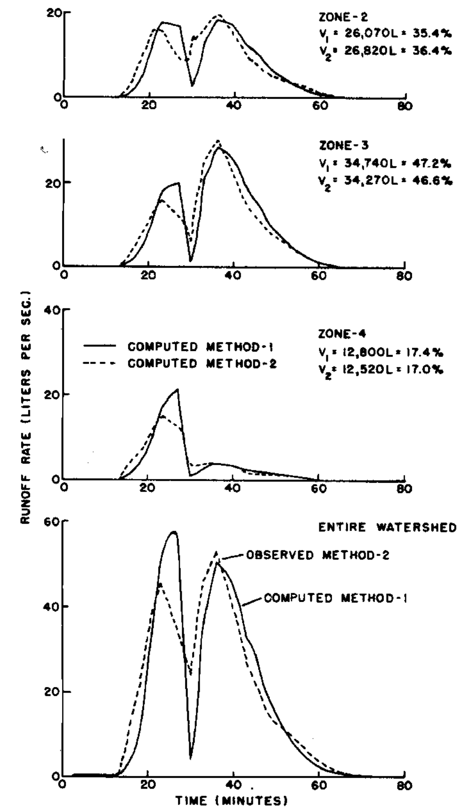

Figure - 12. Computed runoff hydrographs for event of 7/27/76 on Watershed 76.002.

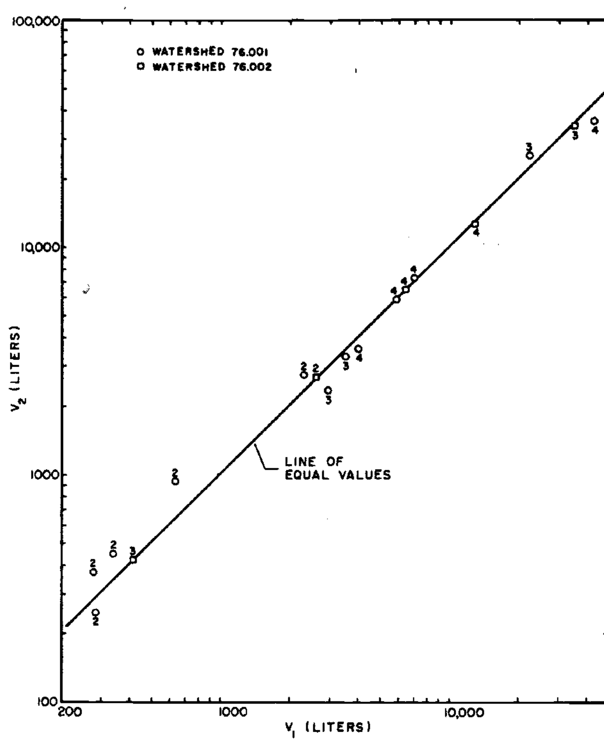

Figure - 13. Volumes of runoff as estimated by the two tracer study methods.

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INFLUENCE OF FOREST DENSITY ON BEDLOAD MOVEMENT IN A SMALL MOUNTAIN STREAM

by

Burchard H. Heede

ABSTRACT

In contrast to three ephemeral streams in the vicinity, Tony Bear Creek, a small perennial stream in the White Mountains of Arizona, showed strong relationships among parameters of hydraulic geometry. Distances between gravel bars and log steps showed an inverse relationship with gradient (r^2 = 0.95). Shape factor and width-depth ratio increased upstream (r^2 = 0.98 and 0.90, respectively), indicating depth decrease toward the headwaters. The longitudinal profile is concave, and small, infrequent channel bars suggest that sediment movement is small. In contrast to the ephemeral streams, Tony Bear Creek is thus judged to be in dynamic equilibrium. Proportion of log steps to total steps (gravel bars plus logs) was much smaller in Tony Bear Creek (about 16%) than in five other mountain streams (about 50%). While all other streams ran through dense forests, only 60% of Tony Bear Creek was in forest, of which 13% had been selectively cut. Thus, forest density determined the proportion of logs incorporated into the stream hydraulic system, which in turn affects bedload movement.

GENERAL DEBRIS--GRAVEL BAR RELATIONSHIPS

Investigations of several small mountain streams in Colorado and Arizona (unusual peak discharges may reach 25 c.f.s.) have shown that heavy organic debris from forests is incorporated into the channels (Heede 1972, 1975, 1976). There it plays an active role in the slope adjustment processes, and thus becomes a part of the hydraulic geometry of the streams.

Most high-gradient mountain streams (average gradients > 0.05 ft/ft) are located in V-shaped valleys or on narrow valley bottoms. These narrow valleys do not allow stream alignment changes, such as formation of meanders, or other hydraulic adjustments--pronounced width increases, for instance--as a means of slope adjustment. Instead, the streams adjust mainly by establishing numerous gravel bars. The process leading to gravel bar formation is bedload movement. If logs and branches form barriers (log steps) across the bed, bedload movement is reduced above these structures and gravel bars do not develop.

My past research has shown that, in small streams at or near dynamic equilibrium, there is an inverse linear relationship between number of gravel bars and log steps and channel gradient. Furthermore, numbers of gravel bars decrease with increasing numbers of log steps. Thus heavy forest debris available to small stream channels evidently determines intensity of bedload movement and resulting gravel bar formations. All former study streams were located within uncut forests or forested buffer strips. Availability of forest debris was therefore dependent only on random fall of trees and large branches; effects of forest density changes could not be studied.

Objectives of the present investigations were to (1) study gravel bar versus log step relationships in a stream flowing through a forest of variable density, and (2) evaluate channel characteristics in perennial and ephemeral streams.

A RECENT EVALUATION

Data collected previously on five streams (Heede 1972, 1975, 1976) were compared with recently acquired data on a perennial stream in the White Mountains of Arizona--Tony Bear Creek.

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The previous investigations dealt with two perennial streams of the Colorado Rocky Mountains (Fool Creek and Deadhorse Creek), and three ephemeral streams of the Arizona White Mountains (North and South Thomas Creek, West Willow Creek). All streams passed through an elevation zone ranging from 10,000 to 8,000 ft.

Tony Bear Creek drains Burro Mountain watershed at an elevation of approximately 8,850 ft. Stream length is about 1.9 mi, but the streamgaging station is installed 0.6 mi upstream from the confluence with a tributary of the Black River. The yearly peak flow has averaged 3.9 c.f.s. during the last 15 yrs. In this period, annual precipitation ranged between 23.53 and 47.33 inches and averaged 31.69 inches. The geologic formations are of volcanic origin and are represented mainly by basalts. Soils of the channel banks generally are alluvium, but the bed itself is predominantly armored by gravel and rocks.

Since Tony Bear Creek carries perennial flow, comparison with the Colorado streams should strengthen characteristics common to perennial streams, and by the same token, may divide it from ephemeral ones.

CHANNEL CHARACTERISTICS

PERENNIAL STREAMS

The perennial streams, although located in two different mountain ranges supporting different forest types, showed similarities in hydraulic geometry. All had a concave profile and exhibited strong relationships between step length of bed structures and channel gradient (fig. 1), as well as between gravel bars and log steps. In Tony Bear Creek, for example, the coefficient of determination (r^2) for the step length -- gradient relationship was 0.75. In Deadhorse Creek, which averaged 4.8 log steps per 50 ft of channel, only 37 percent of the total bed structures were gravel bars, while in Fool Creek, which averaged 2.5 log steps per 50 ft of channel, 53 percent of the structures were gravel bars.

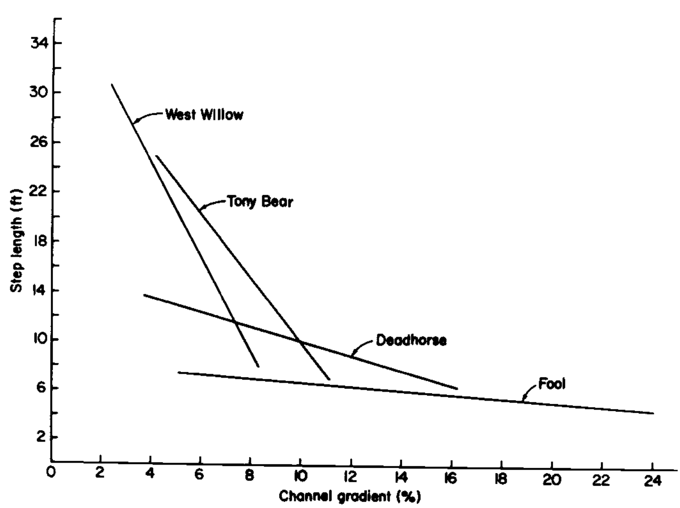

Figure 1.--Step length--channel gradient relationships in perennial streams. While Deadhorse Creek and Fool Creek, both of the Colorado Rocky Mountains, and Tony Bear Creek of the Arizona White Mountains, are true perennial streams, West Willow Creek, also of the Arizona White Mountains, could best be described as quasi-perennial.

In Tony Bear Creek, the width-depth ratio (the coefficient of bank-to-bank width divided by mean depth) and the shape factor (the coefficient of maximum depth divided by mean depth) were closely related to channel gradient (r^2 = 0.98 and 0.90, respectively) when bank-full stage was considered. Both parameters increased upstream, signifying decreasing depth toward the headwater, a well-known criterion for streams in dynamic equilibrium.

Leopold and Maddock's (1953) methods for the treatment of hydraulic variables were applied to Fool Creek. These authors found that hydraulic characteristics of stream channels -- such as depth, width, and velocity -- vary as some power function of the discharge. It was found that Fool Creek behaved like larger streams, but the coefficients of the functions were closest to another yet much larger mountain stream, Brandywine Creek in Pennsylvania (Wolman 1955, Heede 1972). Discharges of Deadhorse Creek and Tony Bear Creek were too small relative to instrument errors to permit mathematical treatment of the flows.

Sediment loads were extremely small in all perennial streams. This was indicated in Tony Bear Creek by rare occurrences of bars, and lack of meaningful sediment accumulations in the stilling basin of the streamgaging station after 15 yrs of operation. Average annual sediment yield amounted to 297 ft^3/mi^2 from Fool Creek and 147 ft^3/mi^2 from Deadhorse Creek (Leaf 1966).

Channel morphology, hydraulic geometry, and sediment load characteristics indicated that the perennial streams were in dynamic equilibrium.

When step length--gradient relationships were tested on West Willow Creek, it was found that this ephemeral stream behaved like the perennial streams (fig. 1). Comparison of flow frequencies with the other ephemeral streams indicated that the ephemeral status of West Willow Creek is borderline (Heede 1976); it may be described better as a quasi-perennial stream. Only during 3 percent of the 10-yr record period was the channel dry (no flow for more than 6 consecutive days). In contrast, the ephemeral Thomas Creeks were dry 14 percent of the time during the same period. Thus, more energy could be expended by West Willow Creek than by the truly ephemeral streams.

The greater activity in West Willow Creek appears to be expressed also by its linear longitudinal profile. This profile is closer to being concave, as in the perennial streams, than convex. It is justifiable to relate West Willow Creek's linear profile to flow activities mainly, because of relatively homogeneous volcanic geology and lack of detectable changes in geologic structure on the watershed as well as missing channel storage changes. Also major tributaries are absent from this small watershed (290 acres). Under such conditions, once dynamic equilibrium is attained, the long profile will be concavely shaped.

In contrast to the perennial streams, sediment loads were high at times in West Willow Creek, and width-depth ratio and shape factor apparently were not related to channel gradient. It was concluded that West Willow Creek was closer to attaining dynamic equilibrium than were the Thomas Creeks. This conclusion was strengthened when additional morphologic aspects were examined. For example, main channel headcuts were found in the Thomas Creeks but not in West Willow Creek.

Overall, in a given period of time, perennial and quasi-perennial streams can expend more energy in the channel forming processes than can ephemeral flows. Dynamic equilibrium can therefore be attained earlier in perennial than ephemeral streams, if factors such as uplift are not at work.

EPHEMERAL STREAMS

In the truly ephemeral Thomas Creeks, no meaningful relationships could be found between hydraulic geometry parameters or their consistency in upstream or downstream development.

Sediment movement had to be judged from channel deposits, since channels were dry or supported only shallow flows during the study periods. North and South Thomas Creek channels covered only one-half and three-quarters of their total valley lengths, respectively. The channels began with an abrupt headcut on the gentle valley floor. Headcutting is expected to proceed unrestricted into the unchannelized portions of the watersheds when flows of sufficient magnitude occur and substantial sediment loads will be added to the flows. Indeed, numerous types of bars as well as frequent scars at bed nickpoints indicated that sediment transport was intense at certain times. This intensity was illustrated by the fact that all major gravel bars and log steps were filled to their crest by sediment deposits. The longitudinal profiles were convex.

Thus, the Thomas Creeks differed drastically from the perennial streams in most morphology and behavior characteristics. Considering all factors and parameters examined, it was decided that these ephemeral streams were not in dynamic equilibrium.

LOG STEP--FOREST DENSITY RELATIONSHIP

In the foregoing section, it was shown that Tony Bear Creek behaved like other perennial mountain streams studied. Similarity was established for hydraulic geometry parameters and for the role of forest debris in the slope adjustment processes (fig. 1).

In Tony Bear Creek, however, only 16 percent of all bed structures were built by debris compared with 41 to 63 percent in the other streams (Table 1). Relative forest density and tree distribution along the stream courses were therefore examined.

Table 1.--Average flow and channel characteristics of small mountain streams.

Stream	Longitudinal profile	Peak flow[1/]	Channel gradient	Spacing of bars and log steps	Log steps
		c.f.s.	ft/ft	ft	Percent of all bed structures
		Perennial flow			
Fool Creek	Concave	14.2	0.102	9.1	46
Deadhorse Creek	Concave	7.8	.137	6.5	62
Tony Bear Creek	Concave	3.4	.067	16.0	16
		Quasi-perennial flow			
W. Willow Creek	Linear	1.9	.051	16.8	63
		Ephemeral flow			
N. Thomas Creek	Convex	1.6	.092	17.0	65
S. Thomas Creek	Convex	1.2	.076	15.8	41

[1/] For reasons of comparability, water year 1973 was excluded in calculation of averages, because a storm occurred with a several-hundred-year return period.

The Arizona ephemeral streams are located in virgin old growth mixed conifer forests. Forest openings along the streams are sporadic and small (normally, a few hundred ft^2). Large amounts of debris are available. South Thomas Creek, for example, averaged about 10 tons per acre of debris larger than 3 inches in diameter within and alongside the channel. The Colorado streams also run through old growth spruce-fir forest with large quantities of debris.

In contrast, only 60 percent of the length of Tony Bear Creek is lined by old growth mixed conifer forest. Meadows line the remaining 40 percent. Logging before the 1950's was selective. In 1958-59, seven blocks were either clearcut or "commercially clearcut" to study the effects of clearcutting on water yield and other aspects of land management (Jones 1967). The clearcut blocks were located away from the stream, so that a minimum 100-ft buffer strip was left between channel and clearcut. Another 13 percent of the stream-side forest was selectively cut. This cut was applied on the east bank only, while on the opposite bank, clearcut blocks, forest and meadows formed a checkerboard pattern. Some stream-side logging had also been performed during early harvest operations. It was not possible, therefore, to distinguish between log steps established in selective cuts and clearcuts.

CONCLUSIONS

The log step--gravel bar relationship on Tony Bear Creek substantiates the postulate that availability of debris influences bedload movement and development of gravel bars. Hydraulic geometry parameters suggest that Tony Bear Creek is typical of the perennial streams studied, as does the log step--channel gradient relationship. Each stream has its own characteristic relationship, however (fig. 1). The large slope difference in the regression curves between perennial and ephemeral stream groups may suggest regional influences; a family of curves may exist for small mountain streams of a physiographic or mountainous region.

Logging debris can form steps in the channel, or may even clog the channel, if logging clean-up is not adequate. Our data indicate, however, that clean-up was adequate at Tony Bear Creek.

Quantitative relationships between forest density and log step formation in small mountain streams would be useful tools for forest managers, who can influence bedload movement by maintaining a stream-side forest that delivers either large or small volumes of heavy debris for log step formation. In future research, several classes of forest densities, related to type, age and health of the forest, should be considered.

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BOTTOM SEDIMENT ANALYSES OF THE RECREATIONAL WATERS OF UPPER SABINO CREEK

by

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ABSTRACT

Bottom sediment quality of the upper four miles of Sabino Creek in the Santa Catalina mountains near Tucson, Arizona was examined from September, 1975 through August, 1976. Two primary bottom sediment parameters were examined: 1) sediment fecal bacterial concentrations, and 2) sediment particle size distribution. Analyses of bottom sediment parameters and selected surface water parameters were conducted to ascertain interrelationships between bottom sediment quality and surface water quality. Results indicate the importance of bottom sediments in the overall quality of the Creek. Bottom sediment fecal bacterial concentrations have a significant influence on surface water fecal bacterial concentrations through suspension of sediment stored bacteria into the overlying water. Significantly higher bacterial concentrations were observed during highest recreational use periods.

INTRODUCTION

Bottom sediment bacterial analyses are increasingly used to evaluate the total quality of a water ecosystem. Previous research of bottom sediment environs restricted their analyses to the benthic fauna, yet recent investigations suggest that bottom sediments may provide substantial information from a microbial standpoint (Van Donsel and Geldreich, 1971). Hendricks (1971) states bottom sediment bacterial analyses should be an integral part of all water quality analysis programs. The mud serves as a concentrated environ where pathogenic and non-pathogenic organisms persist and may serve as a stable index of the quality of the water especially in instances where great variability in bacterial quality of the surface water exists (Van Donsel and Geldreich, 1971).

Sampling surface water alone does not give a true indication of the potential hazardous condition of the water system; bottom sediments serve as a reservoir for bacterial organisms which can be suspended into the overlying surface water by disruption of the sediments (Grimes, 1975, Van Donsel and Geldreich, 1971, and Winslow, 1976). Motschall (1975) indicated surface water fecal coliform concentrations in samples following disruption of stream sediments exceeded corresponding surface water fecal coliform concentrations 37 out of 38 samples.

Van Donsel and Geldreich (1971) examined a wide variety of bottom sediments from clean and polluted rivers and creeks, bathing beaches, and recreational lakes. Results indicated occurrence of fecal coliform in bottom sediments ranged from 100 - 1000 times higher than in the overlying surface water. Two interactive processes to explain the increased recovery of bacteria in bottom sediments are postulated: 1) the benthic environment, as a function of its particle size distribution, favors the absorption of bacteria on individual grains, and 2) the benthic environment provides a favorable environment for bacterial growth and prolonged survival. Hendricks (1970) states sedimentation and absorption to sands and clays could concentrate bacteria in bottom sediments. Experiments by ZoBell (1946) concerning particle size distribution effects on bacterial density indicated bacterial numbers were inversely proportional to particle size; bacterial densities were lowest with large grain sizes. Stream sediments are able to bind basal nutrients loosely and that growth of various enteric bacteria occurs in aqueous extracts of sediments (Hendricks and Morrison, 1967). An analyses of bacterial growth in bottom sediments of the Poudre River reveal extensive growth of enteric bacteria in bottom sediments where nutrients can be in high concentrations (Hendricks, 1970). Survival studies of fecal coliform and salmonella in storm water stored at 20° C show a 90 percent reduction in concentration after two days (Geldreich et al, 1968); survival of fecal coliform and salmonella in bottom

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sediments at an identical temperature show a 90 percent reduction in seven days (Van Donsel and Geldreich, 1971).

STUDY SITE DESCRIPTION

Proximate to the metropolitan community of Tucson, Arizona are the Santa Catalina mountains of Coronado National Forest. Rising to an elevation of 9,157 feet, the mountain range encompasses four life zones, extending from the Lower Sonoran characterized by low annual rainfall (12 inches) and high temperatures to the Canadian characterized by high annual rainfall (26 - 30 inches) and low temperatures.

The combination of unique natural and physical qualities and nearness to a major metropolitan community have made the Catalinas the most popular recreation area in Southeastern Arizona.

During summer months when temperatures may reach 110° F in the desert valley, the Santa Catalina mountains provide a recreational retreat for numerous visitors. Substantial day-use and overnight-use facilities have been constructed to satisfy the approximately 2,000,000 annual visits to the mountain range.

A large portion of the recreational development and uses are concentrated in the higher elevations of the mountain range on Sabino Creek watershed. Day-use and overnight facilities on the upper portion of the watershed include five picnicking areas, three campgrounds, approximately 60 miles of hiking trails, a nature trail complex and a ski area.

In addition some 350 summerhomes and Forest Service lease cabins are situated at higher elevations on the watershed. Summerhaven, a private community incorporating 240 acres and supporting 80 - 100 permanent residents, straddles the upper reaches of Sabino Creek.

Sabino Creek, the major drainage system of the 35.5 square mile watershed, begins its nine-mile passage from the coniferous forests of Mount Lemmon to Sabino Canyon Recreation Area on the desert valley floor. Sabino Creek is an intermittant-perennial stream with yearlong flow occurring with adequate Winter snowfall and Summer rains.

Intense development associated with Sabino Creek has prompted serious questions by U. S. Forest officials and the general public concerning the impact on the water quality resources of the Creek. Potential hazardous conditions of the headwaters of Sabino Creek could be causing detrimental effects throughout the length of the watercourse. The Creek is currently being used as a receiving water for sewage from some cabins and businesses situated on the watershed.

In 1958, Pima County Sanitation officials became concerned with the potential problem of sewage wastes generated by Summerhaven cabins and businesses, and in cooperation with State, County and Federal Health Departments, constructed a sewage disposal plant adjacent to Sabino Creek approximately 1/2 mile below Summerhaven on Forest Service property.

The treatment facility serving some 26 homes and businesses consists of a septic tank/leach field system with the effluent being discharged directly into Sabino Creek. Chlorination of sewage effluent is accomplished utilizing chlorine gas. Because of poor design and maintenance and intermittant operations, the facility is inadequate. Chlorination failures, pipe deterioration, and poor soil conditions for leaching are problems attributable to the treatment system. During high ground water conditions and runoff events water infiltrates the main interceptor line, thus burdening the facility. During low groundwater periods sewage seeps from the main into the surrounding soil with possible entry into the Creek.

Cabins not connected to the sewage treatment facility utilize their own individual septic tank/leaching systems and pit privies. Steep slopes and shallow soils unsuitable for leaching prohibit adequate sewage treatment by these systems. A study by Adams and Geiser (1970) acknowledged dye-tracer tests that concluded the septic tank/leaching systems approximate to Sabino Creek "were little better than direct pipelines through the fractured and decomposed granites from the sources of sanitary wastes to the creek".

Numerous animal enclosures confining horses and other domesticated animals and located immediate to Sabino Creek may be the source of animal feces discharge into the stream.

Further complications associated with the water quality of upper Sabino Creek result from the conflicts between sewage disposal and recreation pursuits. Marshall Gulch picnic ground, accounting for over 68,000 visits in 1973 and 1974 and located proximate to Sabino Creek 1/2 mile below the sewage treatment facility, has been closed since June, 1975. Dye-tracer tests undertaken by the Arizona Department of Health Services revealed the sewage treatment facility was deficient and posing a serious health hazard to visitors using this popular picnic ground. Incompatible uses of upper Sabino Creek, such as intense recreational use pressures and sewage disposal, has forced the Forest Service into a complex management situation in resolving conflicts of poor water quality and high recreational use.

RESEARCH OBJECTIVES

Operating concurrently with a surface water analyses by Brickler, Phillips, and Patterson (1977), this study was designed to analyze bottom sediments characteristics of upper Sabino Creek.

Several research objectives were identified to direct the study in a systematic approach to the water quality problem. These objectives guided the orderly development and pursuit of the study. Research objectives identified were:

1) identify the present bottom sediment quality of upper Sabino Creek, and to establish base information for future bottom sediment analyses.
2) evaluate relationships between bacterial concentrations and particle size distribution of bottom sediments.
3) evaluate relationships of bottom sediment parameters with selected overlying surface water parameters.
4) evaluate the possible health hazard of upper Sabino Creek for recreation purposes utilizing bottom sediment analyses as an indicator.
5) suggest recreation management alternatives in managing the water resources of upper Sabino Creek.

FIELD AND LABORATORY PROCEDURES

Field sampling procedures were designed to allow collection, transportation, and analyses of bottom sediment and surface water samples within the eight hour bacterial reliability time limit (AWWA, 1971). Samples were collected four times per month from August, 1975 to September, 1976 on a Wednesday-Sunday schedule with samples collected every other Wednesday and Sunday. This research design permitted concurrent evaluation of bottom sediment and surface water parameters during low and high recreation use days as well as during expected yearly recreational use fluctuations. Samples were collected from 8 a.m. to 11 a.m.

Eight sampling stations were identified to accurately represent the conditions of the 3.5 mile watercourse studied (Figure 1). Rather than use a random sampling design to delineate station locations, user patterns, property boundaries, suspected water quality problem areas, stream flow regime, and other watershed characteristics were factors that determined locations of sampling stations.

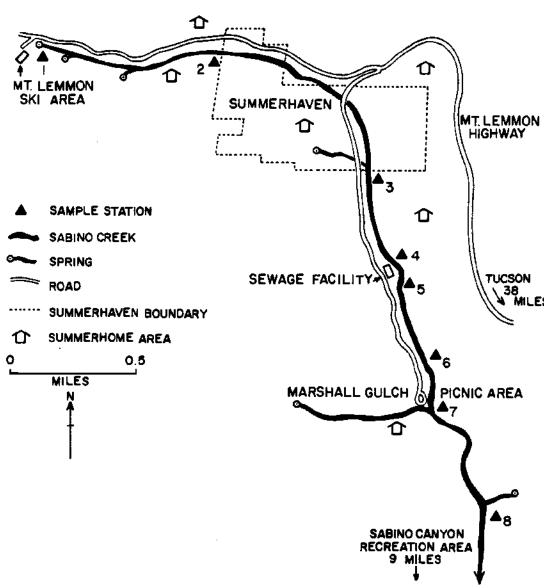

Figure 1. Sampling station locations on upper Sabino Creek.

Bottom sediment water quality parameters measured were fecal coliform bacteria and particle size distribution; surface water parameters included fecal coliform bacteria, suspended sediments, water temperature, and residual chlorine at stations below the sewage effluent discharge.

Bottom sediment fecal coliform bacteria were enumerated using the multiple dilution tube technique described in Standard Methods for the Examination of Water and Wastewater (AWWA, 1971). A most probable bacteria concentration was obtained from MPN tables in Standard Methods (AWWA, 1971).

Surface water fecal coliform and fecal streptococcus bacterial concentrations were enumerated using the membrane filter (MF) technique (AWWA, 1971). Media used for culturing fecal coliform and fecal streptococcus bacteria were M-FC broth and M-Enterococcus Agar, respectively. Fecal coliform bacteria were incubated in a water bath at 44.5 ± .2°C for 24 hours and fecal streptococcus bacteria were incubated in a dry oven at 35 ± .5°C for 48 hours. Bacterial colonies were enumerated with a 10x dissecting scope and recorded in the laboratory data book.

Methods used to analyze particle size distributions of bottom sediments are detailed in Methods of Soil Analysis (Black, 1965). Using the International System of particle size descriptions, percent gravel (particles greater than 2 millimeters in diameter), coarse sand (.2-2 mm), fine sand (.02-.2 mm), silt (.002-.02 mm), and clay (particles less than .002 mm in diameter) were determined using the pipetting method. Suspended sediment analyses methods are detailed in Standard Methods (AWWA, 1971).

RESULTS

Results of bottom sediment fecal coliform bacteria analyses indicate upper Sabino Creek is more hazardous to recreation users than is indicated by surface water bacteria analyses alone. Monthly mean bottom sediment bacteria concentrations were consistently 10 to 10,000 times higher than monthly mean surface water bacteria concentrations. Sampling stations immediately below the sewage treatment facility (stations five and six) exhibited highest bottom sediment bacteria concentrations; 27 percent of all 52 samples taken at station five measured 100,000 or greater fecal coliform/100 ml. Fifty percent of all 52 samples at station six measured 10,000 or greater fecal coliform/100 ml.

Although located on the stream in a relatively undeveloped portion of the watershed, stations one and two exhibited Fall mean bottom sediment bacteria concentrations of 13,614/100 ml and 5888/100 ml respectively. Station eight located approximately 1/2 mile below any developed recreation site measured mean Fall bottom sediment bacteria concentrations of 9141/100 ml. All sampling stations exhibited highest bacteria concentrations during either Summer or Fall months; all stations exhibited lowest bacteria concentrations during Winter months.

Numerous occasions arose when fecal coliform concentrations in bottom sediments exceeded the normal trend when malfunctions occurred in the sewerage system. Bottom sediment and surface water fecal coliform concentrations experienced substantial increases during periods of chlorination failure at the treatment plant (Table 1).

Table 1. Bottom sediment and surface water bacteria concentrations at station 5, 0.0 mg/l residual chlorine.

DATE	BOTTOM SEDIMENTS (MPN/100 ml)	SURFACE WATER (colonies/100 ml)
October 5, 1975	240,000	800,000
November 2, 1975	2,400,000	118,800
November 12, 1975	2,400,000	260,000
December 14, 1975	34,500	153,000
December 28, 1975	700,000	53,200

An apparent sewage leak from a defective pipe during April and most of May caused monthly means for stations three and four to increase drastically during this time. On July 25, 1976 following a period of intense rain, sewage flowed out of a manhole at the treatment plant and entered Sabino Creek downstream from station five approximately 100 yards above station six. Bottom sediment bacteria concentrations at station five and station six were 1090 and 92,000 fecal coliform/100 ml, respectively.

Statistical analyses were utilized to test hypotheses concerning bottom sediment and surface water parameters. Non-parametric statistical tests were employed to test hypotheses because underlying assumptions in normal population statistical analyses could not be satisfied according to the distribution of the data. A significance level of .05 was set for each test.

Fine particles were an important factor affecting increased bottom sediment bacteria densities at some stations. Sampling stations one and two, lying at the uppermost portion of the watershed, accounted for bottom sediment bacteria densities which did not differ significantly from sampling stations three and four, located on a stretch of stream highly impacted by substantial development. Possible explanation for this unexpected occurrence are that stations one and two displayed significantly greater fine particles than stations three and four. In addition, analyses of covariance revealed fine particles were a significant factor in increased bottom sediment bacteria concentrations at stations one and two. Station eight, the most downstream station, displayed significantly greater bottom sediment bacteria concentrations than station seven located 1/2 mile upstream. However, station seven exhibited significantly higher surface water fecal coliform concentrations. Greater distribution of fine particles and the presence of a large pool possibly accounted for entrapment, extended survival, and possible growth of bottom sediment bacteria at station eight.

Chlorine injected into the sewage effluent between stations four and five had measurable effect on bacteria concentrations at station five. Analysis of variance of differing residual chlorine concentration effects on bacteria densities revealed high chlorine inputs into the stream were responsible for significantly lower bottom sediment bacteria concentrations. High chlorine residual also resulted in the absence of observable aquatic life for a few hundred feet below the effluent discharge. Although high residual chlorine concentrations accounted for lower bottom sediment bacteria densities at station five, station five displayed significantly greater bottom sediment bacteria than station four. This suggests that the bacteria input from the sewage treatment facility was great enough to partially counteract the disinfecting effectiveness of high chlorine discharge.

A sampling design allowing for collection of water quality samples during differing recreational use days and recreational use seasons was used to ascertain base information of water quality differences during these times. High recreational use seasons (May through October) exhibited significantly higher bottom sediment and surface water bacteria than seasons of limited recreation use (November through April). All recreational pursuits and second home use was observed to be greatly reduced during low recreational use seasons. Differences of bottom sediment and surface water bacteria was not apparent between samples collected on Wednesdays and Sundays.

Although not statistically significant on an annual basis because of the nature of their distribution, decreased bottom sediment fecal bacteria were graphically illustrated following watershed flushing events. Scouring of bottom sediments with subsequent release of bacteria into the surface water was probably responsible for decreased bacteria concentrations during these flushing events.

CONCLUSIONS

Results of this study indicate the importance of including bottom sediment bacteria enumeration in all recreation water quality analyses. Sampling surface water alone does not give a true indication of the potential bacterial quality of an aquatic ecosystem used for recreational purposes. Bottom sediments, particularly fine sediments, are capable of storing large bacteria densities with extended survival and possible growth. Resuspension of bottom stored bacteria into the overlying surface water may cause potential hazardous conditions to water-oriented recreation users.

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CHEMICAL OXYGEN DEMAND OF THE ANTITRANSPIRANT, FOLICOTE[1]

by

R.H. Garrett and B.E. Kynard[2]

ABSTRACT

During a standard bioassay using fish and the antitranspirant Folicote, a significant deoxygenation of the water was observed. Oxygen demand tests without fish using distilled water indicated that at 25°C Folicote reduced D.O. from saturation (8 ppm) to 0.1 ppm within 60 hrs. Oxygen consumptive qualities of Folicote should be taken under consideration during actual field applications.

INTRODUCTION

Folicote is a wax base chemical antitranspirant that is being considered for spray application to riparian vegetation in order to coat their leaves and reduce water loss due to transpiration (Davenport, present journal). Desert southwest riparian areas are a principal location of potential use. Many riparian areas also contain surface waters which have fisheries resources, especially sport fish and native fishes. The following study examines the effect Folicote has on dissolved oxygen concentrations of water.

In order to determine the ecological effects antitranspirants might have on the aquatic community, static bioassays were conducted using mosquitofish, *Gambusia affinis*, in various concentrations of Folicote. These standard bioassays included monitoring of various physical and chemical parameters such as temperature, pH and dissolved oxygen as well as fish mortalities (Sprague 1973, Doudoroff 1951). During the bioassays, a significant decrease in the amount of dissolved oxygen (D.O.) in the tanks containing Folicote was observed. So, in addition to monitoring the bioassay D.O. changes, further tests without fish were conducted to investigate the chemical oxygen demand of Folicote. All tests were designed to simulate static pool environments in nature because the greatest effects of low oxygen on aquatic life would probably be found in these habitats.

MATERIALS AND METHODS

TESTS WITH FISH

These experiments utilized 12, 21 l., all glass aquaria which were placed in a 112 X 193 X 36 cm. water bath. A constant temperature in all tanks was maintained by thermostat controlled immersion heaters and a circulating pump in the water bath. Each experimental aquarium contained 10 l. of test solution and ten fish. Two controls using only test water and no Folicote were also maintained during the tests. Dissolved oxygen saturation was insured by vigorous aeration from an air pump. Aeration was stopped at the beginning of the test when the chemical was introduced. Dissolved oxygen was monitored at 1, 2, 4, 8, 16, 24, 33, 48, 72 and 96 hr. after the test began using a Yellowspring Instruments Model 57, temperature-oxygen meter. All test water originated from a well at the fisheries research facility of the School of Renewable Natural Resources, University of Arizona, Tucson, Arizona.

TESTS WITHOUT FISH

Four, 1 l. graduated cylinders were used in tests without fish. Prior to tests, the cylinders were cleaned with a 10% solution of HCl and then rinsed with distilled water. Two cylinders were filled with distilled water (control) and two contained water + Folicote (experimental). A 5% solution of Folicote (50 mls. Folicote - 950 mls. distilled water) comprised the test solution. The test was conducted at 25°C.

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2. University of Arizona. Based on part of a thesis of the senior author that will be submitted as partial fulfillment for a M.S. degree in Fisheries Science from the School of Renewable Natural Resources, University of Arizona, Tucson, Arizona, 85721.

Membranes on the oxygen meter were changed every 24 hr. to eliminate error due to wax build-up from the Folicote. Dissolved oxygen readings were taken at 0, 4, 12, 17, 24, 30, 40, 44, 48, 53, 61 and 70 hr. after the start of the experiment using Folicote. Readings of the control solutions were made at 0, 8, 45, 58 and 72 hr. after the start of the experiment.

RESULTS

TESTS WITH FISH

During the 96-hr. experiments, some deoxygenation of the water occurred in all tests, including those tests without Folicote (Figure 1). However, there was a much greater rate of deoxygenation in the tanks containing Folicote. Within 24 hr., dissolved oxygen levels in the tanks containing a 3.5% solution declined from 7.8 ppm to 0.3 ppm. They remained at that level for the duration of the experiment.

TESTS WITHOUT FISH

There was a slight drop from atmospheric saturation even in the cylinders containing only distilled water (Figure 2). However, the decrease was only 0.5 ppm over the 72-hr. period. This was probably due to the inevitable contamination by microorganisms over the 3-day period. In tests containing a 5% solution of Folicote, complete deoxygenation of the distilled water occurred after 61 hr.

DISCUSSION

In these experiments, the antitranspirant Folicote demonstrated a significant oxygen demand in water. The factors in Folicote that are responsible for this phenomenon are unknown. If Folicote is aerially applied to phreatophyte areas which contain surface water, some of it will undoubtedly fall into the water. Since it is very miscible with water, it can exert an oxygen demand throughout the water column.

Moore (1942) using seven species of fish, concluded that an oxygen content of less than 3.5 ppm was essential to the maintenance of fish life at summer temperatures. Doudoroff (1970) indicated that any reduction in the concentration of dissolved oxygen places some stress on fish. In the desert southwest, high summer temperatures coupled with vigorous respiration of aquatic vegetation at night often creates critically low dissolved oxygen problems for aquatic life (Deacon and Minckley 1973). The additional 24 hr. oxygen demand created by Folicote would further stress the system. Field experiments should be conducted to clarify the total effect on the aquatic habitat under normal application rates.

The data in this paper regarding the oxygen demand properties of Folicote should be taken under consideration along with field application rates. Dilution factors should also be estimated prior to application. Factors such as algal blooms, natural night-time D.O. levels and critical biological areas for fish, i.e., spawning or nursery grounds, where accumulation of the chemical may occur, should also be taken into consideration prior to actual field application of Folicote.

Further investigation into the identity of the oxygen consumptive agent in the chemical as well as its biological half-life may be necessary if the dilution factor in actual spraying conditions approximate those in this experiment.

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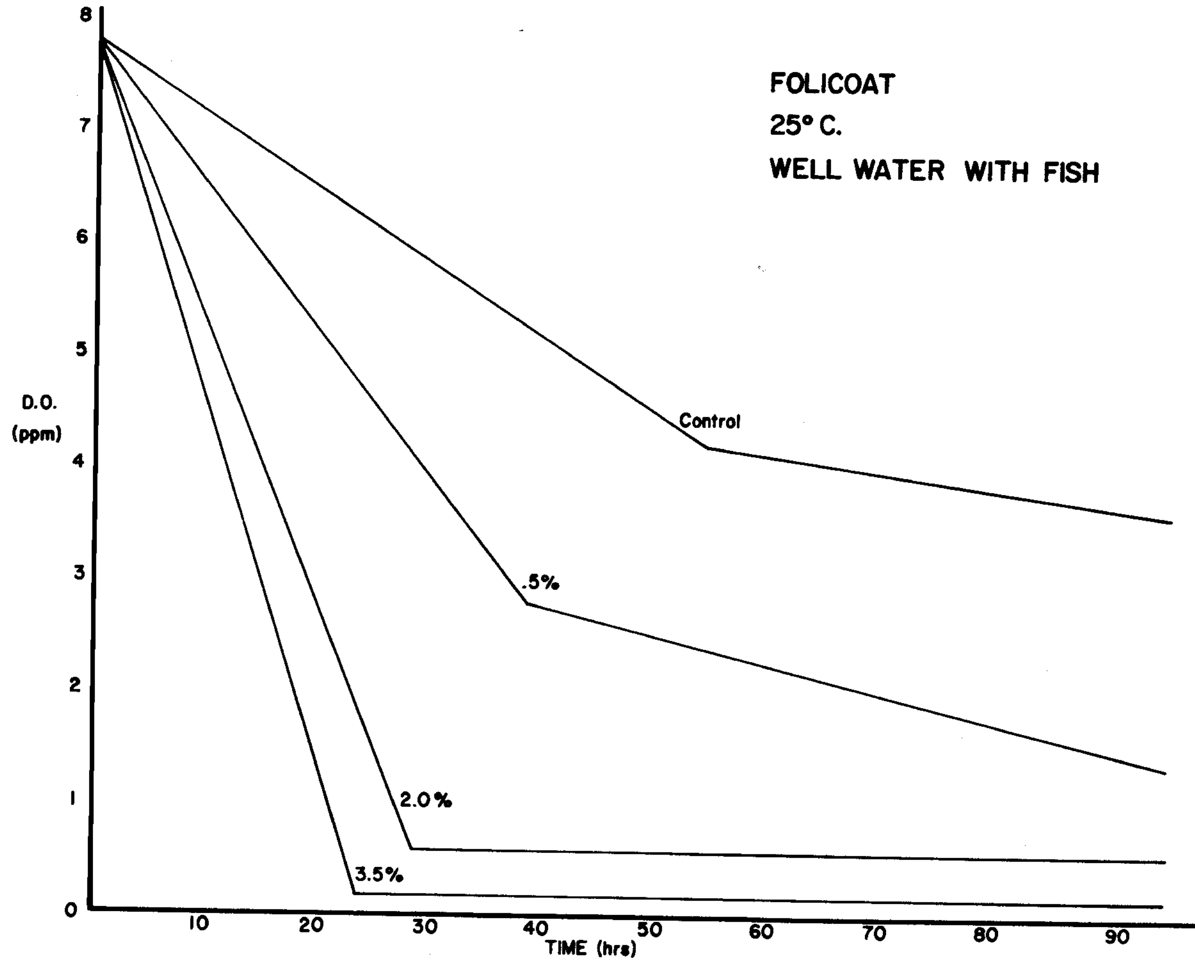

Figure 1. Deoxygenation of water containing fish by Folicote.

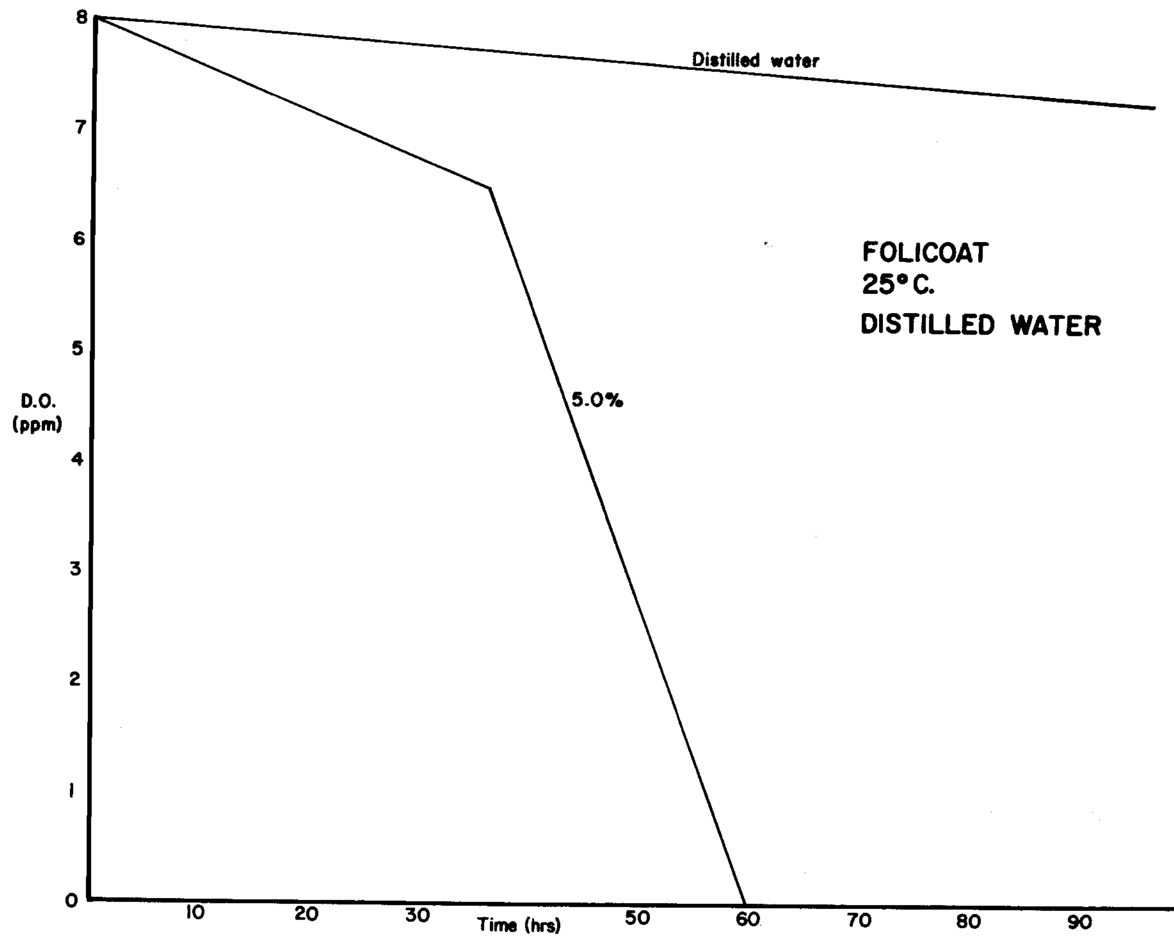

Figure 2. Deoxygenation of distilled water by Folicote.

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STUDENT AWARD PAPER

DIURNAL TRENDS IN WATER STATUS, TRANSPIRATION, AND PHOTOSYNTHESIS OF SALTCEDAR

by

Mary Ellen Williams and Jay E. Anderson

ABSTRACT

Relative water content (RWC), water potential (Ψ), and gas exchange were measured on saltcedar at the Bernardo, New Mexico, lysimeter site. RWC and Ψ were closely correlated; but, water potential measurements, taken with a pressure bomb, were more convenient and reliable. RWC and Ψ decreased sharply from sunup until about 0900, when minimum values of about -26 bars Ψ or 80% RWC were reached. Water status then remained constant or improved slightly through late afternoon. Transpiration rates typically remained high until about noon and then began a steady, gradual decrease that continued throughout the afternoon. The data suggest that water stress may be a factor in initiating stomatal closure; however, transpiration continued to decline despite a constant or improved leaf water status. Maximum net photosynthetic rates occurred by 0900, and depressions throughout the remainder of the day were largely accounted for by increased leaf temperatures. Afternoon depressions in transpiration and photosynthesis occurred in twigs held at constant temperature and relative humidity, suggesting that a diurnal rhythm may be involved in control of gas exchange. Water status of plants growing on the lysimeters was comparable to that of plants in adjacent natural stands; gas exchange rates were slightly higher for the lysimeter-grown plants.

INTRODUCTION

Saltcedar (*Tamarix chinensis* Lour.) is an introduced tree or shrub that covers over 1.3 million acres along the permanent and transient waterways of the southwestern United States. It is of economic concern because of its high consumptive water use, which is estimated to be over five million acre-feet per year (Robinson, 1965). Saltcedars are hydrohalophytic; their roots extend to the ground water table and they are able to tolerate a wide range of soil salinities (Waisel, 1972).

Studies conducted during June, 1975, at the Bernardo, New Mexico, lysimeter site indicated that, under typical summer conditions, a significant afternoon depression of transpiration and photosynthesis occurred. Transpiration depression could result from a direct effect of high temperatures or low relative humidity on the stomatal mechanism (Lange, et al., 1971; Schulze, et al. 1973), or from water stress imposed by the transpirational demand. The present study was undertaken to assess diurnal trends in the water status of saltcedar, to determine if depressions of transpiration and photosynthesis occurred in twigs held at constant temperature and relative humidity, and to determine if changes in transpiration and photosynthesis were correlated with changes in water status. In addition, water status and gas exchange of plants growing on and off the Bernardo lysimeters was compared to ascertain that saltcedar stands on the lysimeters were not atypical.

METHODS

Relative water content (RWC) (Slatyer and Barrs, 1965) was measured on 7 cm saltcedar cuttings that were made with a sharp razor blade and immediately weighed on a Mettler balance to determine fresh weight (FW). The cuttings were placed in 25 ml beakers that contained 5 ml distilled water to which a non-ionic surfactant (Triton X-100) was added (0.1 ml surfactant/100 ml water) to overcome surface tension effects. The twigs were propped against the sides of the beakers to insure that only the cut surface would be immersed. The beakers were set in a tray filled to a depth of 8 mm with water. The tray had a close fitting cover and served as a humidity chamber. Cuttings were allowed to saturate at room temperature in subdued light for two hours and were then removed and blotted with tissue to remove external water. Care was taken to avoid contact between the cut surface and the tissue. Following visual inspection to insure that there was no externally adhering water, staurated weight (SW) was determined. Samples were then dried in an oven for 12 hours at 100°C. Dry weights (DW)

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were determined, and RWC calculated according to the formula:

$$RWC = \frac{FW - DW}{SW - DW} \times 100$$

Plant water potential was measured on excised twigs using the Scholander pressure bomb method (Waring and Cleary, 1967).

The methods for measuring transpiration and photosynthesis are described in a companion paper in this volume (Anderson, 1977).

RESULTS AND DISCUSSION

MEASUREMENT OF PLANT WATER STATUS

Relative water content has proven to be a sensitive, reliable, and convenient means for studying plant water status, and has been used successfully with whole leaves (Anderson and McNaughton, 1973), leaf discs (Slatyer and Barrs, 1965), and conifer needles (Hellkvist, 1973). Because water potential measurements may be less sensitive to small changes in water status when plants are well supplied with water (Slatyer, 1967), we thought the technique might detect small changes in the water status of saltcedar that would not be detected by other methods.

In initial attempts to determine RWC of saltcedar, as much as 40% of the sampled twigs failed to saturate. We considered cutting the stems under water as suggested by Decker and Wien (1960) to avoid introduction of air into the xylem; however, the overlapping nature of the scale-like leaves, which tends to trap a lot of water, and the possibility of hydrating the surface salt crystals, seemed to preclude immersing the twigs. Addition of the surfactant to the solutions improved saturation to near 100% with not more than one twig in a sample of 12 failing to saturate. Twigs that did not gain weight in the saturation chamber were eliminated from the sample.

Saturation curves showed a rapid uptake of water during the first hour with minimal changes over the next two hours. Results within the first three hours were consistent with the water uptake curves of Slatyer and Barrs (1965). There was no significant difference between 2- and 3-hour saturation weights (t = 0.38; $P > 0.5$), and a 2-hour saturation time was selected for convenience.

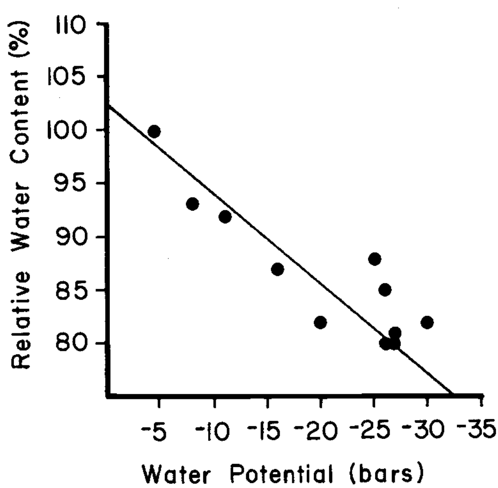

Figure 1. Relationship between relative water content and water potential for saltcedar twigs. Each point is the mean of 10-12 RWC determinations paired with the mean of several water potential determinations taken in the same stand at the same time of day.

Twig saturation times greater than three hours frequently resulted in significant losses in leaf weight, indicating that twigs were losing water in the saturation chambers. We suspected that weight losses beyond three hours might result from changes in the osmotic balance of the saturating solution due to movement of the solutes from the leaves or leaf surfaces into the medium. However, samples returned to the laboratory and tested with a conductance bridge, a refractometer, and a chloridometer failed to reveal any consistent osmotic changes that would explain the water loss. Thus, the explanation of the weight losses with longer saturation times remains unknown.

RWC values were closely correlated with water potential (Figure 1), suggesting that RWC would provide a valid indication of water status in saltcedar. Despite the care taken in handling samples, however, within sample variability of RWC determinations was quite high. Of 46 samples of 12 twigs each, two-thirds had standard deviations of the mean RWC values of 3 or less. Standard deviations of the remaining samples was greater than 3, with a few as high as 6.7. Because of the sample variability, RWC was less sensitive to small changes in water status than the pressure bomb technique. Systematic errors were also apparent when RWC data were collected by different investigators. In order to achieve reliable and consistent estimates, all RWC determinations had to be made by the same person. In addition to the difficulties encountered, the RWC technique proved to be tedious and very time consuming. Therefore, the technique cannot be recommended for saltcedar studies. In contrast, pressure bomb data could be collected and interpreted very quickly, and the water potential data appeared to be more reliable. Minimum water potential values of -25 to -30 bars are very low for plants with an adequate water supply, however, and these values are about 10 bars lower than pressure bomb values for the same saltcedar stand at comparable times determined with a different instrument (D. Davenport, personal communication). Thus, we suspect that there may have been a systematic error in our pressure bomb data. This question will be resolved by further study, but it should not affect the general patterns and interpretations which follow.

DIURNAL WATER STATUS AND GAS EXCHANGE PATTERNS

Diurnal patterns of twig water potential, net photosynthesis, and transpiration are shown in Figure 2. Within one-half hour after sunup, water potential decreased from near zero to -17 bars. This decrease continued until about 0900 at which time near minimum water potential values of about -26 bars were observed. Diurnal curves

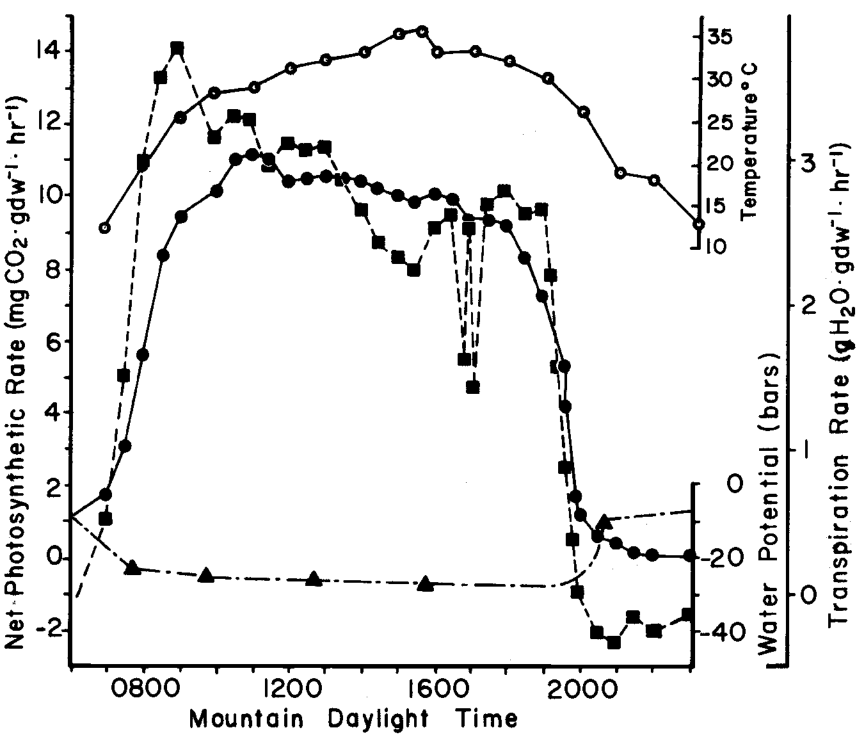

Figure 2. Diurnal patterns of air temperature (O) and transpiration (●), net photosynthesis (■), and twig water potential (▲) for saltcedar on a lysimeter at Bernardo, New Mexico, June 10-11, 1976.

for RWC are similar, with minimum values near 80%. After reaching these minimal values, water potential and RWC usually varied little (± 4 bars; ± 2% RWC) throughout the remainder of the day. Water status improved rapidly after sunset, and full turgidity was reached between midnight and 0500. Although the water potential data shown in Figure 2 indicate a slight decline from 0930 to 2000, the actual mean values do not differ significantly. Data for several other days indicate that water status tends to remain constant or even improve slightly during the afternoon (see Figure 3).

Transpiration increased rapidly following sunup, presumably because of stomatal opening, and then continued to increase as air temperature increased until about 1030. Although air temperature continued to increase after 1030, transpiration leveled off and then gradually decreased throughout the remainder of the day, dropping sharply at dusk. Using an energy budget analysis, Gay, *et al.* (1976) reported that transpiration from saltcedars fell below potential values during the afternoon, and they attributed this decline to increased canopy resistance. In separate experiments (Anderson, 1977), we found that stomatal resistance increased linearly with temperature. This would contribute to the decline in transpiration observed (Figure 2).

Photosynthesis reached its maximum by 0900, while air temperatures were relatively cool (Figure 2). Separate experiments showed that the optimum photosynthetic temperature was 23-28°C and that photosynthesis was typically reduced by about 20% at leaf temperatures of 35°C (Anderson, 1977). Thus, the decline in net photosynthesis after 0900 can largely be accounted for by increases in air temperature. The maximum midday depression of photosynthesis correlates closely with the highest air temperature, and the recovery of photosynthetic rates after 1530 corresponds to decreases in ambient temperature. The two sharp depressions in photosynthesis between 1630 and 1700 were caused by passing cumulus clouds that decreased light intensity about 66%.

CONSTANT TEMPERATURE AND RELATIVE HUMIDITY EXPERIMENTS

In an effort to determine if afternoon depressions of gas exchange were caused only by the effects of temperature and/or the leaf-air humidity gradient, experiments

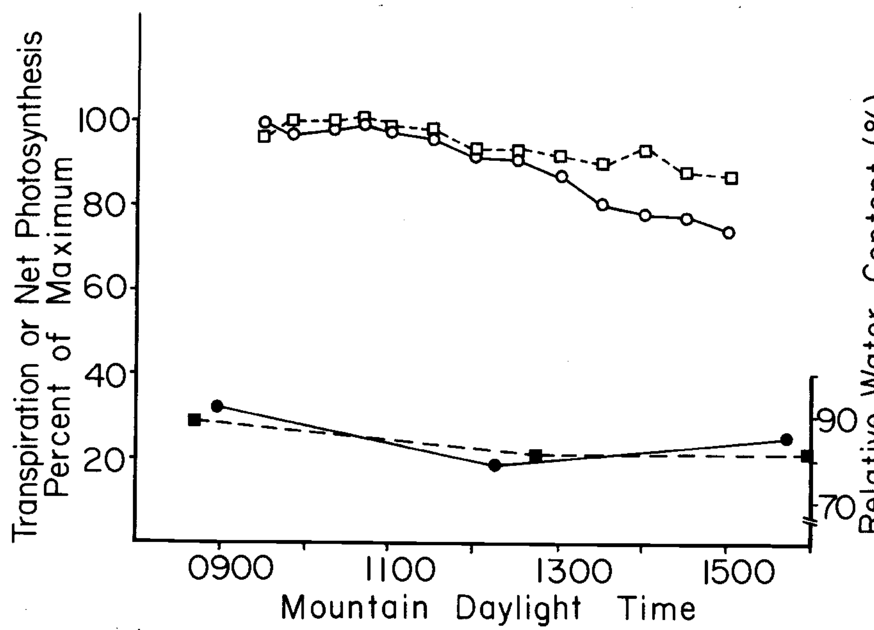

Figure 3. Upper curves: Transpiration (○) and net photosynthesis (□), expressed as percentages of the maximum rates observed, for a saltcedar twig held at constant temperature (30°C) and relative humidity (45%). The plant was growing on lysimeter no. 5.

Lower curves: Relative water content for plants growing on lysimeter no. 5 (●) and in an adjacent natural stand (■). All data were taken on June 8, 1976.

were conducted with those factors held constant. Afternoon depressions occurred in twigs maintained at 30°C and 45% relative humidity (Figure 3). Therefore, increased diffusive resistance during the afternoons does not result entirely from temperature or humidity effects. Water stress may be a factor in initiating stomatal closure; but, while water status remains constant or improves slightly, transpiration and photosynthesis continue to decline. If stomatal resistance was regulated primarily by the water status of the plant, one would expect transpiration to reach a steady state, or to increase with improved leaf water status, under constant environmental conditions. This is clearly not the case. On one occassion when the sky remained overcast until 1130 and air temperatures remained below 30°C throughout the afternoon, depressions that were practically identical to those shown in Figure 3 occurred. Under those conditions, it is unlikely that much water stress developed; yet, the typical transpiration decline was evident by early afternoon. These observations indicate that afternoon depressions in gas exchange cannot be totally accounted for by water stress, temperature, or relative humidity. It is possible that the rates might be depressed by a diurnal rhythm in stomatal resistance, but the reasons for such a rhythm are not at all obvious. At Bernardo, saltcedars growing both on and off the lysimeters are well supplied with water from a 1.5 m water table.

ON-OFF LYSIMETER COMPARISONS

Water status, transpiration rates, and net photosynthetic rates for saltcedars growing on the lysimeters were compared to the same parameters for plants growing off, but in the immediate vicinity. No significant differences in water status were observed (Figure 3). Transpiration rates for plants on lysimeter no. 5 (3.3 g H_2O g dry weight leaf^{-1} h^{-1}) were significantly (t = 3.1 with 10 d.f.; $P < 0.02$) higher than rates for plants in the immediate vicinity (2.6 g H_2O g dry weight leaf^{-1} h^{-1}). Similarly, photosynthesis for lysimeter-grown plants (14.3 mg CO_2 g dry weight leaf^{-1} h^{-1}) was significantly (t = 3.3 with 10 d.f.; $P < 0.01$) higher than for plants growing off the lysimeter (11.2 mg CO_2 g dry weight leaf^{-1} h^{-1}). Rates for plants growing on lysimeter no. 6 were very similar to those for off-lysimeter plants. The reasons for these differences are not apparent, but the differences are not large and it seems safe to conclude that the saltcedar stands on lysimeters 5 and 6 are quite typical of natural stands in the vicinity.

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TRANSPIRATION AND PHOTOSYNTHESIS IN SALTCEDAR

by

Jay E. Anderson

ABSTRACT

Factors controlling transpiration and photosynthesis of saltcedar were investigated in the field near Bernardo, New Mexico. Transpiration rates were similar to those for several herbaceous species, but photosynthesis and water use efficiency were significantly lower in saltcedar. Photosynthesis was light saturated at an irradiance equal to 44% of full sunlight, while the stomata were apparently fully open at light levels greater than one-third full sunlight. Optimum leaf temperatures for photosynthesis were between 23° and 28°C, considerably lower than typical daytime ambient temperatures. Photosynthesis was reduced about 20% at 35°C. Stomatal resistance increased linearly with increases in leaf temperature between 14° and 50°C, with relative humidity held constant. The increase in stomatal resistance could have been caused by direct effects of temperature on the stomata, by increases in the absolute humidity gradient from leaf to air, or by both. Increased stomatal resistance at high temperatures and low relative humidities would account for observed afternoon depressions in transpiration and photosynthesis and increases in canopy resistance. Estimates of stomatal resistance for twigs in full sunlight ranged from 2 to 6 sec cm^{-1}, with most values falling between 3 and 5 sec cm^{-1} when leaves were at 30°C.

INTRODUCTION

Saltcedar (*Tamarix chinensis* Lour.), a naturalized shrub or small tree native to Eurasia, has become the most widely distributed and important phreatophyte in the southwestern United States. From an area of 40 or 50 thousand acres in 1920, it has spread across the floodplains of southwestern rivers to occupy well over one million acres (Robinson, 1965). Estimates of water consumption for mature saltcedar stands, based largely on lysimeter studies, range from 150-210 cm annually (Horton, 1976), suggesting that over five million acre feet of water are consumed by saltcedar in the Southwest each year (Robinson, 1965). These estimates may be valid for warmer, low elevation sites such as the lower Gila and Colorado Rivers, but are probably too high for the entire range of saltcedar. Average evapotranspiration (ET) over six years for saltcedar on the Bernardo, New Mexico, lysimeters at about 4600 feet elevation was 97 cm annually (U.S. Bureau of Reclamation, 1972). Nevertheless, transpiration losses in response to the arid climate are significant where phreatophytes tap the water table.

The difficulty in estimating water consumption by extrapolation from lysimeter studies to saltcedar stands in other areas (Van Hylckama, 1974) has led to attempts to predict ET from meteorogical data and vegetation characteristics (Gay, *et at.*, 1976). Exchange of water vapor between the plant canopy and the atmosphere depends upon air and leaf temperatures, atmospheric humidity, aerodynamic or boundary layer resistance, and leaf diffusion (stomatal) resistance. Stomatal resistance is not a constant in the ET equation (Monteith, *et al.*, 1965), but is influenced by light intensity and plant water status, and may change in response to those same physical factors that drive ET, temperature and atmospheric humidity (Lange, *et al.*, 1971; Schulze, *et al.*, 1973; Hall and Kaufmann, 1975). Thus, reliable estimates of ET from environmental data are dependent upon knowledge of the effects of these factors on leaf resistance (Running, *et al.*, 1975; Aston, 1976). Despite its reputation as "the heaviest water user of all the phreatophytes" (Gay, *et al.*, 1976), such data are not available for saltcedar.

The objectives of this study were to 1) quantify transpiration and net photosynthetic rates, 2) determine the effect of light intensity on photosynthesis and leaf diffusion resistance, 3) estimate leaf resistance under full sunlight, and 4) determine the effects of temperature on leaf resistance and net photosynthetic rate, for saltcedar twigs. A companion paper in this volume (Williams and Anderson, 1977) discusses measurement of water stress and diurnal trends in photosynthesis and transpiration.

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METHODS

Studies were conducted at the U.S. Bureau of Reclamation lysimeter site on the Rio Grande floodplain near Bernardo, New Mexico, during June of 1975 and 1976. Net photosynthesis and transpiration were measured with an open gas-exchange system utilizing the plant cuvette described by Mooney, *et al.* (1971). An intact twig was sealed into the plexiglass cuvette through which air was circulated at a known flow rate. Net photosynthesis was determined by measuring the carbon dioxide concentrations of the air entering and leaving the cuvette with a Beckman 865 infrared gas analyzer. The system was sensitive to carbon dioxide concentration changes of 1-2 ppm. Transpiration rates were determined by measuring the relative humidity of the air entering and leaving the cuvette and calculating the amount of water vapor added by the plant. Relative humidities were determined with narrow range lithium chloride hygrosensors (American Instrument Company, Silver Springs, MD). Accuracy of the transpiration measuring system, determined by integral calibration (Tranquillini and Caldwell, 1972) was ± 2%.

A 15 m umbilical cord containing water, air, and thermocouple lines connected the cuvette to the measuring and recording instruments housed in a small utility trailer. Cuvette temperatures were maintained at desired levels within 0.1°C by circulating coolant from a constant temperature bath through a heat exchanger in the cuvette. Cuvette air was constantly stirred to eliminate temperature and gas concentration gradients, and to reduce boundary layer resistance. Air and leaf temperatures were measured with 36 guage type T thermocouples. Under full sunlight, leaf temperatures were typically within 1°C of air temperatures within the cuvette.

Illumination was provided only by natural sunlight. Photosynthetically active radiation (400-700 nm) was measured with a LI-190S Quantum Sensor (Lambda Instruments, Lincoln, NE).

Leaf area was estimated from twig fresh weights using Candela's (1976) equation,

$$\text{area (cm}^2\text{)} = 80 \times \text{fresh weight (g)},$$

which was determined from studies of silver replicas of saltcedar twigs. The accuracy of the estimates so derived is unknown, but the estimates agree quite closely with those obtained from the projected images on photographs of saltcedar twigs (L. Gay, personal communication).

Stomatal resistance (r_s, in sec cm^{-1}) was determined indirectly from the transpiration rate (T, in mg cm^{-2} sec^{-1}) and the absolute humidity difference between leaf and air ($q_{leaf} - q_{air}$, in mg cm^{-3}) from the equation,

$$r_s = \frac{q_{leaf} - q_{air}}{T}$$

Water vapor saturation within the leaf was assumed for obtaining values of q_{leaf}.

RESULTS AND DISCUSSION

At 30°C and 45% relative humidity, saltcedar twigs transpire a weight of water greater than their own fresh leaf weight each hour (Table 1). These transpiration rates are somewhat higher than typical rates reported for halophytes by Waisel (1972), but, on a fresh weight basis, are similar to the rates for several common herbaceous plants measured under similar conditions with the same gas exchange system (Table 2). Thus, while transpiration of saltcedar may be high compared to other halophytes, it is not unusually high when compared to glycophytes with an abundant water supply. Comparable data for other phreatophytes are sorely needed.

Table 1. Average rates of transpiration and net photosynthesis for 25 saltcedar twigs at 30°C. Twigs were exposed to full sunlight and relative humidity in the cuvette was 45%. Values in parentheses are the 95% confidence intervals.

Transpiration Rate
3.11 (2.87 - 3.34) g H_2O g dry weight leaf^{-1} h^{-1}
1.18 (1.09 - 1.26) g H_2O g fresh weight leaf $^{-1}$ h^{-1}
1.48 (1.37 - 1.58) g H_2O dm^{-2} h^{-1}
Net Photosynthetic Rate
13.4 (12.7 - 14.1) mg CO_2 g dry weight leaf^{-1} h^{-1}
5.07 (4.77 - 5.36) mg CO_2 g fresh weight leaf $^{-1}$ h^{-1}
6.33 (5.96 - 6.70) mg CO_2 dm^{-2} h^{-1}

Photosynthetic rates for saltcedar (Table 1) are considerably lower than the rates for the herbaceous plants (Table 2). Water use efficiency, indexed by the ratio of photosynthesis to transpiration (P in mg CO_2/T in g H_2O) (Downes, 1969), averaged 4.3 for saltcedar, significantly lower than the values for the herbaceous species shown in Table 2. Although transpiration rates are similar, these data indicate that the efficiency of carbon assimilation per unit water loss is low in saltcedar compared to the herbaceous plants. No reasons for the lower water use efficiency are apparent.

Table 2. Transpiration and net photosynthetic rates and P/T ratios for four herbaceous species measured under conditions similar to those for saltcedar in Table 1. Rates are expressed on a fresh leaf weight basis. See text for explanation of P/T ratio.

Species	Transpiration Rate (g H_2O g leaf^{-1} h^{-1})	Net Photosynthetic Rate (mg CO_2 g leaf^{-1} h^{-1})	P/T
Yellow sweetclover (*Melilotus officinalis*)	1.81	13.0	7.2
Yarrow (*Achillea millefolium*)	1.42	9.5	6.7
Canada wild rye (*Elymus canadensis*)	1.13	9.3	8.2
Crested wheatgrass (*Agropyron cristatum*)	1.66	10.9	6.6

Data relating photosynthesis and transpiration to light intensity were collected during two afternoons that gradually became more densely overcast, slowly reducing light intensity (Figure 1). The results for the two afternoons are nearly identical. Since these data were generated under natural light conditions, the relationships shown should be valid for saltcedar under field conditions. Photosynthesis was light

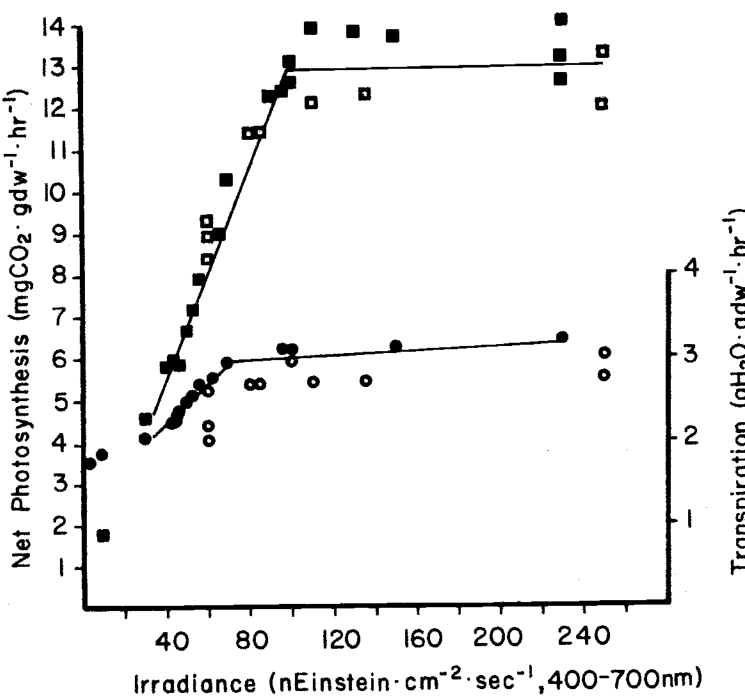

Figure 1. Net photosynthesis (□) and transpiration (○) of saltcedar as a function of light intensity. Closed figures are data for one twig; open figures are data for a second twig taken on a separate day. gdw = grams dry weight of leaf.

saturated at a radiant flux of approximately 110 nEinsteins cm^{-2} sec^{-1} (400-700 nm), equal to 44% of full sunlight. As irradiance levels decreased, no reduction in transpiration was observed until irradiances reached about 80 nEinsteins cm^{-2} sec^{-1}, suggesting that the stomata were fully open at light levels above this value.

Carbon dioxide assimilation was tightly coupled to light intensity. On numerous occassions when a cumulus cloud passed in front of the sun, net photosynthesis was observed to drop as much as 40 or 50% within 1-2 minutes, and then quickly recover as the cloud moved past and the twig was again exposed to full sunlight. These short term reductions in light intensity had little effect on transpiration.

The optimum leaf temperatures for photosynthesis were between 23° and 28°C (Figure 2). The optimum range was well below the typical midday and afternoon temperatures of 32-38°C observed at Bernardo during June. At 35°C, photosynthesis was reduced about 20% below the maximum observed value. There is no doubt that high ambient temperatures contribute to observed depressions in net photosynthesis during the afternoon (see Williams and Anderson, 1977).

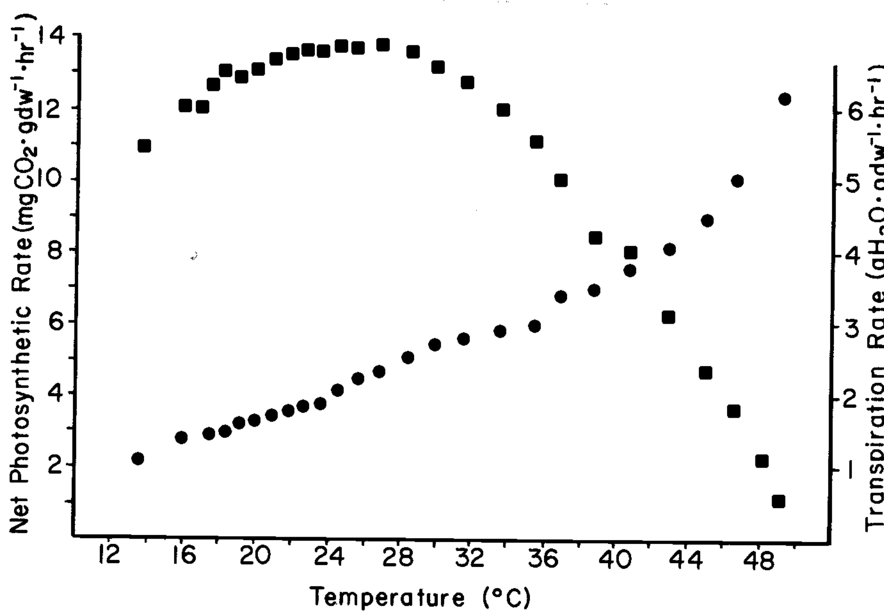

Figure 2. Net photosynthetic rate (■) and transpiration rate (●) for saltcedar as a function of leaf temperature. gdw = grams dry weight of leaf.

Temperature curves for plants grown in the laboratory at 25°C days and 15°C nights were practically identical to that shown in figure 2, indicating that there is little acclimation of the photosynthetic apparatus to the higher ambient daytime temperatures in the field. This result is somewhat surprising in view of the acclimatory response to temperature observed in many plant species (Mooney and West, 1964; Mooney and Shropshire, 1967; Lange, *et al.*, 1974). Pearcy (1976) points out that desert species often show superior abilities to acclimate in order to maintain high rates of productivity under seasonally variable temperatures. Desert ecotypes of *Atriplex lentiformis*, a phreatophyte with the C-4 photosynthetic pathway, have a large capacity for photosynthetic acclimation to high temperatures (Pearcy, 1976). Saltcedar would appear to be much more limited in its acclimatory capacity.

The transpiration values in Figure 2 were used to calculate the stomatal resistances shown in Figure 3. Stomatal resistance increased linearly with increases in leaf temperatures between 14° and 50°C, indicating stomatal closure in response to increasing temperature. Increased stomatal resistance would contribute to the decrease in net photosynthetic rate above 28°C (Figure 2). It would also contribute to the observed afternoon depressions of photosynthesis and transpiration (Williams and Anderson, 1977), and would explain, at least in part, the apparent increase in canopy resistance detected by the energy budget analysis of Gay, *et al.* (1976).

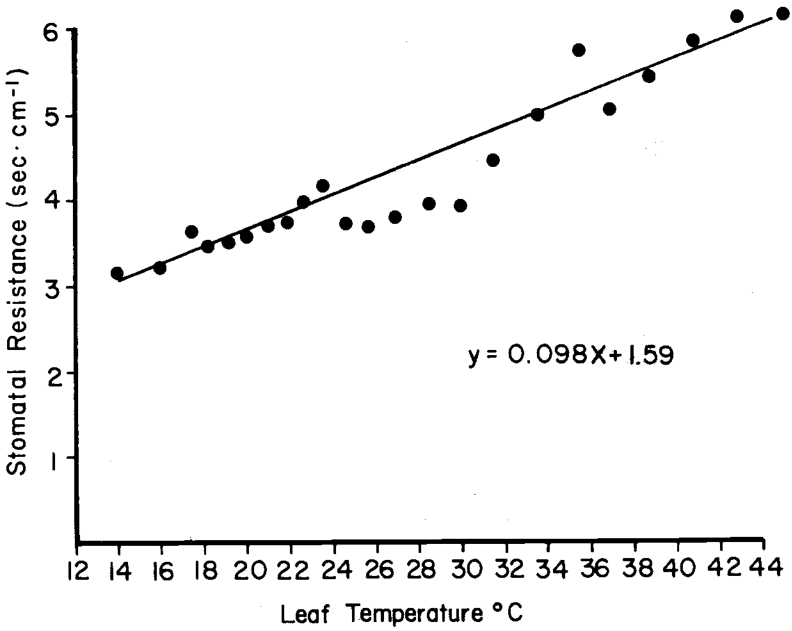

Figure 3. Stomatal resistance for saltcedar as a function of leaf tempearture. Resistances were calculated from the transpiration data shown in Figure 2.

Past studies have yielded conflicting results concerning the response of stomata to temperature. Drake, *et al.*, (1970) found that r_s decreased with increases in leaf temperature in cocklebur, and postulated that this enabled the plant to increase transpirational cooling at high temperatures. Schulze, *et al.*,(1973) reported that r_s decreased with leaf temperature increases in several species when they were well watered, but the relationship was reversed when the same species were under water stress. They reported that the temperature effect was independent of effects of ambient humidity. Hall and Kaufmann (1975) argued that "the influence of temperature on both leaf resistance and net photosynthesis may be highly dependent upon the humidity gradient between the leaf and the air." They conclude that if humidity gradients are allowed to increase as temperature increases, r_s will also tend to increase. But, if the humidity gradient is kept constant, then r_s will either remain constant or it may decrease with increasing temperature.

In the present investigation, it was impossible to maintain a constant humidity gradient from leaf to air as temperature was increased because of system limitations. Cuvette relative humidity was maintained at about 45%, which resulted in an increase in the absolute humidity gradient from 5.6 $\mu g\ cm^{-3}$ at 16°C to 35 $\mu g\ cm^{-3}$ at 45°C. Therefore, the observed increase in r_s with increasing temperature (Figure 3) could have been caused by a direct effect of temperature on the stomata, by the increase in the humidity gradient from leaf to air, or by the combined effects of both factors. While it remains important to sort out the relationships between these factors and r_s experimentally, the present ambiguity does not detract from the significance of the finding that r_s is affected by changes in ambient temperature and/or humidity. In arid regions, as air temperature increases, ambient relative humidity typically drops to very low levels. At Bernardo, relative humidity during the afternoon was typically about 10%. Thus, to improve predictive models for ET from saltcedar, it will be necessary to quantify the interactive effects of temperature and the leaf-air humidity gradient on r_s.

The increase in r_s in response to temperature increases would appear to be an adaptation for water conservation. While there is no obvious need to curtail transpiration when water is freely available from a relatively shallow water table, as exists at Bernardo, such an adaptation could be important in insuring seedling survival until the root system could tap the water table or in enabling the species to invade and succeed in areas subjected to period drought.

Estimates of stomatal resistance under saturating light conditions ranged from 2 to 6 sec cm^{-1}, with most values at 30°C leaf temperature falling between 3 and 5 sec cm^{-1}. These values are not unreasonable, but tend to be somewhat higher than those typically reported for well watered plants. Gay, *et al.* (1976) reported that the mean canopy resistance for saltcedar at Bernardo was 1.9 sec cm^{-1} over a ten hour daytime period. The accuracy of my estimates is largely dependent upon the accuracy of the leaf area estimates (see Methods). A two- or three-fold error in area estimates, which would result in a corresponding error in r_s estimates, might not make the r_s estimates appear unreasonable. However, such errors could result in gross over or under estimates of transpiration from a saltcedar stand. It is imperative that accurate leaf area estimates with known error terms be obtained.

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ESTIMATING PHREATOPHYTE TRANSPIRATION

by

Lloyd W. Gay and Theodore W. Sammis

ABSTRACT

Phreatophyte transpiration on the Colorado River floodplain in western Arizona was evaluated under hot, dry, midsummer weather conditions. The simple transpiration model used related transpiration to the vapor pressure deficit of the air and to the area and the diffusion resistance of the transpiring foliage. There were no independent transpiration measurements for verification of the results. On a relative basis, however, mesquite (*Prosopis* sp.) transpired more rapidly per unit of leaf area than did saltcedar (*Tamarix chimensis*, Lour.).

INTRODUCTION

Large quantities of water are used by riparian vegetation in the arid and semiarid regions of the southwestern United States. Saltcedar (*Tamarix chimensis*, Lour.) and mesquite (*Prosopis* species) occur extensively along the watercourses in the southwest. The term phreatophyte was coined to describe plants of this type, which florish where their roots can reach a plentiful supply of water. Phreatophytes extract water either directly from the water table, or indirectly from the saturated capillary fringe immediately overlying it.

It is evident that phreatophytes use large amounts of water, and it has been widely assumed that much of this consumptive use could be salvaged by the clearing of riparian vegetation. Evidence of substantial water salvage has not been convincing, however, and public opposition to phreatophyte clearance has been spirited and effective. As a consequence, there are few phreatophyte control programs now underway in the Southwest. Alternatives to clearing that have been suggested include management of riparian communities to favor phreatophyte species that use the least amount of water. It is becoming apparent, however, that the extent of water losses and the nature of the processes that control them are not yet well defined, despite a large amount of research that has been carried out (Horton, 1976)

This paper evaluates stomatal resistance as the key factor controlling the transfer of water between riparian vegetation and the atmosphere. A simple vapor transport model is applied to the problem of evaluating evapotranspiration rates from several species on the Colorado River flood plain in western Arizona.

BASIC MODEL

The basic diffusion resistance model relates the transpiration per unit area of individual leaves (E_ℓ) to the vapor concentration gradient between the interior of the leaf and that in the free air, and to the diffusion resistance that exists between these two points. The basic model is

$$E_\ell = \frac{\rho C_p}{\gamma L} (e_s - e)/r_\ell \tag{1}$$

where ρ is air density (g/cm³), C_p is the specific heat of air (cal/g °C), γ is the psychrometric constant (mb/°C), L is the latent heat of fusion (cal/g), e_s-e is the vapor pressure deficit (VPD in mb) of the air with e_s being the saturation vapor pressure at air temperature and e being the actual vapor pressure, r_ℓ is the leaf (essentially stomatal) resistance (s/cm) and E_ℓ is the evaporation rate (μg/cm²-s).

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This model results from a number of simplifying assumptions. For example, diffusion resistance of the air can be neglected, as the rough canopy structure keeps it small with respect to the leaf diffusion resistance. Also, the model estimates the vapor concentration gradient between leaf and air by the vapor pressure deficit in the free air, assuming that the leaf elements are close to air temperature. Both assumptions are reasonable given the small sizes of leaves in saltcedar and mesquite.

The model can be extended to the problem of estimating evaporation (E) from a canopy if an appropriate canopy resistance (r_c) is substituted for the leaf resistance in Equation (1). Federer (1975) showed that the well-known Monteith-Penman model could be simplified into this form whenever the aerodynamic diffusion resistance approaches zero. This is very nearly true for forests and plant communities with rough, porous canopies, such as those of saltcedar and mesquite. The simple model of Equation (1) thus provides a way to estimate evaportranspiration from routine climatological measurements.

FIELD MEASUREMENTS

Field measurements were carried out on the Colorado flood plain near Ehrenburg, Arizona during a warm, dry, clear weather period in June 1976. Incoming solar radiation was measured with an Eppley pyranometer. Air temperature and relative humidity were measured with a hydrothermograph in a weather shelter at 1.5 m height. Spot checks of air temperature and humidity were made with an aspirated psychrometer.

Leaf diffusion resistances were made on various saltcedar and mesquite samples from early morning to dusk, using a null-balance porometer after the design of Beardsell, Jarvis and Davison (1972). No distinction was made between the two species of mesquite present: honey mesquite (*P. juliflora* var. *glandulosa* Torr.) and screwbean mesquite (*P. pubescens* Benth.). The plant water potential (Ψ_ℓ) was measured with a pressure bomb (Scholander, et al., 1964) at the time of each leaf diffusion measurement.

The surface area of the sampled vegetation is needed for the resistance determinations. Dry weight was obtained for each sample, and converted to surface area by the factor of 200 cm^2/g for saltcedar and 150 cm^2/g for mesquite. These factors were developed from subsamples that were dried and then evaluated from projected area measurements made with an integrating densitometer.

RESULTS AND DISCUSSION

The basic measurements are summarized for saltcedar in Table 1 and for mesquite in Table 2. The porometer measurements were repeated on seven clumps of foliage on the same saltcedar plant at approximately two hour intervals from early morning until dark on June 17, 1976. The seven samples were collected at the end of the day and the surface areas measured for the evaluation of leaf resistance. Subsequent measurements of resistance on saltcedar and mesquite were obtained from individual samples on various plants. Leaf water potential measurements with the pressure bomb were made on adjacent clumps of foliage at the time of each resistance measurement.

Table 1. Mean values of salt cedar resistances, Colorado River floodplain, Ehrenburg, Arizona. 1976. Note that the number of samples (n) is given for the mean resistance value (r_ℓ) and mean leaf water potential (Ψ_ℓ). Other data are vapor pressure deficit (VPD) and transpiration flux (E_ℓ).

day	time (hr)	n	r_ℓ (s/cm)	VPD (mb)	E_ℓ ($\mu g/cm^2$-s)	Ψ_ℓ (bars)
6/17	0630	7	17.0	-12.6	0.54	-10.2
	0850	7	13.8	-27.8	1.46	-25.9
	1030	7	19.6	-42.0	1.56	-26.2
	1230	7	33.0	-51.4	1.13	-25.4
	1430	7	36.9	-57.4	1.13	-25.1
	1645	7	38.6	-59.0	1.11	-23.0
	1830	7	35.4	-52.9	1.08	-22.6
	2030	7	67.2	-35.4	0.38	-13.6
	2200	2	68.7	-25.8	0.27	-19.6
6/20	0930	5	42.2	-32.8	0.56	- 6.6
	1020	3	16.9	-41.0	1.76	-32.6
6/21	0730	2	4.3	-14.8	2.50	-22.3
	1030	6	12.2	-46.8	2.78	-31.0
6/22	0715	4	11.8	-21.3	1.31	-19.0
	0910	1	19.5	-33.0	1.23	-27.9

Table 2. Mesquite resistances, Colorado River floodplain, Ehrenburg, Arizona, 1976. Each resistance is derived from a single sample.

day	time (hr)	r_ℓ (s/cm)	VPD (mb)	E_ℓ $\mu g/cm^2$-s	Ψ_ℓ (bars)
6/21	0815	2.8	-22.4	5.91	-24.5
	0825	2.8	-24.5	6.24	-27.2
	0935	2.7	-41.8	11.24	-27.9
	0945	3.0	-39.2	9.58	-29.3
6/22	0735	3.5	-21.2	4.40	-27.2
	0745	6.8	-21.5	2.31	-23.1
	0800	13.8	-23.0	1.21	-21.8
	0815	7.0	-24.1	2.49	-24.0

LEAF RESISTANCE AND TRANSPIRATION.

The diurnal course of the saltcedar leaf resistance and solar radiation is plotted in Figure 1. The skies were cloudless throughout the day, although smoke from nearby field burning activities caused some unsteadiness in the radiation during the mid-morning hours.

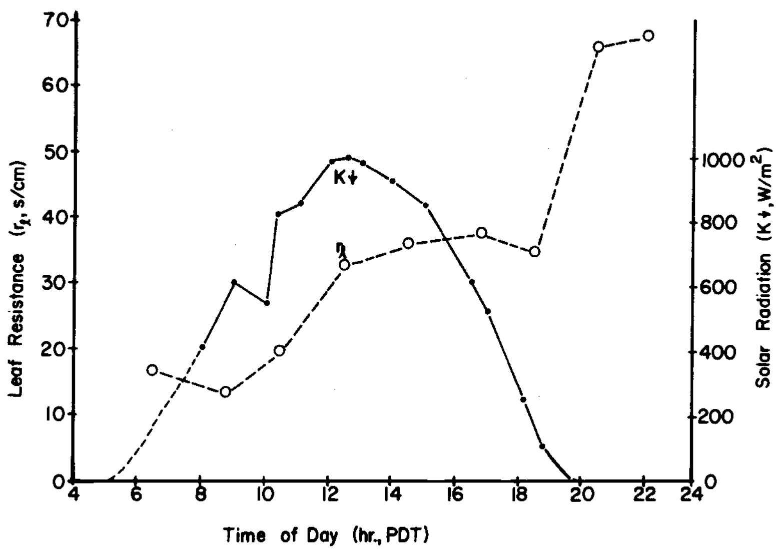

Figure 1. Solar radiation (K↓) and leaf resistance (r_ℓ) of saltcedar, Ehrenburg, Arizona, June 17, 1976.

The resistance measurements began soon after sunup. The initial readings (17 s/cm) indicated that the stomata were open. The values fell slightly, then increased to a plateau of about 35-40 s/cm from midday until sundown. The values climbed sharply to nearly 70 s/cm after dark. The Figure illustrates that the correlation between radiation and leaf resistance is weak. The stomata of many species will remain open once a relatively low level of visible light is exceeded, providing they are unaffected by other environmental factors. The leaf resistance, e.g., stomatal opening, is primarily controlled by physiological characteristics of the plant once the minimum light requirement is satisfied.

These characteristics are not yet defined for saltcedar although they are becoming known for other species. For example, the resistance of northern hardwood species (Federer and Gee, 1976) has been related directly to air temperature and to vapor pressure deficit. It is also indirectly related to moisture stress in the plant as the stomata close whenever the stress becomes too large.

Figure 2 illustrates the relationship between VPD and the leaf resistance throughout the day. The two curves are quite similar as long as the minimum light requirement is exceeded. The relationship is good until dusk; the resistance curve rises

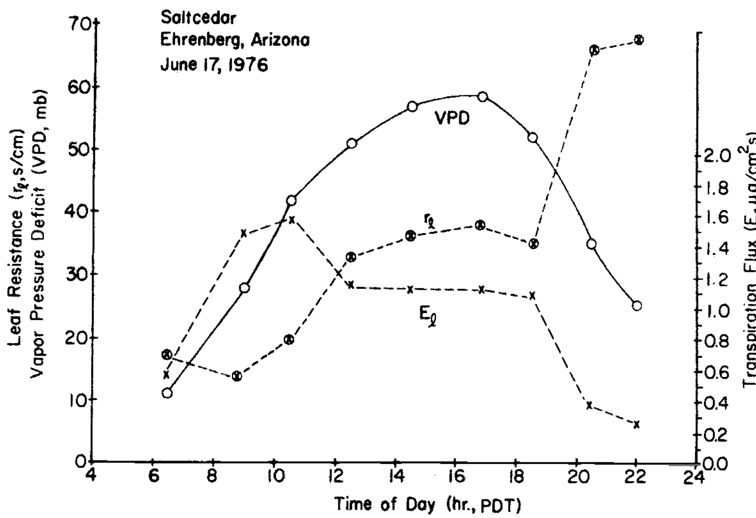

Figure 2. Vapor pressure deficit (VPD), leaf resistance (r_ℓ) and transpiration rate (E_ℓ). Saltcedar, Ehrenburg, Arizona, June 17, 1976.

sharply after dark while VPD continues to become smaller. Temperature is not plotted in the Figure. However, VPD is largely a function of air temperature; both reach a maximum in late afternoon.

The resistance changes tend to equalize or reduce the transpiration rate as VPD increases through the late afternoon period. THe transpiration predicted by the simple vapor loss model in Equation (1) is directly related to VPD. If the leaf resistance were to remain constant, then doubling VPD would double E_ℓ. If VPD increased sixfold, as found on this measurement day, the corresponding sixfold increase in transpiration would be excessively large. It is expected that some increase in resistance must occur to keep transpiration rates moderate.

The transpiration rates predicted by Equation (1) are also plotted in Figure 2. It is evident that the increased resistance more than compensates for the increased VPD, and the transpiration rate thus falls after the early morning hours. This suggests that the plant is exercising some physiological control on the stomata to counteract the evaporation demand of this warm dry atmosphere.

LEAF WATER POTENTIAL AND TRANSPIRATION

The loss of water through the stomata increases the water potential of the leaves. Pressure bomb estimates of the leaf water potential are now thought to be reasonably close to the actual values (Talbot, *et al.*, 1975). The pressure bomb measurements are easy to make, and may eventually provide a basis for evaluating transpiration.

The interaction between water potential and transpiration can be examined with the simple model of Elfving, *et al.* (1972) that links the liquid flow through the soil-plant continuum to the vapor flow between the leaf and the atmosphere. The flow equation is

$$E_\ell = \frac{\psi\ell - \psi s}{r_p + r_s} = \frac{\psi\ell - \psi a}{r_\ell + r_a} \qquad (2)$$

where $\psi\ell - \psi s$ is the difference in potential for liquid flow in the plant and in the soil, r_p and r_s are the soil and plant resistances to liquid flow, $\psi_\ell - \psi_a$ is the potential for vapor flow from the leaf to the atmosphere and r_ℓ and r_a are the leaf and atmosphere resistance to vapor flow. The resistances are expressed in units appropriate to liquid or to vapor flow.

The vapor flow term can be simplified in accord with Equation (1) and the leaf potential becomes

$$\psi_\ell = \psi_s + \frac{\rho C_p}{\gamma L}\frac{(e_s - e)}{r_\ell}\,(r_p + r_s) \qquad (3)$$

$$= \psi_s + kE$$

where k is a constant associated with the resistances for liquid flow through the soil and plant. If the soil and plant resistances remain constant through the day, Elfving's model predicts that the leaf water potential is linearly related to the transpiration rate.

The plot of ψ_ℓ versus E_ℓ for saltcedar and for mesquite in Figure 3 suggests that the simple linear model may indeed define this relationship adequately. The saltcedar

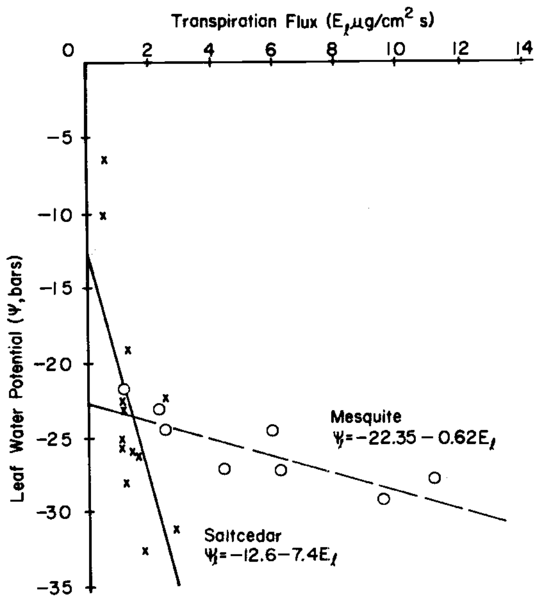

Figure 3. Leaf water potential (ψ_ℓ) and transpiration flux (E_ℓ) in saltcedar and mesquite, Ehrenburg, Arizona, June 17-22, 1976.

relationship is

$$\psi_\ell = -12.6 - 7.4E_\ell \qquad (4)$$

based upon all the observations in Table 1 except for the two after sundown (2030 and 2200 hours, June 17). The visual impression of goodness of fit is not borne out by statistical evidence, however, as the r^2 value for this relationship is only 0.42. Some additional studies must be made to see if the variability could be reduced to an acceptable level. The expression also predicts that the soil potential would be -12.6 bars when the transpiration rate goes to zero. Predawn measurements of leaf water potential will be needed to test the intercept in further experiments.

The mesquite measurements yield the relationship

$$\psi_\ell = -22.35 - 0.62E_\ell$$

with a more reassuring r^2 value of 0.72.

The two species demonstrate quite different behavior. The mesquite indicates that the soil potential is -22.35 bars, which is substantially more negative (greater stress) than that of the saltcedar. This may represent either differences in the water uptake mechanisms of the two species, or the location of the active roots with respect to the water table. The resistance to liquid water movement between the soil and the plant and within the plant is given by the slope of ψ_ℓ versus E_ℓ; the steeper the slope, the greater the resistance to flow. The saltcedar shows much greater resistance than the mesquite. The mesquite is transpiring much more rapidly per unit area than the saltcedar. Most of the readings were two to three times greater, and the maximum rate was nearly five times greater.

Our lack of knowledge of the actual state of moisture available to the roots limits our interpretation of these results. The Ehrenburg region is the driest in Arizona; it has an annual rainfall of only 9 cm. The depth of the water table was not measured directly at the field site. However, 31 observations of water table depth by the U.S. Geological Survey in this region on June 16 averaged 3.1 m. This is not an unreasonable depth for the roots of riparian vegetation to reach, so one would expect that the extensive vegetation on the flood plain is tapping the water table of the Colorado River. The soil potentials predicted by the model (-12.6 and -22.35 bars) are much too low for vegetation with ready access to ground water. If the water table underwent rapid flucuations associated with varying discharge from the Colorado River dam system, then it is possible that few active roots were tapping the capillary fringe. We do not have enough information to do more than speculate of the validity of these low soil potentials.

TRANSPIRATION FROM RIPARIAN STANDS

The diffusion resistance model may possibly provide simple estimates of transpiration from plant communities. Cunningham et al. (1973) used this method to estimate mean weekly transpiration from a riparian community over an entire growing season. No independent estimates were available for comparison, however, and his transpiration rates appeared high. The energy budget or Bowen ratio method is applicable to extensive, uniform stands. Gay, et al. (1976) have reported the results on one of the few such studies to be carried out over saltcedar; their measurements extended over only a single day. The two methods need to be compared to determine the closeness of agreement.

The results obtained here can be extended from a unit leaf area basis to an entire stand by multiplying with the leaf area index (LAI). There are very few LAI estimates for stands of riparian vegetation. We sampled a 3.25 m^2 plot through the canopy of two different saltcedar stands of approximately 5 m height. The over-dried foliage was converted to area by the previously determined factor of 200 cm^2/g. The LAI of the first plot was 8.1 and the second was 7.45. The vegetation at this experimental site was discontinuous, however, and additional sampling would have to be undertaken before an average stand LAI could be estimated. The measurements of Cunningham et al. (1973) gave a total LAI of only 2.5 for their saltcedar stand.

The maximum transpiration loss for the saltcedar was 2.78 $\mu g/cm^2$-s, which is equivalent to the evaporation of 0.1mm an hour per unit leaf area. The evaporation rate from a dense stand (LAI = 8) would be 0.8mm per hour. The higher rates for mesquite (say 10 $\mu g/cm^2$ s) yield a loss of 0.36mm per hour from a unit leaf area. LAI of a mesquite stand is substantially less than that of saltcedar, however. A plausible (though arbitrary) estimate of mesquite LAI = 3 would yield maximum hourly loss rates of about 1mm per hour from a mesquite stand.

These estimates are rather close to the maximum hourly transpiration rate of 1mm that was measured for saltcedar by Gay et al. (1976). Midday values of this magnitude are associated with total daily losses of 8 to 10mm for clear weather conditions. This is in line with estimates of saltcedar and mesquite transpiration made elsewhere. Overall, the loss rates based upon these diffusion measurements appear a little low for a saltcedar stand, but quite reasonable for the mesquite.

CONCLUSIONS

A simple diffusion model gave reasonable estimates of transpiration although no direct comparisons were made with other methods. The leaf diffusion measurements required for the model are relatively easily obtained with a porometer. The leaf area index is needed to extend the transpiration estimates from a unit area to a stand basis, and considerable sampling may be necessary to obtain this value.

The transpiration rates ranged from 0.5 to 2.78 $\mu g/cm^2$-s per unit of leaf area in saltcedar and from 1.2 to 11.2 $\mu g/cm^2$-s in mesquite. If the water loss rates were projected to a stand basis, the larger leaf area index of saltcedar (as high as 8.1) would tend to compensate for the lower rate per unit of leaf area. The mesquite leaf area index was not measured, but it is probably less than 3.0. Thus the water loss from a stand may be much closer than that indicated by the unit area water loss rates.

The diffusion resistance model can be applied to plant communities of irregular dimensions, or to clumps, while other methods, such as the Bowen ratio or energy budget, need large, uniform areas of vegetation for application. A definitive comparision between methods is now needed.

The diffusion resistance model also provides an insight into the response of the plant to soil-water potential and to vapor pressure deficits. A simple linear model did not appear to adequately link soil potential, leaf potential and transpiration rates. The soil potential predicted by the model was much lower than expected for plants with ready access to the ground water table. Further work is needed to determine whether phreatophytes normally have access to ground water throughout the growing season, or whether the discrepancy is associated with either measurement errors or failure of the model to adequately represent the process.

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REDUCING PHREATOPHYTE TRANSPIRATION

by

David C. Davenport and Robert M. Hagan

ABSTRACT

Transpiration rates (T) of riparian phreatophytes can be high. Antitranspirant (AT) sprays can curtail T without the ecological imbalance made by eradication. Saltcedar (*Tamarix* sp.) and cottonwood (*Populus* sp.) in 15-gal. drums enabled replicated trials on isolated plants or on canopies. T of isolated saltcedar plants could be 2x that of plants in a fairly dense canopy. T for a unit ground area of saltcedar varied from 2.2 (sparse-) to 15.8 (dense-stand) mm/day in July at Davis. Extrapolation of experimental T data to field sites must, therefore, be made carefully. Wax-based ATs increased foliar diffusive resistance (R), and reduced T of saltcedar and cottonwood 32-38% initially and 10% after 3 weeks. R increased naturally in the afternoon when evaporative demand was high and if soil water was low. Nocturnal T of salt cedar was 10% of day T. AT effectiveness increased with a higher ratio of day: night hours, and with lower soil water stress. Therefore, AT will be most effective on long summer days in riparian areas where ground water is available.

INTRODUCTION

Water use by, and management of, riparian phreatophyte vegetation was recently reviewed by Ffolliott & Thorud (1975) and Horton (1976). Methods for controlling phreatophytes have included expensive physical and chemical eradication measures. However, permanent eradication is seldom achieved, and the side effects of such drastic techniques can result in a severe ecological imbalance. The antitranspirant (AT) approach seeks to curtail transpiration of phreatophytic vegetation, such as saltcedar (*Tamarix* sp.), without removing the vegetation or damaging the environment (Brooks & Thorud 1971; Davenport et. al. 1976). This paper reports experiments by the University of California (Davis) on the use of ATs to reduce phreatophyte transpiration. It is part of a regional project funded by the Office of Water Research & Technology (USDI), and involves expertise from Arizona, California, Colorado and Idaho to study phreatophyte water use, its reduction by AT and the effects of AT on riparian wildlife.

In June, 1974, cuttings of saltcedar (*Tamarix pentandra*) and cottonwood (*Populus* sp.) were each taken from a single mother plant (to eliminate genetic variability), rooted, and transplanted outdoors in 15-gallon drums (42 cm diameter X 48 cm depth). The drums were painted white to avoid high soil temperature in summer and were filled with a light commercial potting mix to reduce dead weight. Irrigation was applied to the soil surface, and evaporation from the soil was minimized by a plastic disc on the surface of each drum. By August, 1975 the plants were over 1 meter tall. Daily transpiration per plant, measured by periodic weighing, was as much as 4 kg of water, and the accuracy of the weighing system was about 1.5% of this daily loss. Thus, even a 5% reduction of daily transpiration by the AT was easily detected. Variations of transpiration rates between plants was minimized by running uniformity trials before each experiment. The advantages of the 15-gal. weighable drums for these AT/transpiration studies are: (a) cheap and manageable, permitting many units for adequate replication and several different experiments in one season; (b) big enough to produce plants with reasonably large individual canopies; and (c) larger canopies can be produced by grouping individual units, enabling measurements of transpiration, and AT coverage and effectiveness, for canopies of various densities. Most lysimeter installations do not have this much versatility and are considerably more expensive to install.

Two wax-based, food-grade ATs were used in these trials: 1) Mobileaf FG (Mobil Chemical Co., Richmond, VA.), and 2) Folicote (Crystal Soap and Chemical Co., Lansdale, PA.). These were sprayed on the foliage as emulsions with water by a Solo back-pack mist blower at various dilutions and application rates.

AT EFFECTS ON COTTONWOOD

Mobileaf FG and Folicote at 6% dilution were equally effective in significantly reducing transpiration of adequately watered cottonwoods, by nearly 40% initially, the effect decreasing with time (Table 1). Porometer measurements on the lower surfaces of the cottonwood leaves (stomata occur on both surfaces) showed the ATs had made a 4 to 5-fold increase in resistance to water vapor diffusion. The average values of 10 readings per treatment were respectively, 0.16, 0.62, and 0.87 min cm^{-1} for Control, Mobileaf FG and Folicote.

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Table 1: Transpiration reduction of cottonwood in 15-gal. drums by 6% antitranspirant (Davis, 1975).

Days after spray	1	4	8	13	23	29
Transp. reduction (%)	38	37	18	8	6	2

AT EFFECTS ON SALTCEDAR

After a uniformity trial, 24 drums of saltcedar were selected to give 4 replicates of each of the following Folicote AT sprays: 0 (Control), 3, 6, 8, and 12%, sprayed at about 600 ml/plant (high); and 12%, sprayed at about 300 ml/plant ('low'). Before spraying, transpiration among plants varied by no more than ± 3% (Fig. 1). After spraying, on Sept. 9, transpiration was significantly ($P < 1\%$) reduced as much as 33% by the 12% dilution and 22% by the 12% (low), indicating the importance of applying a sufficient volume of any one dilution. The 12% (low) AT treatment was only slightly more effective than the 6%, and about as effective as the 8%, dilution sprayed at 'high' volume. One week after spraying, the 6-12% dilutions reduced transpiration only 8-12%.

On Sept. 29 the saltcedar plants were retreated as follows: the previous 6% and 12% drums were re-sprayed, respectively, with 5% and 10% Folicote at 750 ml/plant; the 12% (low) drums were re-sprayed with 10% (low), i.e., at 375 ml/plant; the 8% and control drums were not sprayed, but transpiration measurements were continued on them; the 3% AT, being virtually ineffective, was removed from the experiments. Plants sprayed with 6% Folicote on Sept. 9 continued to transpire about 10% less than Control in early October, but this was not statistically significant. On the other hand, maximum transpiration reductions, 2 days after re-spraying with 5 and 10% Folicote, were, respectively, 23% and 35% ($P < 1\%$), and for the 10% (low) treatment about 20% ($P < 1\%$) - Fig. 1. The duration and magnitude of these reductions was confounded by 1) unusually cool, foggy, and rainy weather in the second week of October, and 2) new growth on the plants. However, 2 weeks after re-spraying, the AT still appeared to reduce transpiration by about 10-20%.

The AT effects on saltcedar in 15-gal. drums were further confirmed in June, 1976, when we sprayed 10% Folicote by a back-pack mist blower on a natural stand of saltcedar on the U.S. Bureau of Reclamation's 1000-ft^2 lysimeter tanks at Bernardo, New Mexico. After correcting for inherent differences between tanks (caused by varying plant densities), we again observed a 30-35% reduction in water use initially, diminishing to 10% after three weeks, with no signs of plant damage.

The importance of accounting for variations in plant size when assessing AT effects is borne out in the following comparison of transpiration from a control and an AT-treated plant in 15-gal. drums (Table 2). The treated plant had about 30% more foliage than the control and transpired only about 10% less water on a per plant basis. However, when transpiration was expressed on an equal fresh or dry weight basis transpiration reduction by AT was about 30%. It is interesting that the saltcedar could daily transpire water equal to 10x its fresh weight or 30x its dry weight.

Table 2. Influence of amount of salt cedar foliage, measured as fresh or dry weight (FW or DW), on interpretation of antitranspirant (AT) effectiveness. (Davis, 1975)

Treatment	Drum No.	Foliage (g/plant) FW	DW	Transpiration (g/day) /plant	/gFW	/gDW
Control	31	293	89	2750	9.37	30.76
AT	28	384	116	2514	6.54	21.75
% of Control		131	129	91	70	71

TRANSPIRATION RATES OF SALTCEDAR CANOPIES

The preceding transpiration data on saltcedar were based on measurements from isolated plants, i.e., no foliage overlap with neighboring plants. Individual plant studies were made because they helped answer the primary question - can antitranspirants reduce saltcedar transpiration? However, it is also necessary to know the magnitude of water loss from canopies of various densities. The large numbers of saltcedar drums enabled this evaluation simply by surrounding the drums to be measured by other 'guard' drums of saltcedar at the desired spacing. In a preliminary test of this method a uniformity trial on 2 pairs of isolated drums showed approximately equal transpiration rates. When one pair of plants was moved into a 'close' canopy (no ground visible); transpiration/plant was consistently about 50% of that of isolated plants. Increasing the spacing between plants to form a 'medium-close' canopy (some ground visible) increased their transpiration/plant to about 80% of that of isolated plants.

It is difficult to ascertain the rate of transpiration per unit foliar surface area (A) of saltcedar plants because of problems of accurately measuring A of the feathery foliage. The most realistic determination of A for natural stands is by aerial photographic surveys, expressing A as area of land covered by the vegetation. However, it is difficult to correct for varying plant densities to accurately estimate leaf area index. An attempt to relate saltcedar transpiration per unit of land area with

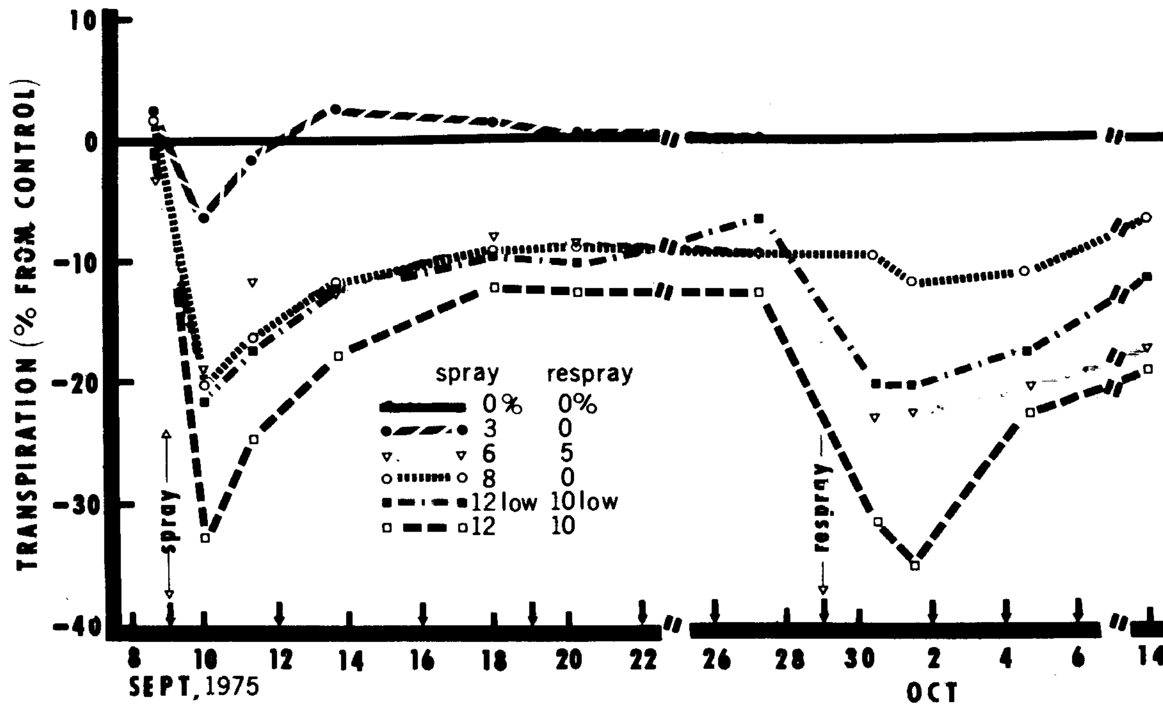

Figure 1. Effects on transpiration of saltcedar in 15-gal. drums of various dilutions of Folicote antitranspirant sprayed at 600 ml/plant or 300 ml/plant (low). (Small arrows show watering dates).

varying canopy densities was made in July, 1976, by grouping 100 drums of saltcedar into canopies (including some guard area around the experimental plants) with plant spacings of: 1) 0.4 x 0.4 m (very dense; no ground visible from above); 2) 0.8 x 0.8 m (moderately dense; some ground visible); 3) 1.6 x 1.6 m (sparse; much ground visible); and 4) isolated plants. The corresponding water use in kg/plant/day were: 1) 2.53; 2) 4.13; 3) 5.65; and 4) 5.73. However, when expressed per unit area of land, in gallons of water transpired/acre, the daily T rates for the three canopy densities were: 1) 16,894; 2) 6,906; and 3) 2,357. These were respectively equivalent to 1) 15.80; 2) 6.46; and 3) 2.21 mm water use/day. Thus, under the conditions of this experiment, in July at Davis, a moderately dense stand of saltcedar can use 6.5 mm/day (not unexpected), but at 4x this density water use can be more than doubled (Fig. 2).

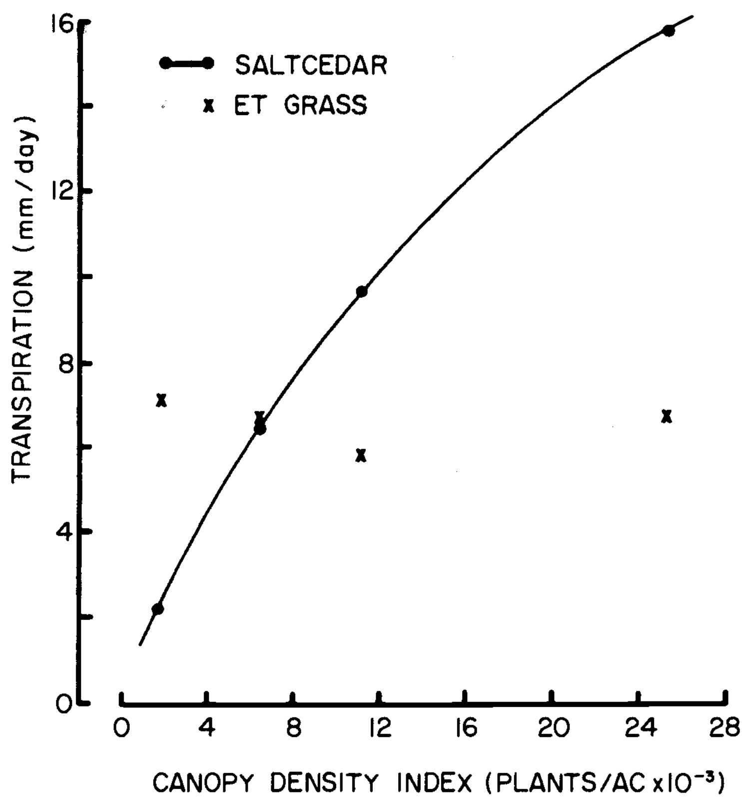

Fig. 2. Effect of density of saltcedar canopy on its transpiration rate. Evapotranspiration rates from a lysimeter of mown grass, measured on the same dates as saltcedar transpiration, are shown for comparison. (The canopy density index is for saltcedar plants of 15-gallon drum size).

Although the isolated plant studies provide a convenient means of assessing percentage transpiration reductions due to AT, the actual magnitudes of transpiration could be less than those estimated for isolated plants. Furthermore, the amount of AT spray coverage on an isolated plant, accessible from all sides, is likely to be greater than on plants in close canopies which are accessible mainly from above. However, for a plant in a dense canopy sprayed from above, most of a given volume of spray would be concentrated in the upper section of the plant where the highest rates of transpiration occur. We therefore attempted to determine if spraying AT from above (simulated aerial spray) on the top canopy only of a moderately dense stand of saltcedar (growing in a group of 15-gallon drums) was as effective as spraying each plant completely. Transpiration reduction by 10% Folicote was initially about 40% for the fully sprayed, and 30% for the top sprayed, plants (Table 3). After a week the reduction in both cases was about 23%. However, since the top spraying required about 40% less AT than the full application, the amount of water saved per unit of AT spray applied could be 30-70% more efficient for an aerial spray covering the upper portion of a moderately dense saltcedar canopy than for a spray operation aimed at coverage of the entire canopy.

Table 3. Water savings by 10% Folicote antitranspirant ('AT') on saltcedar when spraying the plant completely (Full) at 0.7 liters/plant, or from above on only the upper canopy (Top) at 0.4 liters/plant. (Davis, '76).

Water saved by 'AT'	8/31-9/2		9/2-3		9/8-9	
	Full	Top	Full	Top	Full	Top
% transpiration reduction	41	33	39	30	23	22
kg water saved/plant	2.03	1.64	0.89	0.67	0.41	0.40
kg water saved/liter 'AT' sprayed/plant	2.90	4.10	1.27	1.68	0.59	1.00

WATER STRESS AND STOMATAL CLOSURE IN SALTCEDAR

Although saltcedars can consume large quantities of water, van Hylckama (1970) pointed out that they do not always transpire at the potential rate. We noted in summer at Davis that diffusive resistance (measured by a porometer) of saltcedar foliage tended to increase in the afternoons, especially as soil moisture becomes more deficient. Stress in the 15-gal. drums was easily induced by withholding irrigation. Thus, after 4 days without irrigation, the transpiration rates had decreased by 75-80%, and the rate in the afternoon was 12% less than in the morning because of stomatal closure (Table 4).

Table 4. Saltcedar transpiration rate changes with time. (Davis, '76).

Days since irrig.	Late A.M.			P.M.			Rel.Transp. (PM/AM x 100)
	Time	Temp. °C	Transp. g/hr/pl.	Time	Temp. °C	Transp. g/hr/pl.	%
1	1100	31	529	1430	37	617	117
2	1200	30	408	1530	29	406	99
3	1100	25	259	1330	27	234	90
4	1200	27	154	1530	29	135	88

Porometer measurements on saltcedar indicated incomplete stomatal closure at night. However, nocturnal transpiration was only 10% of the daytime rate. Reduction of transpiration at night by the AT is therefore of little consequence. AT effectiveness was noted to increase with: 1) a higher ratio of day-to-night hours; and 2) when soil water was not limiting. Therefore, AT spraying is expected to be most effective when it is most needed for reducing water loss, i.e., on long summer days in riparian areas where groundwater is always available for transpiration. Furthermore, since transpiration transmits pure water to the atmosphere, curtailment of this loss by an AT should improve the quality of ground- and stream-water. The importance of this effect will vary with local conditions and is yet to be evaluated.

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STATISTICAL MODELS AND METHODS FOR RIVERS IN THE SOUTHWEST

by

Sidney Yakowitz

ABSTRACT

Riverflow modeling is believed useful for purposes of decision making with respect to reservoir control, irrigation planning, and flood forecasting and design of structures to contain floods. This author holds the view that present riverflow models in vogue are unsatisfactory because, for one thing, sample simulations according to these models do not resemble observed southwestern river records. The purpose of this paper is to outline a general Markov model which assumes only that rivers have a finite memory. We show how to calibrate the model from river records and then present evidence to support our contention that some success has been realized in mimicking typical flows by our simulation procedure.

REVIEW OF STATUS OF STREAMFLOW MODELING

The objective in streamflow modeling is as follows. A sequence $\{X_i\}_{i=1}^{n}$ of measured daily flows of a particular river at a particular gauging station is presented. The hydrologist is required to provide some model and calibrate this model by statistical analysis of the record $\{X_i\}$. This model should be successful in duplicating certain salient features of the recorded streamflow. Of course, the choice of features to be preserved in the simulated record depends on the decision problem for which the river flow analysis is ultimately to be used.

In Figure 1, we have presented a connected plot of a USGS record of a representative three years of flow at a certain station on the Cheyenne River. This sporadic behavior of no flow interrupted by bursts of flow is characteristic of many rivers in the southwest. Currently, the most popular streamflow models discussed in the literature are autoregressive moving average (ARMA) models. Such models are elaborately discussed in the monograph by Fiering (1967) and also in the papers by Jackson (1975a and 1975b), Weiss (1977), Kottegoda (1972), Ven Te Chow and Kareliotis (1970), and Mejia and Rodrigues-Iturbe (1974), to mention but a few of the many works on this subject.

An ARMA model for streamflow $\{X_i\}$ is characterized by the stochastic difference equation

$$X_{i+1} = \sum_{i=0}^{N} a_i X_{n-i} + \sum_{j=0}^{M} b_j U_{n-j} \tag{1}$$

where the U_j's are independent, identically distributed random variables. (Sometimes the U_j's have different distributions according to the season in which day j falls, but this adaptation is not essential to the comments to follow.)

There are several drawbacks to using the ARMA model for modeling streamflows in the southwest, as this investigator has discussed in Yakowitz (1972) and (1973). First, if the noise input $\{U_j\}$ is assumed Gaussian (or even nonzero with probability 1), either the flows will never be identically zero, or else negative flows will be possible. On the other hand, if the U_j's have high probability of being zero, so that decays to zero flow are possible, then for any stable linear difference equation of the form (1), the decay will be exponential; that is,

$$X_n \approx \lambda^{n-N} X_N$$

where λ is the largest (in modulus) root of the polynomial associated with the homogeneous version of the difference equation (1) and N is the last day of positive input U_i. But examination of records shows that southwestern rivers tend to die away faster

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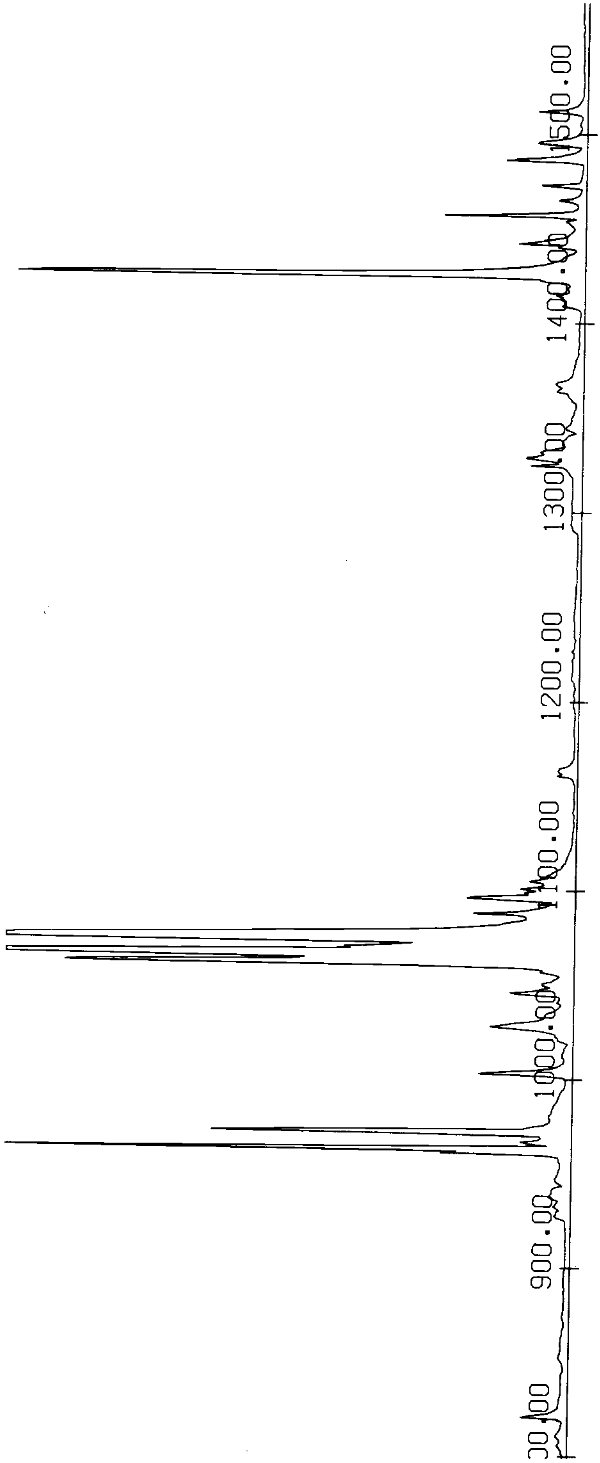

Figure 1. Record of the Cheyenne River

than exponentially during dry periods. Secondly, according to the ARMA models (1), if dry periods are possible, the episodes of flow in the model must be evenly distributed along the time axis (because the U_i's must be independent) whereas characteristically, southwestern rivers exhibit bursts of activity associated with several consecutive days of precipitation.

Another point is that there is no physical reason to think that streamflow satisfies the linear difference equation (1), since channel flow equations themselves are nonlinear differential equations and thus lead to nonlinear difference equations. We mention in passing that the broken line process (e.g., Mandelbrot, 1972) and the Markov-ARMA model of Jackson (1975a,b) are also subject to the above-listed limitations.

As a consequence of these ideas, this investigator has been casting around for alternative models which are more inclusive and yet computationally manageable. One type of model which circumvented the above drawbacks was described in Yakowitz (1973), but it must be admitted that statistical analysis required by this model was somewhat sophisticated and this model also had some arbitrary elements. In the next section, we describe what we feel is a promising and general approach toward overcoming the limitations inherent in current models.

A GENERAL STREAMFLOW MODEL AND A STATISTICAL PROCEDURE

We make the assumption that the streamflow process $\{X_i\}$ is a Markov chain of known order r. That is, for every integer n and for every vector $\underline{X}_n = (X_n,\ldots,X_{n-r+1})$, and every event A,

$$P[X_{n+1} \in A | X_j,\ j \leq n] = P[X_{n+1} \in A | \underline{X}_n]. \tag{2}$$

It may be demonstrated that the ARMA process (1) is a particular type of Markov chain of order $r < M + N$, but it is evident that there are many Markov chains which are not representable as ARMA processes. The papers by Denny, Kisiel, and Yakowitz (1974), Yakowitz and Denny (1973), and Yakowitz (1976) are addressed to the problem of inferring the Markov order from streamflow records. The initial state $\underline{X}_r$ having been specified, the probabilistic behavior of a Markov chain is completely determined by the transition probability function $F(y|\underline{X})$ where

$$F(y|\underline{X}) = P[X_{n+1} \leq y | X_n = \underline{X}].$$

In principle, the task of statistically inferring $F(y|\underline{X})$ from the observed streamflow record $\{X_i\}$ would seem impossible because there is an uncountable infinitude of distribution functions F to approximate, one for each possible r-tuple $\underline{X}$. But we have discovered a rule which gives a good approximation for modest size samples and, as proven in Yakowitz (1977), has the property that as the record length n increases, provided only that $F(y|\underline{X})$ is continuous in $\underline{X}$, if $F_n(y|\underline{X})$ is constructed according to the algorithm given below, for every y and every possible* r-tuple $\underline{X}$,

$$F_n(y|\underline{X}) \overset{n}{\to} F(y|\underline{X}).$$

ALGORITHM FOR APPROXIMATION OF TRANSITION FUNCTION

Assume the record length n and the record $\{X_i\}_{i=1}^{n}$ is specified.

STEP 1

Choose some representative set $\mathcal{Y} = \{\underline{Y}_1,\ldots,\underline{Y}_M\}$ of vectors (r-tuples). They should be chosen so that $M \simeq \sqrt{n}$, and so that they are placed as well as possible to lie "close" to r-tuples characteristic of the record. We used the K-means algorithm for cluster analysis to choose these vectors. (See Hartigan, <u>Clustering Algorithms</u>, 1975, for details.)

STEP 2

For each j, $1 \leq j \leq M$, partition the flows into sets S_j, where

$$S_j = \{X_{i+1}:\ ||\underline{X}_i - \underline{Y}_j|| \leq ||\underline{X}_i - \underline{Y}_k||,\ 1 \leq k \leq M\}$$

In words, S_j is composed of the flows that come after the states which are closer to $\underline{Y}_j$ than any of the other representative vectors

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*Excludes vectors having negative components and components greater than the capacity of the river banks, <u>etc</u>.

STEP 3

Use any standard method of statistics to infer a cumulative distribution function $F_n(y|\underline{Y}^j)$ from the numbers in S_j, $1 \leq j \leq M$.

STEP 4

For any x and y, we approximate $F(y|\underline{X})$ by $F_n(y|\underline{Y}^*)$, where $\underline{Y}^*$ is defined to be the representative vector in $\mathcal{Y}$ which is closest to $\underline{X}$.

It would seem reasonable that under the continuity condition for $F(y|\underline{X})$, as the size of the sample increases and consequently, the set $\mathcal{Y}$ of representative vectors become more numerous in the set of all possible vectors, that the asserted convergence takes place. This mathematical fact is proven in Yakowitz (1977). The author is preparing a paper for a hydrology journal which describes this algorithm in greater detail and discusses hydrological ramifications and simulation results more fully.

In Figure 2, we present the simulated graph obtained by applying 30 years of daily record (divided into two annual seasons) into the transition function algorithm just described. The plots were obtained by computer simulation of the Markov chain using the inferred transition function $F_n(y|\underline{X})$.

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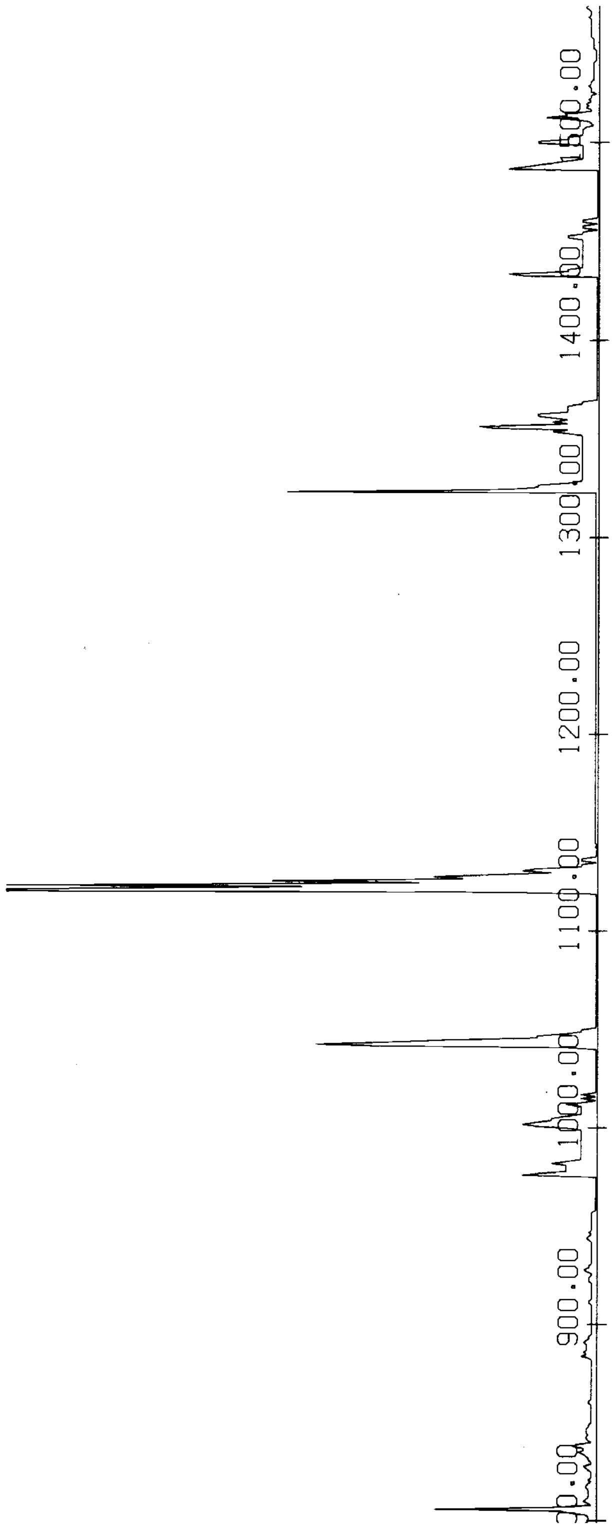

Figure 2. Simulated Record of the Cheyenne River

HYDROLOGY AND WATER RESOURCES IN ARIZONA AND THE SOUTHWEST, VOLUME 7, p. 153-162

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SIMULATION OF SUMMER RAINFALL OCCURRENCE IN ARIZONA AND NEW MEXICO

by

Herbert B. Osborn and Donald Ross Davis

INTRODUCTION

Thunderstorms produce most of the annual rainfall and almost all runoff from arid and semiarid rangelands in the Southwest. Thunderstorms also produce major flood peaks from small (100-square miles) watersheds in the Southwest. Therefore, developing models that can be used for predicting runoff in river basins, for flood plane zonings, and for estimating flood damage, is important to engineering design, particularly in regions where thunderstorms are a significant portion of the rainfall and runoff. Such models also provide basis for estimating erosion and sediment transport, as well as estimating precipitation available for forage growth.

Osborn, Lane and Kagan (1974) used records from 95 recording rain gages on the 58-square-mile U. S. Department of Agriculture Walnut Gulch Experimental Watershed in southeastern Arizona to develop a simplified stochastic model for air-mass thunderstorm rainfall. Osborn, Mills, and Lane (1972) used the thunderstorm rainfall model and a previously developed rainfall-runoff relationship (Osborn and Laursen, 1973) to predict runoff from Walnut Gulch, and reported the resulting accuracy and certainty of the output.

A regional model based on Walnut Gulch and Alamogordo Creek air-mass thunderstorm rainfall models, Agricultural Research Service (ARS) and National Weather Service (NWS) 24-hour rain gage records in Arizona and New Mexico, and the NWS climatological data for the Southwest is being developed. The regional model includes a prediction model for thunderstorm rainfall at a point which is based on daily point rainfall occurrence probabilities (> 0.01 inch) from 15 years of records from 15 NWS 24-hour recording and 7 standard rain gages in Arizona and New Mexico (Figure 1).

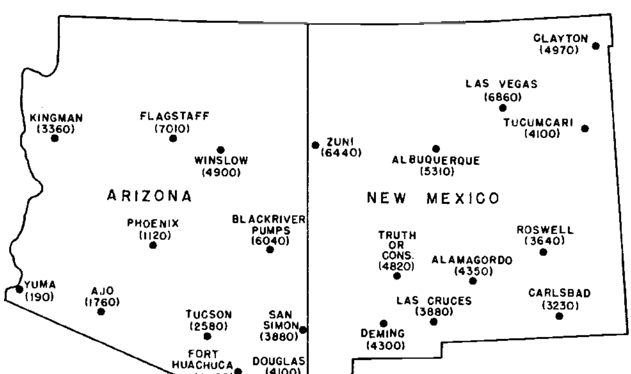

Fig. 1. Location and elevation of 22 selected NWS rain gages in Arizona and New Mexico.

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The 15 stations with recording rain gages were chosen primarily for continuity of record and thunderstorm identification. Using 15 years of record (1958-1972) for evaluation seemed to be a good balance between fewer stations with longer records, and more stations with shorter records. The 7 stations with standard gages were chosen primarily to fill gaps in the 15-gage network.

PREDICTION OF RAINFALL OCCURRENCE

There are significant differences in thunderstorm rainfall in different regions of Arizona and New Mexico which complicate such a model (Petterson, 1969, pp. 130-131; Osborn, 1971). In southeastern Arizona, for example, most thunderstorms can be classified as air-mass. Thus, the Walnut Gulch air-mass thunderstorm model is based on this simplifying assumption, whereas in eastern New Mexico, for example, frontal activity is an important consideration in estimating rainfall from summer thunderstorms. In the higher mountains of northern and central Arizona and New Mexico, low intensity winter rain and snow are a more important source of precipitation than are summer thunderstorms, although thunderstorms still produce a significant amount of rainfall.

The proposed rainfall occurrence model has three parameters: elevation, latitude, and longitude. We used these parameters because they could be identified at any location, as opposed to trying to fit known rainfall distributions at certain locations with one, or a combination of mathematical distributions that are assumed to represent subregions as well as the specific point.

RAINFALL OCCURRENCE

In developing the model, the 22 stations were considered representative of their geographic and topographic locations. However, most of the stations are located in or near cities, and not for geographic or climatological considerations. The stations ranged from near sea level (Yuna) to over 6,000 feet (Flagstaff and Las Vegas), from northern Arizona and New Mexico (Flagstaff, Winslow, Albuquerque, and Las Vegas) to southern Arizona and New Mexico (Yuma, Douglas, Las Cruces and Carlsbad). For example, smoothed curves for average daily point rainfall probability at Douglas, Flagstaff, Tucson, and Phoenix, in Arizona, and Albuquerque, Las Cruces, Roswell, and Tucumcari, in New Mexico, illustrate both the similarities and differences in summer rainfall in the Southwest (Figures 2 and 3). The curves are the accumulation of events which may result from one or more of several atmospheric conditions. The conditions are extremely simplified in the model to represent moisture flows into Arizona from the Southwest (SW), the "monsoon" season when moisture flows into the Southeast from the Gulf of Mexico (SE), and frontal (continental) storms pushing into Arizona and New Mexico from the north and west.

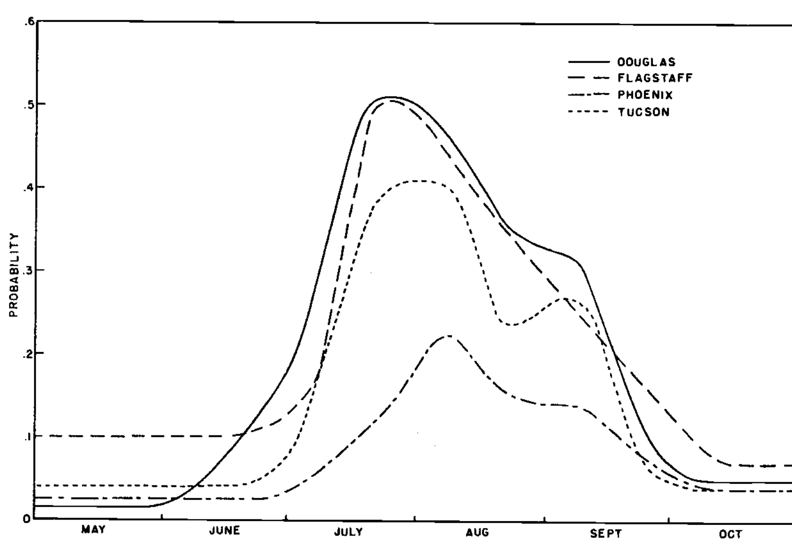


Fig. 2. Average seasonal rainfall probabilities for selected Arizona NWS rain gages.

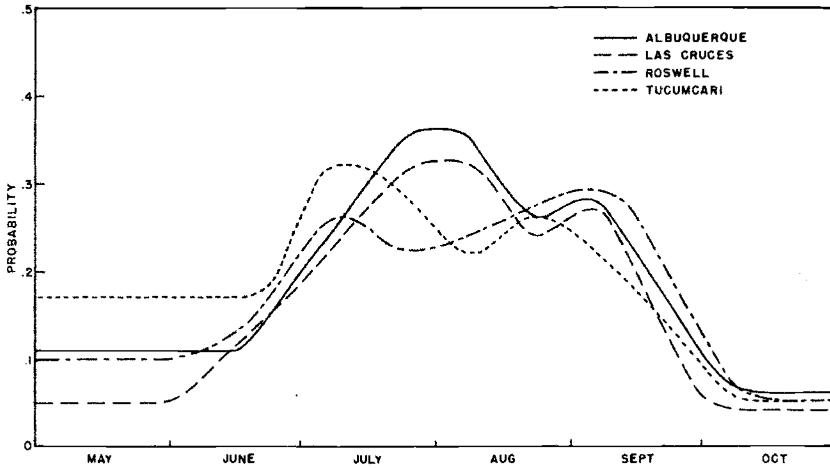
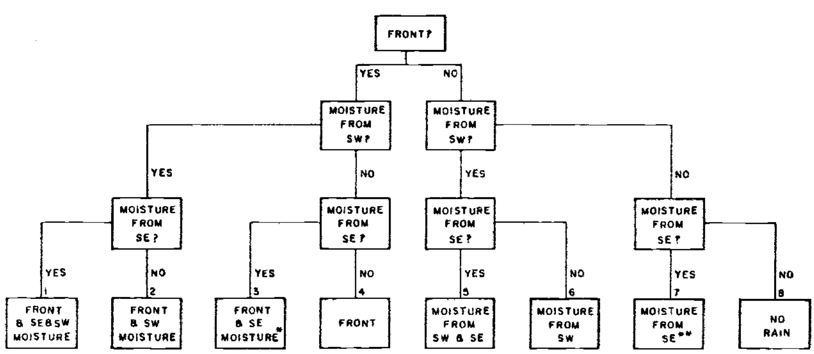


Fig. 3. Average seasonal rainfall probabilities for selected New Mexico NWS rain gages.

The model is an effort to follow, with simplifying assumptions, what actually happens, physically, to produce rainfall in Arizona and New Mexico. A flow diagram (Figure 4) follows through a logical sequence in determining if rainfall occurs. As already mentioned, the magnitude and areal extent of predicted events are based on stochastic models of thunderstorm rainfall developed from records from the Walnut Gulch and Alamogordo Creek Watersheds.



* AREAL RAINFALL GENERATED WITH ALAMAGORDO CREEK THUNDERSTORM RAINFALL MODEL.

** AREAL RAINFALL GENERATED WITH WALNUT GULCH AIR-MASS THUNDERSTORM RAINFALL MODEL.

Fig. 4. Simplified schematic diagram of summer rainfall occurrence in Arizona and New Mexico.

All probabilities for each of the three systems are determined independently, as indicated in Figure 4, and the "combination" events are assumed to represent the less frequent, exceptional storms that occur in the Southwest.

FRONTAL RAINFALL OCCURRENCE

Frontal rainfall frequency from May through September was assumed constant over time at any specific location. Based on trial and error, the probability of occurrence of frontal rainfall on day n, $P_F(n)$, assuming no frontal rainfall on the previous day, was expressed by the equation:

$$P_F(n) = .12 + .008\ (103-\ell_o),- 0.012\ (37-\ell_\alpha),\ P_F(n) \geq 0, \tag{1}$$

where ℓ_o = longitude in degrees, and

ℓ_α = latitude in degrees.

The approximate limits in the equation are:

$103^o < \ell_o < 114^o$

$31^o < \ell_\alpha < 37^o$

Once frontal rain occurs, the system tends to persist. Continued rainfall from the system seems highly correlated with elevation, whereas the initial occurrence of frontal rainfall is most highly correlated with latitude, as well as significantly correlated with longitude.

If frontal rainfall was predicted on day n, the chance of rainfall on day n+1, $P_F(n)$, was given by the equation:

$$P_F(n+1) = P_F(n)\ \frac{h}{1000}$$

where $P_F(n+1) \leq 0.75$, and h = elevation in feet ($1000^{ft} < h < 8000^{ft}$).

Also, $P_F(n+2) = P_F(\underline{n+1})$; $P_F(n+3) = P_F(n+2)$, etc. (2)

SW RAINFALL OCCURRENCE

From May through September, the average probability of SW rainfall at any location was assumed constant over time. SW rainfall occurrence decreases with latitude and increases with longitude and elevation. The probability of occurrence of SW rainfall on day n, $P_{sw}(n)$, assuming no SW rainfall on the previous day, was given by:

$$P_{sw}(n) = .08 + .00001\ h + .01(31-\ell_\alpha) - .01\ (114-\ell_o), \tag{3}$$

$$P_{sw}(n) \geq 0.$$

Once SW rainfall occurs, there is a much greater chance of rainfall the next day. This persistence is highly correlated with elevation, suggesting that the system, although present over a wide region, may be too weak or lack the moisture to produce rainfall at lower elevations. If rain was predicted on day n, the chance of rain on day n+1, $P_{sw}(n+1)$ was given as:

$$P_{sw}(n+1) = P_{sw}(n)\ \frac{h}{1000}$$

where

$$P_{sw}(n+1) \leq 0.65.$$

Also,

$$P_{sw}(n+2) = P_{sw}(n+1);\ P_{sw}(n+3) = P_{sw}(n+2),\ \text{etc.} \tag{4}$$

Once no rain is predicted, the program returns to $P_{sw}(n)$.

COMBINED FRONTAL AND SW RAINFALL

If both frontal and SW rainfall were predicted on the same day, a much greater chance of rainfall occurring was assumed on the following day. Assuming F and SW are independent, both frontal and SW rain have been predicted on day n, $P_{F+SW}(n+1)$ was given by:

$$P_{F+SW}(N+1) = P_F(n+1) + P_{SW}(n+1) - P_F\ (n+1) \times P_{SW}\ (n+1) \tag{5}$$

where $P_{F+SW}(n+1) \leq 0.85$

also $P_{F+SW}(n+2) = P_{F+SW}(n+1)$, etc.

As before, once no rain is predicted, the program returns to $P_F(n)$ and $P_{SW}(n)$.

SE EVENTS

Approximate values for the occurrence of air-mass thunderstorm rainfall were developed by subtracting estimates of frontal and SE events from all summer rains. The resulting curves indicated three distinct subregions within Arizona and New Mexico with different air-mass thunderstorm frequency characteristics (Figures 5 and 6).

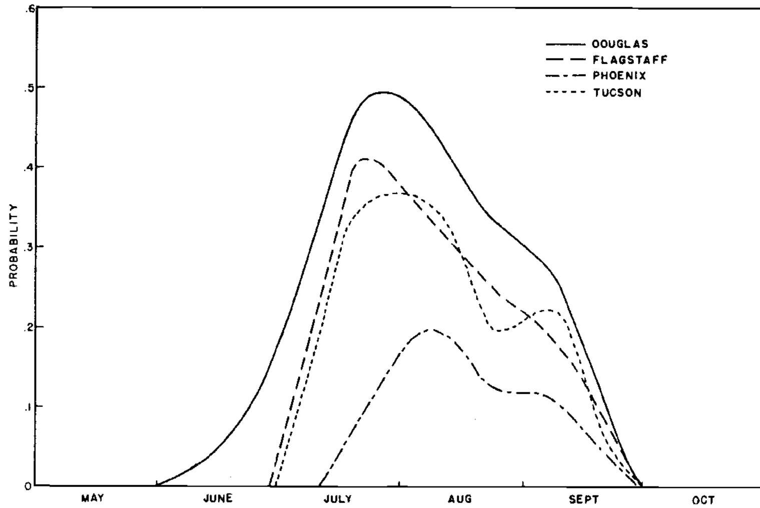


Fig. 5. Average seasonal air-mass thunderstorm rainfall probabilities for selected Arizona NWS rain gages.

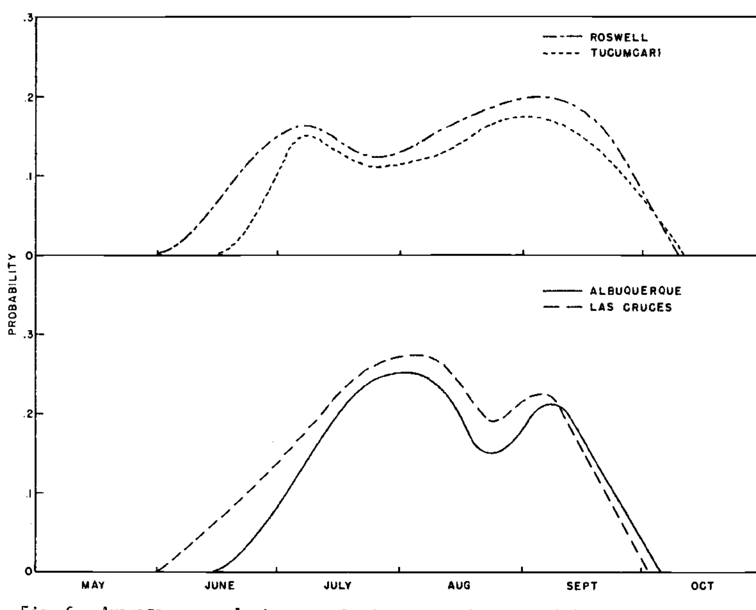


Fig. 6. Average seasonal air-mass thunderstorm rainfall probabilities for selected New Mexico NWS rain gages.

Region I - Eastern New Mexico

Region II - The Rio Grande Valley, western New Mexico, and the upper Gila and Little Colorado River Basins

Region III - The remainder of Arizona

Roswell, Las Cruces, and Douglas were chosen as the base stations for Regions I, II, and III, respectively, to predict air-mass thunderstorm rains primarily because of their location and their good records.

Although a Bernoulli random variable adequately described the occurrence of air-mass thunderstorm rainfall during the peak of the season, a second variable was needed to predict the beginning of the season. The beginning date for the "monsoon" season (SE) was generated using a random variable normally distributed around June 22 for Roswell, June 15 for Las Cruces, and July 3 for Douglas (dates were estimated from NWS data). For the first two regions, 4 days are added to the mean of the normal distribution for every added degree of latitude. For Region III, 2 days were added for each degree of longitude, as well as 4 days for each degree of latitude, and 3 days were subtracted for each 1,000 feet elevation. These values were estimated by trial and error based on NWS data.

Occurrence of air-mass thunderstorm rainfall was determined using frequency curves from the 8 stations (Figures 5 and 6), and adjusting the curves according to the latitude and elevation at the desired location. Occurrences increase with elevation and decrease with latitude in all three regions. The basic equation was

$$P_{SE}(n) \text{ at location} = P_{SE}(n) \text{ at base station} \times R, \tag{6}$$

where $P_{SE}(n)$ = the probability of air-mass thunderstorm rainfall occurring on a given day, and

R = the ratio between probabilities at the given location and the base station.

The multiplier, R, for a given location was determined from the following set of equations. The equations varied only in the base latitudes and elevations for each region (which are for the base stations at Roswell, Las Cruces, and Douglas).

$$\text{Region I} \quad - R_1 = 1 + .14\ (33.4 - \ell_\alpha) - .10\ (\frac{3640-h}{1000}) \tag{7}$$

$$\text{Region II} \quad - R_2 = 1 + .14\ (32.4 - \ell_\alpha \quad - .10\ (\frac{3880-h}{1000}) \tag{8}$$

$$\text{Region III} - R_3 = 1 + .14\ (31.5 - \ell_\alpha) - .10\ (\frac{4100-h}{1000}) \tag{9}$$

where $1000^{ft} < h < 8000^{ft}$. The equations were determined primarily from estimates of July-August air-mass thunderstorm rainfall. Since the estimates were inexact, statistical correlation between the estimated and predicted values would be misleading.

EVALUATION

The model was based on location parameters with an effort to explain the storm systems, but we made no attempt to rigorously define these systems. Such terms as "frontal occurrence," "southwest moisture," "southeast moisture" are used as general support for a three-component prediction model, based on one topographic and two geographic parameters. Rigorous definitions of these terms and the rainfall associated with them would be too complex to use in a regional model. The model was developed to predict rainfall occurrence, with an effort to relate the equations logically to the meteorology of the Southwest. The model has a Markovian feature, since rainfall occurrence on any day depends on whether or not it rained on the previous day.

However, the principal assumptions that were made and the rules that were possibly violated with these assumptions should be discussed. The equations purportedly relate to frontal systems, flow of moist air into Arizona and New Mexico from the southeast and southwest, the coexistence of these systems, and their persistence. Among the principal assumptions are:

(1) Frontal rains (or rains from frontal systems) can be assumed random from May through September.

(2) SW rains (rainfall occurring from moisture pushed into Arizona and New Mexico from tropical storms in the Pacific) can be assumed random from May through September.

(3) Persistence of either frontal systems or SW moisture is highly dependent on elevation.

(4) SE rainfall can be predicted by a seasonal Bernoulli random variable based on probabilities from a base station in each of three designated subregions.

(5) Any two, or all three, systems can occur simultaneously to produce rainfall events.

In the western United States, frontal systems tend to move further south in the winter. However, based on NWS weather maps, frontal systems are still fairly frequent in the Southwest in the summer, particularly in the northern regions of the southwest. Because of the low probabilities, it is difficult to determine a meaningful distribution for summer frontal occurrence other than the constant probabilities assumed in the model.

There is even less information on the effects of Pacific tropical storms on rainfall in the southwest. However, more recently, satellites have provided better definition of these storms, and some estimate of occurrences, other than the constant probability in the model, might be used to estimate the variability of summer rainfall occurrence in time.

The high correlation between rainfall persistence and elevation is probably primarily a question of whether or not rainfall can reach the ground at stations at lower elevations. The system persists independently of elevation, even though the rainfall is correlated with elevation.

The question of persistence of SE rainfall will be discussed in a later section.

Actually, the three systems normally do not develop independently (See any text on Meteorology.). Moist air moves into the Southwest from the Gulf of Mexico and/or the Pacific after the prevailing path of frontal systems has moved northward. However, NWS weather maps do suggest the possibility of joint occurrence of such systems, although the probabilities and results of such occurrences are uncertain. A mixture of SE and SW moisture may be more common in the Southwest, although identifying the differences in results may be even more difficult.

The 22 stations used in developing the model were considered representative of their geographic and topographic location. However, there may be anomolies in Arizona and New Mexico that are not explained by the model. For example, annual and seasonal rainfall differ considerably at the same elevations just southwest and northeast of the Mogollon Rim in central Arizona. Presently, there are insufficient data available to determine whether thunderstorm frequency also varies significantly from that predicted by the model.

ALL EVENTS

The average number of events in a season (N) was determined from 15 years of record at 22 rain gage locations in Arizona and New Mexico (Figure 1, Table 1). Through regression analysis using elevation, latitude, and longitude as independent input variables, we developed two equations. The first equation is:

$$E(N) = 196 + 0.00398h + 0.811\, \ell_\alpha - 1.99\, \ell_o, \qquad (10)$$

where R^2 = .87 and SEE = 2.65,

ℓ_α = latitude in degrees

ℓ_o = longitude in degrees

applies to Regions I and II, New Mexico and the upper Gila and Little Colorado River basins in Arizona.

The second equation is:

$$E(N) = 333 + 0.00467h - 3.11\, \ell_\alpha - 1.97\, \ell_o, \qquad (11)$$

where R^2 = .98 and SEE = 1.90,

applies to Region III, the remainder of Arizona. In general, observed and predicted values vary appreciably only at a few stations (Yuma, Winslow, Carlsbad, Las Cruces, and Zuni) out of the 22 used in the analysis (Table 1).

Estimates based on equation 11 were compared with a study of the effects of elevation on rainfall in the Catalina Mountains of southern Arizona (Duckstein et al., 1973; Battan and Green, 1971). Based on seven seasons of recording rain gage records in the Catalina Mountains, Duckstein et al. (1973) found that the number of events per season was strongly correlated with elevation as by:

$$E(N) = 12.44 + 3.12\, h, \qquad (12)$$

where R^2 = .88 and SEE = 2.15 and

where h = elevation in 1,000 feet.

For the seven seasons, there was an average of 23 events at the Tucson International Airport. For 15 years of record, there were 28 events, or roughly 20% more than were estimated from the shorter record. Other records in the vicinity also indicated a larger average number of events. When the average number of seasonal events were increased by 20%, equation 12 becomes

$$E(N) = 17 + 3.87\, h, \qquad (13)$$

and assuming one latitude and longitude for the Catalina Mountains, and h in thousands of feet, equation 11 becomes:

$$E(N) = 15 + 4.5\,h. \tag{14}$$

TABLE 1.

Average number of observed and predicted rainy days, June through September, for 22 selected stations in Arizona and New Mexico.

Station	Elev. (ft)	Long. (°)	Lat. (°)	Observed Rainy Days (N)	Predicted Rainy Days E(N)
Albuquerque	5310	106.6	35.0	32	33
Alamogordo	4350	106.0	32.9	30	29
Carlsbad	3230	104.3	32.3	22	27
Clayton	4970	103.1	36.4	41	40
Deming	4300	107.7	32.2	26	25
Las Cruces	3880	106.7	32.4	28	25
Las Vegas	6860	105.2	35.7	43	43
Roswell	3640	104.5	33.4	30	30
Truth or Conseq.	4820	107.3	33.2	27	29
Tucumcari	4050	103.6	35.2	34	35
Zuni	6440	108.8	35.1	31	34
San Simon	3880	109.1	32.2	24	20
Black River Pump	6040	109.8	33.5	30	29
Ajo	1760	112.9	32.4	17	18
Douglass	4100	109.6	31.5	36	38
Flagstaff	7000	111.7	35.1	36	36
Ft. Huachuca	4660	110.3	31.6	39	39
Kingman	3360	114.0	35.2	15	15
Phoenix	1120	112.0	33.4	14	14
Tucson	2580	110.9	32.1	28	27
Winslow	4900	110.7	35.0	26	29
Yuma	194	114.6	32.6	4	7

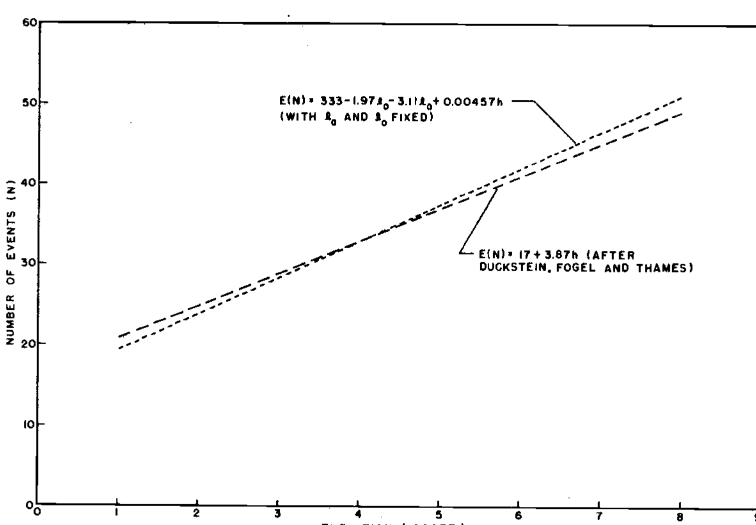


Fig. 7. Comparison of 2 equations for estimating the number of summer rains in the Catalina Mountains of southern Arizona.

The curves are similar (Figure 7), suggesting the equations developed from NWS stations may provide good estimates of summer rainfall occurrence in other mountainous regions of the Southwest, and not just for the populated "valleys."

Estimates of the number of seasonal occurrences can be used as a check of the equations within the rainfall occurrence model. For example, $P_{SE}(N)$ for any station can be estimated by subtracting $P_f(N)$ and $P_{SW}(N)$ from P(N) (Table 2). The resulting values for $P_{SE}(N)$ should equal average seasonal values predicted with equations 6, 7, 8, and 9.

TABLE 2.

Average frequency of storms/season for eight selected Arizona and New Mexico rain gage locations, June through September (events).

Station	E(N)	P(N)	P_fN	$P_{SW}N$	$P_{SE}N$
Douglas	36	.30	<.01	.02	.27
Flagstaff	36	.30	.04	.05	.21
Tucson	28	.23	<.01	.03	.19
Phoenix	14	.13	<<.01	.02	.12
Albuquerque	32	.26	.10	0	.16
Las Cruces	28	.23	.05	0	.18
Roswell	30	.25	.07	0	.18
Tucumcari	34	.28	.14	0	.14

PERSISTENCE

Several investigators have used Markov Chain models to predict point rainfall occurrence. Smith and Schreiber (1973) assumed all events were of the same population and successfully fitted daily rainfall occurrence at three stations in southeastern Arizona with a segmented first-order Markov Chain model. Woolhiser (1975) has proposed a three-parameter mixed-exponential Markov Chain model of daily rainfall, based primarily on data from the Great Plains area. Possibly this model, or a variation, could be adapted to the Southwest as a substitute for the more cumbersome empirical equations that are presented here.

Other investigators, like Allen and Haan (1975), have used Markov Chain models to fit rainfall distributions in the eastern United States, and some of these may have application in the Southwest.

Separate equations were developed in the model to account for persistence in frontal activity and moisture from the southwest. No persistence equation was included for moisture from the southeast.

Moisture from the southeast particularly dominates summer rainfall in southeastern Arizona (Figures 2 and 5). Osborn, Mills, and Lane (1973) modeled storm occurrence as a seasonal Bernoulli random variable, based on occurrence of storms of more than 0.2 inch on Walnut Gulch (located between Tucson and Douglas, Arizona). A comparison of 12 years of simulated and actual storms of 1 inch or greater on Walnut Gulch indicated that the occurrence of these larger (major runoff producing) events on Walnut Gulch on successive days were similar for simulated and actual data. Although there was no statistical difference in the persistence pattern for the major events between simulated and actual data, the model seemed to simulate greater persistence than the actual data. Therefore, since the principle purpose of the regional rainfall model is to simulate occurrences that can be used to predict runoff, the model does not include a persistence equation for southeast moisture.

SUMMARY

A regional model based on NWS and ARS precipitation and climatological data in the Southwest is being developed. The model includes independent outcome of 3 types of rainfall, as well as any combination of the 3 types. The model can be used to predict the occurrence of rainfall for engineering and watershed design purposes.

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DISTRIBUTION OF PRECIPITATION ON RUGGED TERRAIN IN CENTRAL ARIZONA

by

Alden R. Hibbert

ABSTRACT

A 3-year study was conducted using tilted, vertical, directional, and recording rain gages (52 in all) to evaluate rainfall distribution on the Three Bar experimental watersheds in central Arizona. The tilted gages did not improve the determination of mean areal precipitation on the small watersheds because about as many tilted gages caught less rain as caught more. Although rugged and steep, the local topography exerted only minor effects on rainfall distribution compared to the major influence exerted by the Mazatzal Mountains to the windward (southwest). Forty-nine percent of wind travel was from the southwest quarter and wind averaged 4.4 mph when rain was actually falling. Wind exceeded 10 mph 9 percent of the time and 15 mph 0.4 percent of the time. Mean annual precipitation on the 600-acre study area ranged from 30 inches at 5,000 feet elevation to 22 inches at 3,400 feet (5 inches per 1,000 feet). Results of this study indicate that precipitation averages about 36 inches at 6,200 feet elevation along the Mazatzal crest near Four Peaks, about 6 inches more than published data show for the site.

INTRODUCTION

A late winter storm in April, 1976 dropped about an inch of rain in the Phoenix area and 3 inches in Payson, some 75 miles to the northeast. Other official weather stations in the central Arizona highlands reported intermediate amounts. Elevation was an obvious factor, though not the only one, affecting the amounts received. Other less easily measured factors, such as wind blowing over uneven terrain, can materially alter the distribution of rain and snow in mountain areas. An example of how rainfall can vary on steep terrain is available for the April storm on the Three Bar experimental watersheds, located roughly midway between Phoenix and Payson on the northeast slopes of the Mazatzal Mountains near Four Peaks. Rainfall varied from 3.41 inches at 3,300 feet elevation to 4.14 inches at 5,150 feet elevation, the upper gage catching 21 percent more rain than the lower gage. The gages are 1.6 miles apart.

Most reporting stations in the central highlands at elevations similar to or higher than Three Bar caught much less rainfall. The Three Bar area appears to be one of the wettest places gaged in Arizona within the elevation range of 3,300 to 5,200 feet. Mean annual precipitation ranges from 22 inches at 3,400 feet to 30 inches at 5,000 feet elevation.

Mountainous terrain presents special problems in measurement of precipitation. Many gages would be required, often in inaccessible sites, to adequately sample the highly variable distribution patterns. For expediency, however, rain gages are often located along travel routes, and mountain tops are sometimes gaged where access is provided for other purposes. While these arrangements may be the only practical way to get estimates of precipitation in remote areas, the results can be misleading if the problems associated with the rainfall measurements are not taken into account. Mountain tops and prominent ridges make poor gaging sites because strong winds reduce gage catch. Gages in exposed sites can be fitted with shields to reduce wind effect, but shielding alone does not insure an accurate catch, especially of snow. Because of these deficiencies, the distribution of precipitation in rugged terrain is seldom well defined, and the amount received at high elevations is often underestimated.

Because of uncertainty about variability of precipitation on the Three Bar experimental watersheds, a dense network of rain gages was installed in 1968 to evaluate the distribution of rain on the steep slopes of these small catchments. The Three Bar study area is located between the Tonto arm of Roosevelt Lake and the Mazatzal Divide about 8

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miles to the southwest (fig. 1). Watershed management and game management research have been conducted by the U. S. Forest Service and Arizona Game and Fish Department in the area since the early 1950's.

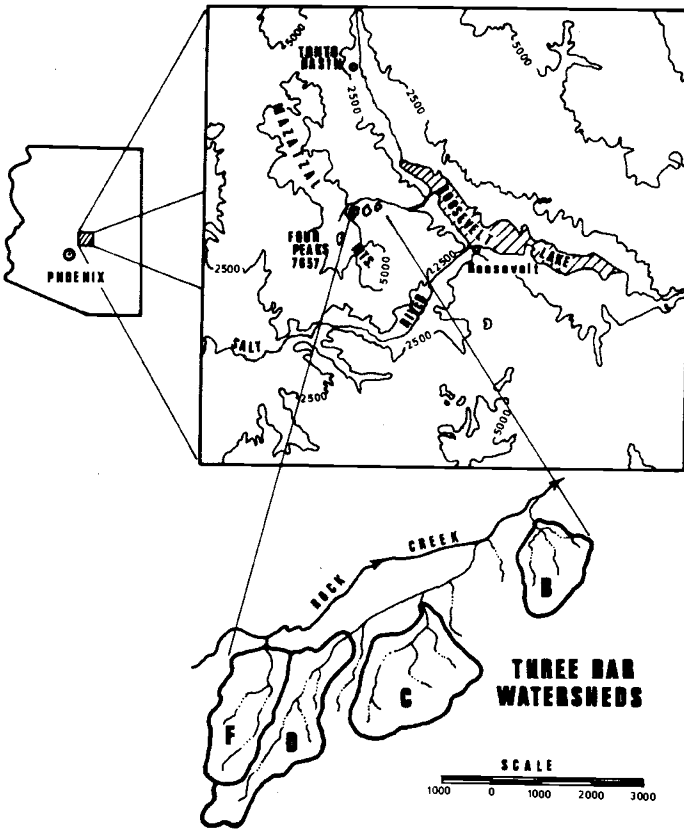

Figure 1. The Three Bar experimental watersheds lie on the eastern slopes of the Mazatzal Mountains between Four Peaks and Roosevelt Lake in central Arizona.

Four small chaparral-covered watersheds (46 to 95 acres) and intervening spaces comprise the study area of about 600 acres. The topography is steep and broken (fig.2). Extremes in elevation range from 3,300 feet on Watershed B to 5,250 feet on D. The distance between these points is 8,700 feet for an average gradient of 22 percent. Individual watersheds are even steeper; average gradients vary from 26 percent on C to 43 percent on F. Slopes are steepest in the upper portions of the watersheds, where they sometimes exceed 70 percent. There is a pronounced tendency for rainfall to increase with elevation. The catch at the top of Watershed D averages almost 40 percent greater than at the bottom of Watershed B.

PROCEDURES

A total of 52 precipitation gages at 27 locations were operated over a 3-year period to get the data used in this study. All gages had 8-inch-diameter orifices installed 3 to 4 feet above the ground (fig. 3) except where otherwise noted. Twenty-two of the gages were installed in the standard vertical position (orifice horizontal);

Figure 2. Chaparral covered Three Bar watersheds (B is out of sight to left) showing location of site C7/C6 and the climatic station near the stream gage.

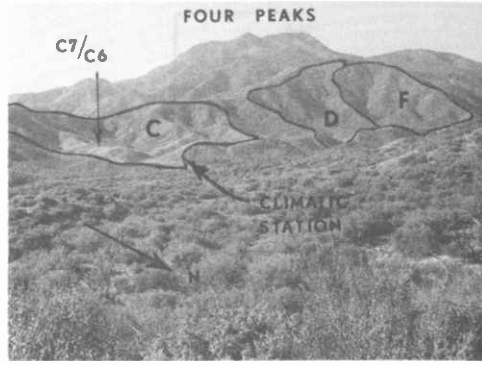

Figure 3. Instrumentation at site C7/C6 on intermediate ridge in lower, central watershed C. Instruments from left to right: vertical and tilted rain gages, wind direction indicator, shielded rain gage, directional rain gage (vectopluviometer) with cup anemometer mounted on top, and recording rain gage (weighing type). Both wind speed and direction were continuously recorded on a strip chart.

five of these were equipped with Alter wind shields designed to reduce distortion of catch caused by wind turbulence around the gage orifice. Three of the shielded gages were mounted on towers 6 to 10 feet high. Another 22 gages were installed so that they tilted normal (orifice parallel) to the slope of the hillside where they were located. Tilted and vertical gages were paired at 13 sites to evaluate differences in catch due to tilting. Directional rain gages (vectopluviometers) were installed at five of these sites to determine the direction of wind and inclination of rainfall, an index of wind speed. Recording rain gages were located at three sites to determine rainfall intensity. In addition, wind direction and speed were continuously recorded at the C7/C6 site in lower, central watershed C (figs. 2 & 3).

The watersheds were divided into facets (fig. 4) by visually selecting areas of relatively uniform slope and aspect on a detailed map with 10-foot contour intervals. Constraints on numbers of gages and difficulty of access in some areas resulted in fewer gages in portions of watersheds D and F than in C and B. Nine gages which had been installed years before were used even though their locations did not necessarily fit the prescription. A tilted gage was installed in each facet except at D-4 and at each of the four stream gaging sites. Each tilted gage was installed so that its direction and tilt were the same as the average aspect and slope of the facet in which it was placed. The aspect and slope were determined first from the contour map and later verified and modified as necessary from measurements taken in the field with hand-held abney level and compass.

Tilting the gage gives a more accurate measure of precipitation reaching the sloping hillside than does a vertical gage whenever wind causes rain drops to be inclined from the vertical (Hamilton 1954, Corbett 1967, Jackson and Aldridge 1972, and Sevruk 1974). The difference in catch between vertical and tilted gages depends on degree of tilt, wind direction, and wind velocity. Vertically falling rain is measured equally well by either gage, as is rain driven by wind at right angles to the direction of tilt. The actual catch of tilted gages must be corrected by dividing the catch by the cosine of the angle of tilt to account for reduction in orifice area (as projected to a horizontal surface) caused by tilting (Hamilton 1954).

The vectopluviometer is designed with four vertical orifices at right angles to each other, each facing a cardinal direction (fig. 3). Only inclined rainfall

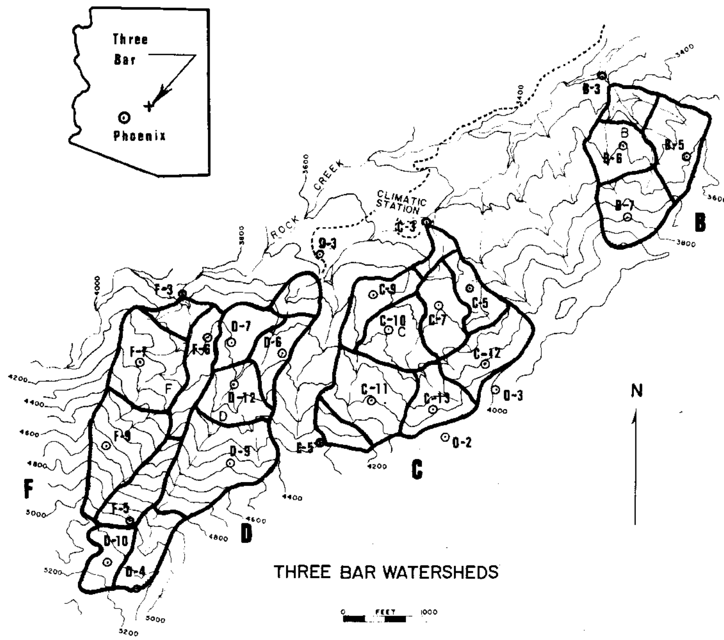

Figure 4. Refined facet breakdown with one tilted gage in each facet except that gages B-3, C-3, D-3, F-3, and D-4 are vertical only.

(horizontal component) can enter these orifices. Vertically falling rain must be caught in an adjacent, standard gage. The amount caught in each of the vectopluviometer openings is indicative of the direction and force of wind during rainfall. According to Hamilton (1954), average storm direction (ω) and angle of inclination of rain from the vertical (i) are found by

$$\omega = \text{arc tan } \frac{E - W}{N - S} \tag{1}$$

$$i = \text{arc tan } \frac{N - S}{R \cos \omega} \tag{2}$$

where N, E, S, W are component catches of vectopluviometer quadrants and R is catch of an adjacent vertical gage.

Gages were read at intervals of 1 week to 4 months. In all, 21 readings (observations) were made during the 3-year period (July 1968 - June 1971). Bears were particularly attracted to the gages in early spring, presumably because of the oil added to prevent evaporation. Damage by bears resulted in loss of about 7 percent of the data. Statistical analyses were made on uninterrupted data only. For other purposes, missing data were estimated by double-mass plottings or by a ratio method using nearby gages.

TILTED VERSUS VERTICAL GAGES

Of 13 pairs of gages, 5 tilted gages caught more rain than vertical gages, 4 caught less, and 4 showed no significant difference. Some of the gages did not perform as anticipated, based on their orientation with respect to the indicated prevailing wind. Since 10 of the gages tilted away from the prevailing wind (table 1 and fig. 5), their catches should have been less than vertical gages. However, three of them (O3, C12, C13) actually caught more rain and 3 others were not significantly different from vertical gages. The probable explanation is that wind was modified by local topography sufficiently to cause the observed differences in catch.

Only at the five sites with vectopluviometers (fig. 5) was it possible to demonstrate how wind affects the catch of tilted and vertical gages. The vectopluviometers at B5/B8 and O2/O1 (table 1) indicated that wind blew against the tilt (the gage tilted into the hemisphere from which the wind came), which caused them to catch more rain

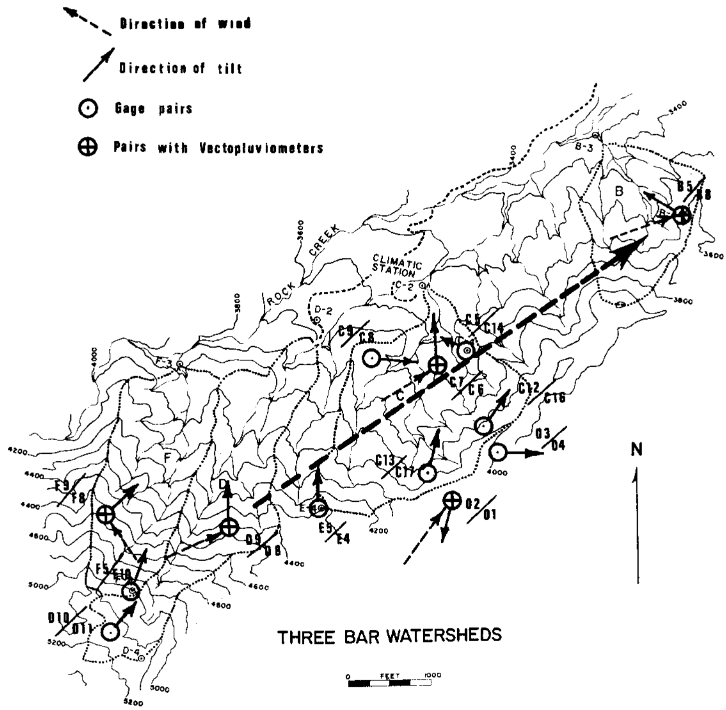

Figure 5. Solid arrows indicate direction of tilt for each of 13 pairs of gages. Broken arrows indicate direction of prevailing wind during rainfall at each of 5 sites with vectopluviometers. The large broken arrow indicates the weighted average direction obtained by combining all data from the five vectopluviometers.

than the vertical gages. The opposite was true at C7/C6 and D9/D8 where wind blew mostly with the tilt; these tilted gages caught less rain. The vectopluviometer at F9/F8 showed wind to be almost at right angles to the direction of tilt, and the catch difference at this site was not significant. Possibly, the lack of significance in the differences shown by the three other pairs of gages (C5/C14, F5/F10, D10/D11) may be explained in the same way. Tilted gages F5 and D10 at two of these sites face the same general direction and are immediately upslope from F9/F8. They could easily be affected by the same wind patterns observed at F9/F8.

It may be inferred from these results that tilted gages did not improve the determination of mean precipitation on the experimental watersheds, since about as many tilted gages caught less rain as caught more. For example, inclusion of 6 tilted gages (at paired-gage sites) had no significant effect on the estimate of total precipitation received on watershed C because 3 (C7, C9, E5) of the 6 tilted gages caught less rain while 2 (C12, C13) caught more rain (C5 was not significantly different) than adjacent vertical gages. Thus there was no advantage demonstrated by the tilted gages, except to illustrate how wind and topography can affect local distribution of precipitation within these small watersheds.

SHIELDED GAGES

Only one of the four shielded gages caught significantly more rain than its adjacent vertical gage. This gage (C15) was moderately exposed on an intermediate ridge at the C7/C6 site (figs. 2 & 3) where surrounding shrubs had been removed prior to the study. Without replication it is difficult to know if the combination of ridge exposure and lack of protective shrubs explain the higher catch by the shielded gage. However, because shields were designed to improve gage accuracy under conditions like these, it seems reasonable to assume that the shielded catch is the more accurate for the site. At the other less exposed sites, it appears that shields were not beneficial. Based on these limited results, shields should not be necessary where surrounding vegetation is at least as high as the gage orifice, and wind during rainfall is no greater than was found on these watersheds.

WIND DIRECTION AND INTENSITY

Wind prevailed from the southwest (fig. 6). By octants, 33 percent of total wind travel was from the southwest, 21 percent from the west, and 11 percent from the south. Nearly one-half (49%) of the wind was from the southwest quarter (180° - 270°). These wind measurements were made at the C7/C6 site (figs. 2 & 3), thought to be fairly representative of the watersheds generally. However, wind varies considerably because of local topography as illustrated by the following examples. Wind averaged 93 miles per day (3.9 mph) for 2 years at the C7/C6 site, but only 30 miles per day at the climatic station 1,000 feet to the north and 150 feet lower elevation near Rock Creek (fig. 2). The lower site is in a topographic depression and is partially protected by brush, while the upper site is moderately exposed on a grassy ridge. Also, a consistent diurnal pattern of wind movement prevailed most days on watershed C. Early morning wind is light and flows downslope, out of the south. About sunup the wind picks up and gradually switches direction until by midmorning it is moving upslope, out of the northeast. In the early afternoon the wind begins to shift back, and by midafternoon is out of the southwest. Here it remains until near midnight when speed diminishes and alters course slightly to be once more from the south.

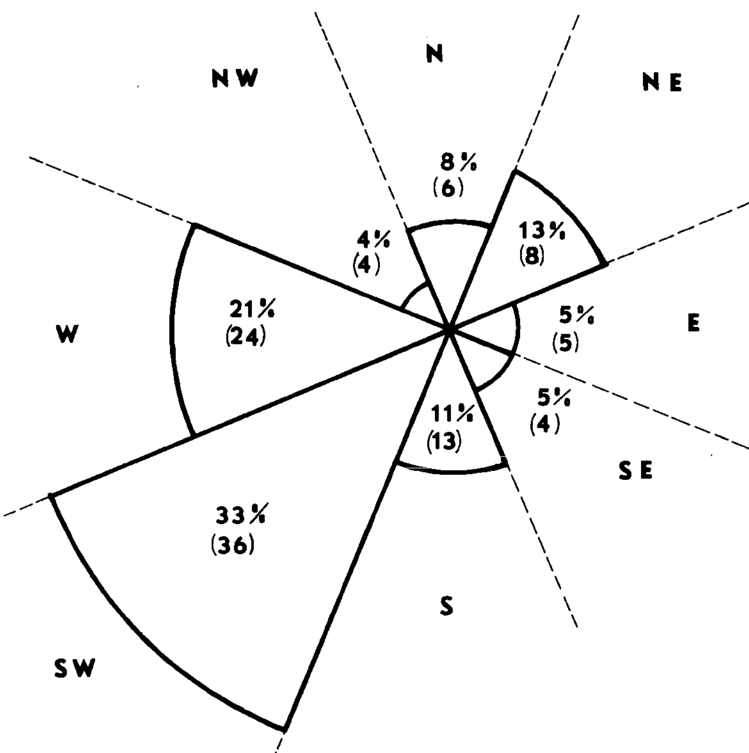

Figure 6. Wind prevailed from the west southwest. Numbers indicate percent of wind travel accounted for by each octant (parentheses indicate wind during rainfall).

To determine wind behavior during rainfall, 29 events were analyzed, including the heavy storm on Labor Day weekend 1970. During actual rainfall, wind direction was similar to non-rain periods, except that a greater percentage of the wind was from the southwest, west, and south octants (figures in parentheses in fig. 6). Also, average wind speed was slightly greater (13%) during rainfall than when it was not raining.

In the course of a year it actually rained less than 2 percent of the time, or about 25 minutes for each 24 hours on the average. The longest period of continuous rainfall was 21 hours, the shortest, a summer shower, 10 minutes. The longest rainless period lasted 67 days. The combined duration of the 29 rainfall events was 175 hours; during this time, 29 inches of rain fell, and wind averaged 4.4 mph. Wind exceeded 10 mph 9 percent of the time, and exceeded 15 mph 0.4 percent of the time. The higher wind speeds came during two summer convection storms when wind speed averaged 18.3 and 15.6 mph for 20 minutes each. Wind gusts were not analyzed separately, but no extremely high gusts were noticed while processing the records.

The 1970 Labor Day Weekend storm was considered a 100-year or greater event over much of central Arizona (Thorud and Ffolliott 1973). At the C7/C6 site, rainfall totaled 7.25 inches during 41 hours, which included some rainless intervals. Wind prevailed from the southwest during most of the storm, and averaged 5.8 mph during the 25 hours that rain was actually falling. The strongest winds occurred on the afternoon of the 5th and coincided with the most intense rainfall. Wind averaged 14 mph for 20 minutes while 0.63 inch of rain fell. A short time later, wind was equally strong for a full hour, although rain intensity had dropped to about one-third inch per hour.

Wind direction during rainfall (table 1) was also available from the vectopluviometers by use of equation 1. The mean wind direction indicated by the vectopluviometer at the C7/C6 site agreed very closely with the mean direction measured by the adjacent wind recorder. Wind at each of the five vectopluviometer sites (small broken arrows in fig. 5) was out of the southwest or west with the exception of the F9/F8 site on

Table 1. Direction and angle of tilt and mean difference in catch per observation between tilted (T) and vertical (V) gages arranged in order of increasing angle of tilt. Also included for sites with vectopluviometers are mean wind direction and mean inclination of falling rain.

Gage Pairs (T/V)	Aspect (Dir. of gage tilt)		Slope (Angle of gage tilt)		Mean difference in catch per observation		No. of observations	Level of Signif.	Mean[1/] Wind Dir. ($\bar{\omega}$)	Mean Inclination ($\bar{I}$)
	Deg. N. AZ	Octant	Deg.	%	Inches	% $\frac{100(T-V)}{V}$			Deg. N. AZ	Deg. from Vertical
C7/C6[2/]	355	N	11.3	20	-.11±.15	- 3.7	20	.01	58	20
C9/C8	97	E	12.4	22	-.08±.06	- 2.6	20	.001		
C5/C14[3/]	297	NW	16.7	30	.04±.15	1.7	20	ns		
D10/D11	42	NE	18.8	34	-.10±.25	- 2.7	18	ns		
B5/B8[2/][3/]	300	NW	23.3	43	.25±.25	10.4	21	.001	73	20
02/01[2/][3/]	195	S	25.2	47	.17±.17	6.2	15	.01	38	12
E5/E4	356	N	25.2	47	-.27±.03	- 6.9	18	.01		
D9/D8[2/]	0	N	27.5	52	-.18±.23	- 6.0	18	.01	64	14
03/04	95	E	28.4	54	.16±.32	5.2	18	.05		
C12/C16	35	NE	29.7	57	.37±.34	14.1	19	.001		
F9/F8[2/]	48	NE	31.0	60	-.16±.40	- 5.4	21	ns	327	6
C13/C17	15	N	33.0	65	.17±.20	5.5	19	.01		
F5/F10	20	N	35.0	70	-.14±.32	- 3.7	18	ns		

1/ Direction of arrow flying with the wind.

2/ Vectopluviometers adjacent to underlined pairs.

3/ General prevailing wind direction (57°) is against tilt of these gages; with tilt of all others.

watershed F, where wind prevailed from the southeast, possibly due to eddy currents around the steep (60-70%) upper slopes of the watershed. All of the data from the five vectopluviometers were combined to get the average wind direction for the experimental area (heavy broken arrow in fig. 5), which also shows wind out of the southwest (arrow flying with the wind points 57^{0}).

Inclination of rainfall (table 1) at each of the vectopluviometer sites was determined by equation 2. Mean inclination was 20^{0} at the C7/C6 site, where an average wind speed during rainfall of 4.4 mph was recorded by the wind gage. Since the inclination of rainfall is a relative measure of wind speed, it is assumed that on the average wind at 4.4 mph will drive the rain at an angle of about 20^{0} from the vertical. Furthermore, since the mean inclinations at the other four sites with vectopluviometers ranged between 20^{0} and 6^{0}, it seems safe to conclude that wind speed was no greater, and at most sites less, than about 4.4 mph.

DISTRIBUTION OF PRECIPITATION

Areal distribution of precipitation on the Three Bar study area is illustrated in figure 7. Precipitation decreases fairly uniformly downslope from southwest to northeast, which is also the direction of prevailing wind. The isohyetal lines were visually fitted using all of the data collected during the 3-year study. The lines were then uniformly adjusted to represent mean annual precipitation based on nine original gages that were in service from 1957 to 1974. The precipitation gradient averaged 5 inches per 1,000 feet of elevation in the direction of wind flow, which is also roughly at right angle to the Mazatzal ridge and the general contour of the lee side of the mountain front (fig. 8). In the lower portion of the study area the isohyetes did not necessarily parallel the local contour lines, an indication that local relief was not the dominant factor in the distribution of rain over the area.

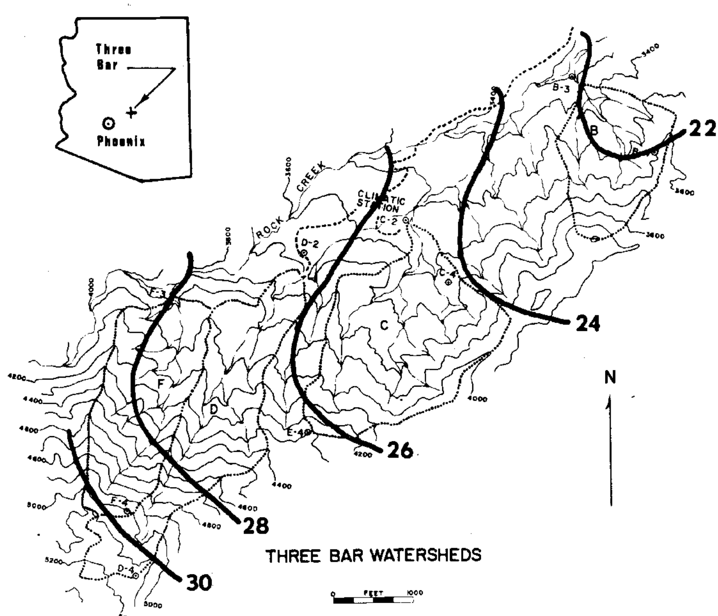

Figure 7. Areal distribution by isohyetal analysis adjusted to mean annual precipitation in inches for 18-year period (1957-1974).

The major physical feature in the surrounding area that might be expected to exert a dominant influence on precipitation is the Mazatzal Divide 1.5 miles to the southwest (fig. 8). Dominated by Four Peaks in this area, the main ridge bears northwest-southeast and is 1,000 or more feet higher than the upper edge of the study area. The prevailing southwest winds blow roughly at right angles across the divide and down over the watersheds. Presumably, orographic uplift of moist air increases precipitation on the windward approach. Then, as the air flows over and down the lee side of the mountain, precipitation rapidly decreases until the terrain levels off. Although local topography clearly modifies wind patterns, and to some extent the local distribution of rain as shown by the tilted gages and vectopluviometers, the general distribution of rain over the study area appears to be controlled largely by the Mazatzal Divide and the leeward flank of the mountains.

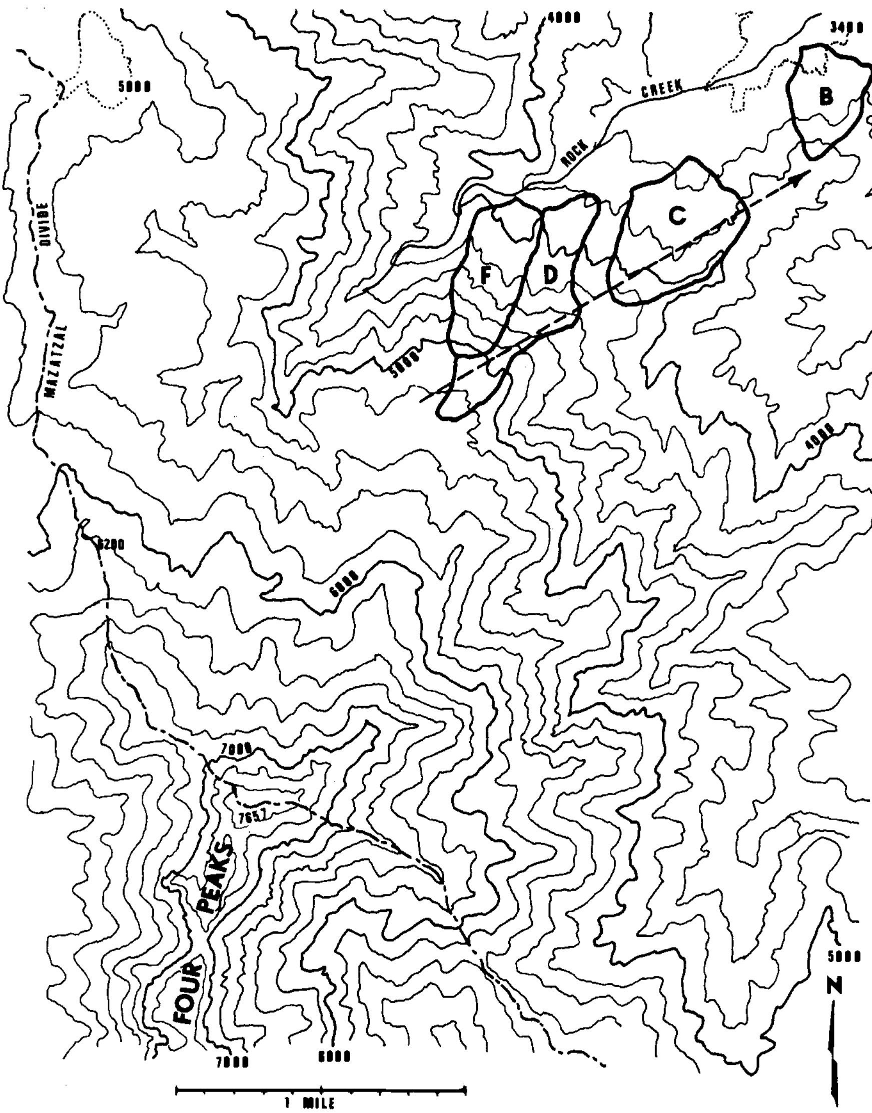

Figure 8. Three Bar watershed in relation to Mazatzal Divide and Four Peaks. Broken arrow shows direction of prevailing wind during rainfall.

How representative of surrounding areas is the distribution pattern defined on this small study area? By extending the 5 inches per 1,000 feet gradient 3.5 miles downslope from watershed B, 16 inches of precipitation is indicated where Tonto Creek enters Roosevelt Lake at 2,200 feet elevation (fig. 1). This amount coincides precisely with the 16-inch isohyete shown for this site on the U. S. Weather Bureau isohyetal map (WR-1210-A) of normal annual precipitation for Arizona (1931-1960). The 16 inches is also in line with long-term means of two nearby gaging stations, Roosevelt and the Reno Ranger Station in Tonto Basin (Sellers and Hill 1974). Precipitation at Roosevelt (2,205 feet) 9 miles to the southwest averages 14.15 inches and at Reno Ranger Station (2,420 feet) 8 miles up Tonto Creek the average is 16.75 inches. This close agreement between extrapolated and measured precipitation indicates a relatively constant precipitation gradient from upper watershed D on the study area to Roosevelt Lake, even though the terrain slopes much more gently below (6%) than within the study area (22%).

Upslope, between the study area and the Mazatzal Divide, no precipitation data are available and the accuracy of extrapolated values is less certain. However, it is obvious that precipitation continues to increase with elevation, only the rate of increase can be questioned. If the 5 inches per 1,000 feet gradient is extrapolated upslope from the 30-inch isohyete on watershed D at 5,000 feet elevation (fig. 7), the amount indicated at 6,200 feet on top of the Mazatzal Divide is 36 inches (fig. 8). This is about 6 inches (20%) more than is indicated for this site on the U. S. Weather Bureau isohyetal map (WR-1210-A), which shows a 30-inch isohyete encircling Four Peaks at about 6,000 feet elevation. This map estimate is low because the same amount is known to occur at 5,000 feet on the study area, where it is apparent from the vegetation that precipitation is not as great as higher on the mountain. Chaparral, which dominates the slopes below 5,000 feet at Three Bar, changes to oak-woodland and ponderosa pine between 5,000 and 6,000 feet. Above 6,000 feet, quaking aspen thrives in cove sites along the northeast exposure of Four Peaks, suggesting that precipitation is greater there than lower on the study area.

Possibly, precipitation does not continue to increase at 5 inches per 1,000 feet all the way to the crest of Four Peaks (7,657 feet), or perhaps even to the top of the divide which varies from 5,800 to 6,500 feet in this area. However, it is certain that precipitation above 6,000 feet exceeds 30 inches; quite probably it is 35 inches or more.

The question logically arises: what is the precipitation like on the windward (southwest) side of the Mazatzal Divide? It is generally believed that less rain falls on leeward than on windward exposures at comparable elevations. This phenomenon is known as the rain shadow effect. Since no rain gages are available on the windward side, vegetation provides the only means of comparison. Casual observations by the author have not disclosed anything about the vegetation on the windward side to indicate that it gets more rain. Actually, the opposite appears to be true; near the top of the divide, the lee side appears to be the wettest. There are two possible explanations. First, the lee side near the top of the divide may be a dump zone for rain and snow that are diverted by strong winds blowing across the summit and dropped as the wind slows on the lee side. This effect should not carry far down the lee side. Second, and probably the most important, the lee side is a northeast exposure, and as such is much cooler, especially during the winter months when the sun angle is low. Precipitation could actually be less on this cool exposure and yet appear wetter than on the warmer southwest side. Thus the rain shadow effect, if it exists, is probably masked by the local climates on these slopes.

SUMMARY ANO CONCLUSIONS

The general distribution of precipitation over the Three Bar experimental watersheds is controlled largely by the presence to windward of the Mazatzal Mountains, over 6,000 feet high. Local topography appears to have only minor, localized effects on rain distribution. Prevailing winds blow across the Mazatzal Divide and flow down over the easterly slopes, crossing the watersheds from the southwest to northeast. The terrain is rugged, but the average slope is not particularly steep in the direction of prevailing wind, except on the upper watersheds. From the Mazatzal Divide at 6,200 feet, average slope is 16 percent down to the watersheds, 20 percent across the watersheds, and 6 percent between the watersheds and Tonto Creek at Roosevelt Lake. The precipitation gradient is essentially constant at 5 inches per 1,000 feet of elevation from Tonto Creek to the upper watersheds. While the gradient could not be verified between the watersheds and the divide, the 36 inches of precipitation indicated by extrapolation to the divide appears consistent with the vegetation growing above 6,000 feet. The results of this study suggest that precipitation in the Mazatzal Mountains near Four Peaks may be underestimated by 5 inches or more on the Weather Bureau's isohyetal map of Arizona.

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BAROMETRIC RESPONSE OF WATER LEVELS IN FLAGSTAFF MUNICIPAL WELLS

by

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Flagstaff municipal water wells at the Woody Mountain Well Field and the Lake Mary Well Field yield water from the Coconino Sandstone, which is the principal aquifer for the Flagstaff area. Locations of these well fields are shown on Figure 1. Analysis of water level data from observation wells during aquifer performance tests indicates that the Coconino is a nonartesian aquifer; however, the water levels in the municipal wells rise at times of low barometric pressure and decline at times of high barometric pressure. Jacob (1940) indicates that this kind of barometric response is interpreted to show artesian conditions, and may be used to compute the coefficient of storage of the artesian aquifer.

HYDROGEOLOGIC CONDITIONS

The sequence of rock units, from the surface, in the Lake Mary and Woody Mountain areas is as follows: alluvial and colluvial deposits, volcanic rocks, Moenkopi Formation, Kaibab Limestone, Coconino Sandstone, Supai Formation, Redwall Limestone, Martin Limestone, and Precambrian metamorphic rocks. Alluvial and colluvial deposits comprise a mixture which ranges in size from silt to boulders, lie above the water table, are permeable, and enhance rapid infiltration of surface water. Volcanic rocks include ash, cinders, bombs, and lava-flow rocks. The maximum thickness of lava-flow rocks penetrated by a Lake Mary well is 121 feet and by a Woody Mountain well is 611 feet. Pyroclastic volcanic materials provide an excellent medium for water infiltration. Intense fracturing in some lava-flow rocks may provide recharge conduits to the aquifer system. The Moenkopi Formation occurs as erosional remnants overlain by volcanics. It consists of sandstone and mudstone, lies above the water table, and where unfractured, acts as a barrier to water percollation. The Kaibab Limestone lies above the water table and ranges in thickness from 202 feet in Lake Mary well LM-4 to 428 feet in Woody Mountain well WM-3. The Kaibab contains numerous joints, fractures, and faults, which have been enlarged by solution activity, and is an excellent recharge medium.

The Coconino Sandstone is the principal aquifer at the Lake Mary and Woody Mountain well fields. The thickness of the Coconino ranges from 740 feet in Lake Mary well LM-4 to 905 feet in Woody Mountain well WM-1. The water table occurs at depths below the top of the Coconino ranging from four feet at Woody Mountain well WM-5 to 572 feet at Woody Mountain well WM-1. Water moves slowly through unfractured Coconino and wells in such strata have specific capacities of less than one gallon per minute per foot of drawdown (gpm/ft). Fracturing enhances yields from the Coconino. Wells drilled into highly fractured portions have specific capacities that exceed 4 gpm/ft.

More complete descriptions of the hydrogeological and geophysical conditions at the Woody Mountain Well Field area are given by Harshbarger and Carollo (1973), Scott and Montgomery (1974), Montgomery and DeWitt (1975) and Scott (1974), and at the Lake Mary Well Field by Koval (1976) and by Harshbarger and Associates (1976 and 1977).

AQUIFER PERFORMANCE TESTS

Aquifer performance tests have been made at individual wells in the Woody Mountain and Lake Mary well fields from 1956. Long-term aquifer performance tests using six wells at Woody Mountain and four wells at Lake Mary were made in 1972 and 1975 respectively.

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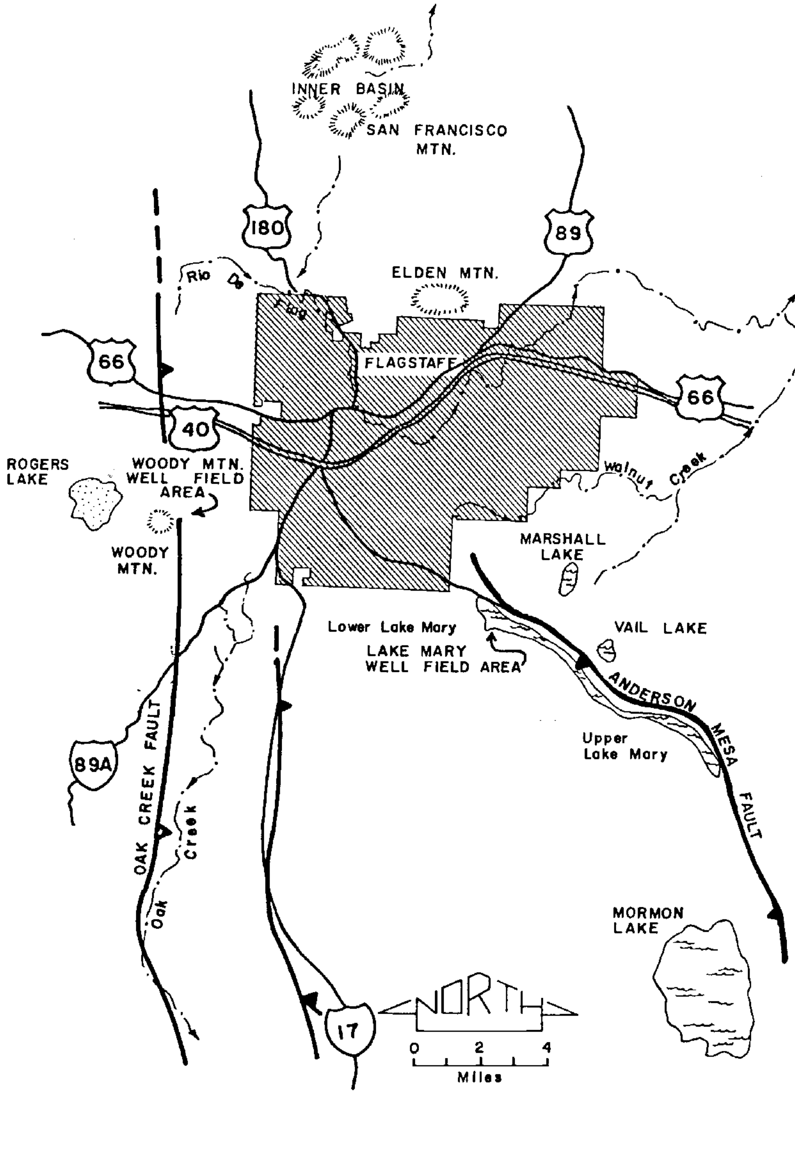

Figure 1

LOCATION MAP

WOODY MOUNTAIN AQUIFER TEST

Beginning on April 10, 1972, Woody Mountain wells WM-2, WM-3, WM-4, and WM-6 were individually turned-on at eight to seventeen day intervals. By May 20, 1972, all four wells were operating at a continous composite rate of 1,702 gpm. WM-1 and WM-5 were not pumped and served as observation wells. The pumping phase was completed on November 4, 1972 after 202 continuous days of pumpage. The recovery phase extended into 1973. Transmissibility at individual wells ranged from 7,400 to 31,300 gallons per day per foot (gpd/ft). Coefficient of storage computed using water level data from both observation wells was 0.08 (Harshbarger and Carollo, 1973). These coefficients are interpreted to indicate nonartesian conditions in the Coconino aquifer at Woody Mountain.

LAKE MARY AQUIFER TEST

The Lake Mary aquifer test began by pumping LM-2 on March 7, 1975. Pumping was initiated at LM-4 on April 3, 1975. Wells LM-1 and LM-3 were not pumped and served as observation wells. The pumping phase was completed on October 18, 1975 after 225 days of discharge at a continuous composite rate of 1,301 gpm. The transmissibility at individual wells ranged from 4,000 to 15,000 gpd/ft. Coefficients of storage computed from observation well water level data ranged from 0.05 to 0.10. These coefficients are interpreted to indicate nonartesian conditions in the Coconino aquifer at the Lake Mary well field.

BAROMETRIC PRESSURE

Barometric pressure was measured at Pulliam Airport. The airport is located approximately four miles east of the Woody Mountain well field and approximately five miles northwest of the Lake Mary well field. Barometric pressure in inches of mercury was converted to barometric pressure in feet of water for use in determining barometric response and barometric efficiency of water wells.

BAROMETRIC RESPONSE

Barometric response in the observation wells at Woody Mountain and at Lake Mary were apparent during both the pumping and recovery phases of the 1972 and the 1975 aquifer tests. The relationship of barometric pressure and hydrographs for water levels in the Woody Mountain wells is shown on Figure 2 and in the Lake Mary wells on Figure 3. Both Figures indicate a close inverse relationship between changes of barometric pressure and changes in water levels. The least squares line of best-fit was calculated for each hydrograph and a line parallel to the best-fit line was constructed to establish a datum for measuring water level change.

BAROMETRIC EFFICIENCY

The barometric efficiency of the Woody Mountain and Lake Mary wells treated on Figure 2 and 3 was determined by plotting the water level changes as ordinates and the corresponding changes in atmospheric pressure as abscissas on rectangular coordinate graph paper (Ferris and others, 1935). The slope of the line of least squares best-fit drawn through the plotted points is the barometric efficiency. The plot used to determine barometric efficiency for well LM-3 is shown on Figure 4. The barometric efficiency computed for selected Flagstaff wells, together with the correlation coefficient (r^2) which measures the degree of dependency of water level on atmospheric pressure, are tabulated below:

WELL	BAROMETRIC EFFICIENCY	(r^2)
LM-1	100%	0.93
LM-3	96%	0.96
LM-4	100%	0.84
WM-5	112%	0.84

COEFFICIENT OF STORAGE

Jacob (1940) has shown that barometric efficiency can be used to calculate the coefficient of storage of an artesian aquifer. The relationship is as follows:

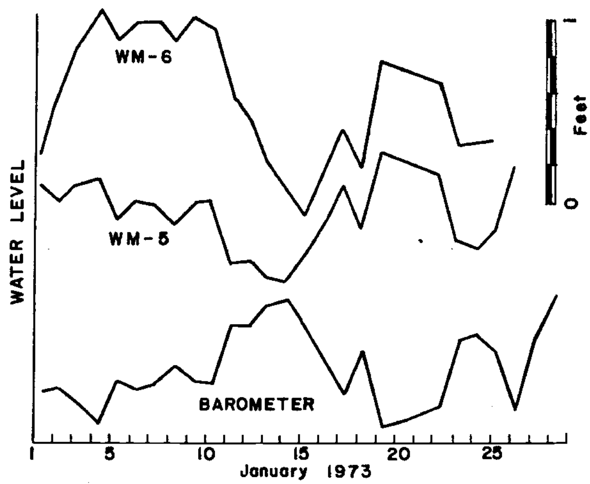

Figure 2

WOODY MOUNTAIN WELLS
RELATIONSHIP OF BAROMETRIC PRESSURE
AND HYDROGRAPHS FOR WATER LEVELS

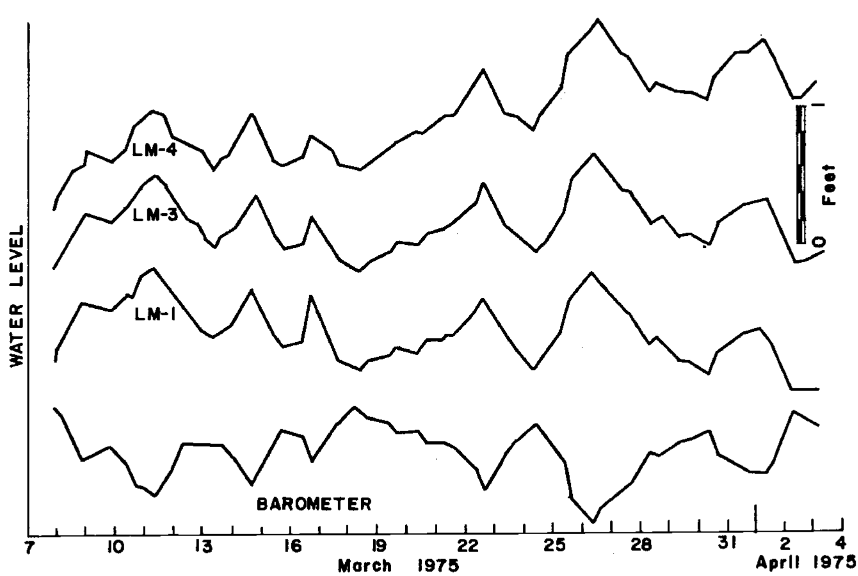

Figure 3

LAKE MARY WELLS
RELATIONSHIP OF BAROMETRIC PRESSURE
AND HYDROGRAPHS FOR WATER LEVELS

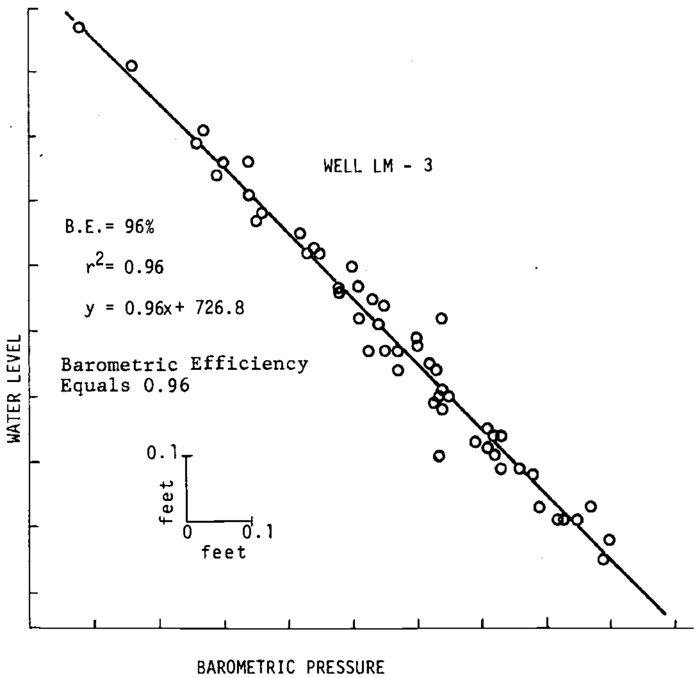

Figure 4

BAROMETRIC EFFICIENCY OF
LAKE MARY WELL LM-3

$$S = (G\ P\ m\ B)\frac{1}{B.E.}$$

Where S = coefficient of storage

G = unit weight of water

P = porosity

m = saturated thickness

B = bulk modulus of compression of water

B.E. = barometric efficiency

The coefficient of storage calculated for the Coconino aquifer using this relationship and the saturated thickness for the Woody Mountain and Lake Mary wells are tabulated below:

WELL	SATURATED THICKNESS IN FEET	CALCULATED COEFFICIENT OF STORAGE
LM-1	899	2.5×10^{-4}
LM-3	395	1.2×10^{-4}
LM-4	882	2.5×10^{-4}
WM-5	1100	2.8×10^{-4}

CONCLUSIONS

The barometric efficiencies and the coefficients of storage calculated from the barometric response of water levels in the Woody Mountain and the Lake Mary wells are within the range which indicates artesian conditions, although it is known that the Coconino aquifer is non-artesian. The reason for the strong barometric response is not known but may be due to the thick and fine-grained character of the rocks which lie between the land surface and the water table. Barometric changes are transmitted slowly through this rock sequence, which allows the water levels in the wells to respond to short-term changes in barometric pressure as if the aquifer were artesian. The relations given in this paper, indicate that coefficients of storage computed from barometric efficiency in aquifers which are overlain by thick and fine-grained sedimentary strata may be incorrect and should be viewed with caution until confirmed with other analysis.

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EFFECT OF ILLUVIATED DEPOSITS ON INFILTRATION RATES AND DENITRIFICATION DURING SEWAGE EFFLUENT RECHARGE

by

Richard Alan Herbert

INTRODUCTION

Ephemeral stream channels are used by some southwestern communities for disposal of sewage effluent. One community that disposes of its sewage in this manner is Tucson, Arizona. Since 1955, the principal drainage tributary of the Tucson Basin, the Santa Cruz River, has been receiving discharged secondary effluent from the City of Tucson sewage treatment plant (Wilson, Herbert, and Ramsey, 1975). In fiscal year 1973-1974, 31,460 acre-feet of effluent was released into the ephemeral stream channel (Dye, 1974). Davidson (1973) estimated that more than 90% of the effluent released into the channel is being recharged and is affecting both ground water levels and water quality. In addition, Cluff, DeCook, and Matlock (1971) observed that water levels in the vicinity of the Santa Cruz River have begun to rise, and that the nitrate content of ground water in the recharge area has increased steadily. Because the current supply of ground water is being depleted about five times faster than it is being replenished (Arizona Water Commission, 1975), strong consideration has been given to ground-water recharge of sewage effluent from proposed county treatment facilities (Ehrich, Kluesener, and Harper, 1973). In effect, the recycling system would be similar to the method the city has used for effluent disposal since 1955 and would reduce the present overdraft by replacing a portion of the used water with treated effluent.

Unfortunately, there is a potential danger of ground water contamination when recharging sewage effluent (Huges, 1975), since the fate of microorganisms and certain chemical constituents during recharge is not fully understood (Schaub et al., 1975).

Recently, there has been great concern about nitrates, enteric viruses, and organic toxins reaching the ground water system during rapid infiltration of sewage (Sorber, Schaub, and Guter, 1972). The main consideration of the study reported herein is the fate of nitrates in the recharging effluent. As mentioned earlier, Cluff et al. (1971) observed an increase in nitrate content of the ground water along the Santa Cruz River. However, Wilson et al. (1975) indicated that the overall quality of ground water in the area of recharge may be better than that of the ground water upstream of the Tucson sewage treatment plant, and observed during a one-year study that recharge of sewage effluent in the river did not contribute nitrate to local ground-water supplies.

In a study of land application of waste water, Schaub et al. (1975) observed a black asphaltic-appearing layer at a depth of about 18 inches (approximately 46 cm). Sebenik, Cluff, and DeCook (1972) observed a similar black, odoriferous layer in the upper soil water interphase layer of the Santa Cruz River. Thomas, Schwartz, and Bendixen (1966) reported that the black ferrous sulfide layer that develops under sewage spreading is an indicator of reducing conditions. Since reducing conditions are necessary for denitrification of nitrates, the fate of nitrate in recharging sewage may be related to the formation of the black layer found in the deposits along the Santa Cruz River.

McGauhey and Krone (1967) summarized information on mechanisms of soil clogging, and indicated that there may be a relationship between reduced infiltration rates and the development of a black, ferrous sulfide layer. Mitchell and Nevo (1964), however, suggested that reduced infilitration rates are due to a building up of bacterial polysaccharides rather than the black layer, and Rice (1974) concluded that the principal cause of clogging is deposition of suspended solids on the soil surface.

Obviously, the interrelationships between the various water quality changes and sewage effluent recharge are not fully understood. The objective of this study was to determine the interrelationships among nitrogen transformations, infiltration rates, and development of the black layer found in the Santa Cruz River downstream of the Tucson sewage treatment plant.

MATERIALS AND METHODS

The interrelationships among infilitration rates, nitrogen transformations, and black layer development were tested by percolating sewage effluent through three, clear acrylic columns filled with deposits from the Santa Cruz River. An additional column was flooded with tap water to serve as a control.

Infilitration rates were determined by measuring the daily flow rates. Samples of the sewage, tap water, and outflow from each column were collected and analyzed to determine the nitrogen transformations. Finally, the black layer development was characterized by visual observations and manometer readings from tensiometers installed at various depths in the profile.

MATERIALS

Column construction

Four, clear acrylic columns, 122 cm long by 10.17 cm in diameter, were used for this investigation. The columns were mounted in an enclosed wooden frame. Each column extended through the top of the frame a few centimeters to simulate field conditions. The outside of the wooden housing was painted white to minimize heat absorption and the inside was painted black to minimize light reflection and algae growth. One side of the frame was hinged to allow access and observation of the soil columns. Two plastic pipe, constant head manifolds were constructed to supply the control column with tap water and the remaining three columns with sewage.

A pilot study was conducted using a single column to determine if the black layer would develop in a soil column flooded with sewage effluent. The layer first appeared at the top of the river sand in the column and then extended to about 20 cm below the surface. From these data, it was decided that tensiometers should be located at 2, 20, and 35 cm below the soil surface. The top, middle, and bottom tensiometers would allow pressure readings near the surface of, within, and below the black layer, respectively. A monometer board was constructed with a cover and mounted on one end of the wooden enclosure.

Soils. Two separate experiments were run during this investigation. For the first run, a mixture of river sand was used from randomly selected locations along the Santa Cruz River. As the first experiment proceeded, the flow rates of the columns flooded with sewage rapidly decreased to zero. Consequently, a second run was made using a fine pea gravel in place of the river sand. It was hoped that flow rates through the gravel would remain high enough to allow sampling throughout an extended period of time.

Water Supply. The experimental apparatus was set up beside the chlorine contact chamber of Plant No. 1 at the City of Tucson Sewage Treatment Plant. The location not only provided a continuous supply of secondary sewage effluent, but there was a supply of tap water and electricity as well.

A small submersible pump installed several feet upstream of the chlorination point fed a continuous supply of unchlorinated sewage effluent to one of the manifolds. By continuous pumping, a fresh supply of sewage was maintained at a constant head for all of the columns being treated with sewage. A contant head of tap water was maintained for the control column by attaching the second manifold to a fresh water spigot via a small diameter hose.

METHODS

After the hydraulic properties of the soil columns were characterized with tap water, in both runs, sewage was applied to columns 2,3, and 4 without allowing them to drain. Sewage was applied continuously for 28 days for the first run and for 64 days during the second run. All columns were allowed to drain and dry overnight at the end of each run. They were reflooded and water samples were taken in an attempt to observe a high nitrate peak similar to that reported by Lance and Whisler (1972). In addition to the first drying period during run 2, the columns were allowed to dry a second time. The second drying period lasted several days before the columns were reflooded and sampled.

Daily flow measurements were taken for each column. Air temperature, temperature of inflow and outflow of sewage and tap water, and the time of the measurements were also recorded. Daily flow rates were later plotted for both runs.

Total flow volumes through each column were estimated by averaging the flow rate between two readings and multiplying by the time elapsed between those readings. These values were later used for determining the amount of nitrogen applied and removed by the infiltrating water.

The level of the meniscus in each manometer was recorded daily at about the same time the flow measurements were made.

Samples of the applied sewage and tap water and the outflow from each column were collected at random time intervals. All samples were immediately transported for analysis.

RESULTS

BLACK LAYER DEVELOPEMNT

During the 12-hour period of tap water application on the river sand (run 1), there was no black layer visible in any of the four columns. Continued application of tap water to the control column did not result in any visible black deposits. The three columns treated with sewage during the first run began to develop a black layer in the sludge overlying the sand after four days. At the beginning of the fifth day of sewage application, the layer had migrated 3.2, 3.5, and 3.8 cm into the sand of columns 2, 3, and 4, respectively. The black deposits continued to spread downward throughout the remainder of the experiment. On the last day of continuous flooding, the thickness of the layer was about 5.4, 10.2, and 13.5 cm in columns, 2, 3, and 4, respectively. Upon drying of the columns, the balck layer gradually disappeared for about two days until there were only minor traces remaining.

In the second run, after seven days of flooding the gravel with tap water, there were no traces of black deposits in any of the columns. Again, continued application of tap water in the control column did not result in any visible black deposits. Six days after the treatment columns were flooded with sewage, the black layer began to develop at the surface of the gravel in columns 3 and 4. On the seventh day, all three treated columns had several centimeters of black deposits at the surface and points and pockets of black throughout the remainder of each column. Within a few more days, all three columns had turned almost completely black with column 3 being the darkest in color and column 2 the lightest. The black deposits persisted until the bottom orifices were freed from obstructions, at which time the flow rate increased markedly in the treated columns and the lower portion of the black layer became slightly lighter.

REDUCTION IN INFILTRATION RATES

Hydraulic conductivity values for the columns in both runs are presented in Table 1. As would be expected, the hydraulic conductivity of the gravel in run 2 was much higher than that of the sand in run 1. Variation among columns for each run was minimal however, the slight differences can probably be attributed to variations in packing.

Table 1. Hydraulic Conductivity Values for Each Column for Both Runs.

Column No.	Hydraulic Conductivity, K (cm/min) Run 1	Run 2
1	.35	3.96
2	.49	2.87
3	.28	3.16
4	.31	3.07

During the initial flooding with tap water in run 1, column 2 had the highest hydraulic conductivity and flow rate; column 1, the control column, was second highest; column 4 was third highest; and column 3 had the lowest hydraulic conductivity and flow rate. Almost immediately after sewage was applied to columns 2, 3, and 4, the flow rates dropped considerably and after about a day the rates leveled off and asymptotically approached zero for the remainder of the experiment (Figure 1). During this time, the manometers showed negative pressure heads in the treated columns.

An important observation is that column 2 initially had a higher flow rate than the control column, but upon application of sewage the rate dropped markedly below that of the control. Statistical analysis revealed that there was no significant difference among columns during the characterization period, but after application of sewage there was a highly significant difference between the treated columns and the control at the .05 level of confidence.

During the initial flooding with tap water in run 2, column 1, the control column, had the highest hydraulic conductivity and, therefore, a higher flow rate than columns 2, 3, and 4. Upon application of sewage, the flow rate in the treated columns again dropped considerably, while the control column continued to follow a characteristic curve. After about a week, the flow rate in the treated columns decreased to almost zero. The flow rate remained extremely low for about three more weeks and the manometer readings gradually changed from negative pressure heads to higher and higher positive heads. Eventually, the columns were probably saturated throughout, i.e., a perched water table developed above the base of the column. After a total of about 47 days from the start of the experiment, clogging in the column outlets was discovered and alleviated. Upon unclogging of the columns, the daily flow rates varied considerably; however, the average rate of the treated columns was considerably lower than that of the control column (Figure 2) and the level of the manometers began to drop off again. A statistical analysis revealed that there was a significant difference in flow between the control column and the treated columns after sewage application.

The initial decrease in flow for both runs was due mainly to surface clogging, which was also observed by Rice (1974). During the second run, the clogging of the outlets gradually overshadowed the surface clogging. Clogging of the outlets remained the predominant factor of reduced flow rates until the clogging was alleviated, at which time surface clogging again became the predominant factor.

NITROGEN TRANSFORMATIONS

The complete data from the nitrogen analyses will not be presented here due to space limitations but a discussion of the results will be included in a later section.

There were no changes in the nitrogen species for the control columns during either run. Total nitrogen in run 1 was reduced by 42.7, 86.3 and 59.6 percent in columns 2, 3, and 4 respectively, with the average reduction being 62.9 percent. The reduction in total nitrogen as determined by a Student T test was signigicant at the .05 conficence level, but not at the .01 level.

During the second run, columns 2, 3, and 4 showed a 16.4, 16.2 and 15.0 percent reduction in total nitrogen, respectively, with an average of 15.9 percent. The reduction was highly significant at the .01 confidence level.

DISCUSSION

RELATIONSHIP BETWEEN BLACK LAYER DEVELOPMENT AND INFILTRATION RATES

During both runs, the infiltration rate dropped immediately upon application of sewage and the black layer did not appear until several days later. Therefore, the black layer is not a cause of reduced infiltration rates. However, there was some correlation between the infiltration rate and the thickness of the black layer. Observations during both runs revealed that, in general, the faster the flow, the thinner the black layer and vice versa. Winneberger et al. (1960) reported that ferrous sulfide deposits penetrated downward according to the laws that govern the movement of particles in a porous medium, and McGauhey and Krone (1967) stated that the removal rate of particles by a porous medium during the infiltration process increases as the accumulated solids increased. So, it seems reasonable to assume that, for higher infiltration rates, there would be a more rapid accumulation of fine particles closer to the surface, which would result in a thinner black layer. One obvious problem with this theory is that run 2 had much higher flow rates and thicker black deposits than run 1. However, the clogging of the outlets during run 2 caused the gravel to become saturated, similar to a perched water table condition in the field. The saturated conditions eliminated most of the oxygen and, consequently, the black layer developed throughout the length of the columns. Had the water table conditions not developed, the black layer may have developed in a manner similar to that in run 1. However, the larger pores in the gravel would probably have allowed deeper penetration of the fines before they could begin to accumulate and increase the removal rate. In fact, during the short period after the black layer began to build up and before the water table conditions developed, the black layer was thicker than it was during the same period in run 1.

The above interpretation of Winneberger's theory depends on downward filtration of ferrous sulfide precipitated at the surface. However, observations of the black layer during its development seem to indicate that the iron in the soil combines with sulfates dissolved in the percolating sewage upon development of anaerobic conditions. Evidence to support this observation was reported by Mitchell and Nevo (1964). They stated that microorganisms utilizing organic matter released H_2S, which moved down the profile where it reacted with iron in the sand, forming a black, ferrous sulfide layer. Since observations during this study do not coicide with the findings of Winnegerger et al. (1960), another plausible explanation will be presented here.

The suspended solids in the percolating sewage could have been filtered out by filtering processes similar to those described above. After the initial deposition, the infiltration rate decreased, which was the case for both runs, and particles continued to be deposited on the surface. An interface between the bottom of the deposited material and the underlying soil created a barrier to water movement and water table conditions developed above the interface, thus creating anaerobic conditions and the black layer. Sakthivadivel (1966) found that gradually reducing the flow rate loosened bridged particles and allowed them to move down in a porous filter. So the downward extension of the black layer may be due to a downward migration of the interface as the filtered particles break loose and find their way through the underlying pores. Unfortunately, the manometer data for run 1 do not support the theory that a water table exists above the interface. However, the finer material in the upper layer may hold enough water to create anaerobic conditions while at the same time exerting a suction on the tensiometer within the layer. Some evidence to support either of the above speculations was obtained during field investigations. Well points installed within the Santa Cruz River revealed a shallow water table. Although the distribution of the black layer within the soil profile at the location of the well points is not known, the black layer was observed at the surface and could have formed in the saturated zone. Although this is all speculation, it could support the water table theory. In addition, while an observation pit was being dug adjacent to the river, a large, black clump of clay was exposed in an area surrounded by normal-colored sand. This observation seems to indicate that the clay held enough water to create anaerobic conditions and, therefore, the black layer, but the surrounding sand did not. A more detailed study, possibly using a combination of tensiometers and redox probes, is needed to determine what mechanism is responsible for creating the anaerobic conditions under which the black layer is developed.

Development of the black layer under water table conditions may be a very important process during ground-water recharge of sewage effluent in natural drainage channels. In addition to being an indicator of the conditions required for denitrification, the black layer may be a source of organic carbon and/or a sink for heavy metals and possibly other contaminants as well (Schaub et al., 1975). More studies should be conducted to determine this relationship.

RELATIONSHIP BETWEEN BLACK LAYER DEVELOPMENT AND NITROGEN TRANSFORMATIONS

There was no apparent relationship between the thickness of the black layer and the amount of total nitrogen removed. However, there was a large difference between the amount of nitrogen removed in run 1 and the amount removed in run 2. On a percentage basis, the river sand had a greater average removal than the gravel. Since the river sand had a higher clay content, which is normally associated with a higher cation exchange capacity, a higher percentage of ammonia was adsorbed in the first run than the second and, because there was no correlation between the thickness of the black layer and the nitrogen transformations within each run, it can be assumed that the differences in the black layer are not responsible for the differences in the amount of total nitrogen removed.

Figure 3 shows the total nitrogen in the sewage and the outflow of the treated columns throughout run 2. The reduction in total nitrogen between the sewage and the three columns appears to have been by dentrification and/or adsorption of ammonia by the clays. The high nitrate peak observed after an extended period of drying in run 2 (Figure 4) was not observed after the short drying period in run 1 and a longer drying period would have been required to determine the extent of removal by adsorption.

Figure 4 shows the total nitrogen in the sewage and the outflow of the treated columns for run 2. Since the clay fraction of the gravel was so low, very little adsorption of ammonia was expected. However, the first set of samples taken after the nine-day drying period was high in nitrates. This high nitrate peak was similar to that observed by Lance and Whisler (1975). They attributed the high nitrate peak to nitrification of adsorbed ammonia subsequent to column aeration. Possibly, ammonia was adsorbed by organic matter that had been filtered out by the gravel. Upon drying, the ammonia was exposed to the soil atmosphere and nitrified. Reflooding washed the nitrates through the columns.

The nitrogen data indicates that the majority of the nitrogen removed was due to removal of organic nitrogen. The organic nitrogen may have been filtered out and a portion of it may have been mineralized. However, the extent of mineralization is unknown. Adsorption of, or nitrification of, ammonia and subsequent denitrification may also have taken place.

Although run 2 had a lower percentage of total nitrogen removed, the flow rate was much higher. Consequently, a much larger volume of nitrogen was removed during the second run. For run 1, there was an average of 24 pounds/acre/day (27 kilograms/hectare/day) removed, while about 141 pounds/acre/day (158 kilograms/hectare/day) were removed during run 2. Unfortunately, the total volume of nitrogen passing through the columns was also much greater for run 2.

Bouwer (1974) demonstrated that recharge basins could be managed to achieve a 30 percent removal of nitrogen and Lance and Whisler (1975) showed that even higher removal rates could be attained by increasing the carbon content or decreasing the flow rate. Higher removal rates could probably have been achieved in this study if the ammonia in the sewage had been nitrified before it entered the black layer. Schaub et al. (1975) found high concentrations of organic carbon in the black layer, which would seem to indicate that a carbon source is not a limiting factor for denitrification, provided the ammonia is first nitrified and the nitrate remains in contact with the bacteria for a long enough time. However, this remains to be proven.

If the detention time within the black layer were a limiting factor, recharge basins used for reclaiming sewage effluent might be managed to obtain the thickest possible black layer, which would give the longest possible contact time during recharge. However, high infiltration rates and nitrifying conditions must also be maintained. Although these mechanisms may not seem to be compatible, studies on the subject might be warranted because nitrogen removal during recharge of waste water is of such great import.

RELATIONSHIP BETWEEN INFILTRATION RATES AND NITROGEN TRANSFORMATIONS

There seems to be some correlation between the rate of flow and the amount of nitrogen removed. When the outlets became almost completely clogged during run 2, the ammonia concentration of the outflow was greater than the inflowing sewage. This phenomenon is probably not indicative of what would happen during normal free flow conditions. In fact, there was a greater percent removal during the first run which had the slower infiltration rates. These results are similar to results of experiments by Lance and Whisler (1973), where they observed a greater percent removal of nitrogen at lower infiltration rates. However, the different infiltration rates in Lance and Whisler's study were obtained by packing the soil to different densities rather than using different soil types.

SUMMARY AND CONCLUSIONS

Two separate column studies were conducted at the City of Tucson Sewage Treatment Plant to determine the interrelationships among nitrogen transformations, infiltration rates, and development of a black layer during sewage effluent recharge. Four clear acrylic columns were uniformly packed with river sand for the first study (run 1) and the sand was replaced with gravel for the second study (run 2). Sewage efluent was continuously applied to three of the columns for 28 and 64 days during the first and second runs, respectively. The remaining column was continuously flooded with tap water and served as a control in both cases. Infiltration rates and manometer readings were recorded daily and random samples of the inflow and outflow of each column were collected and analyzed for the various nitrogen compounds.

Infiltration rates decreased rapidly upon application of the sewage and within a few days a black layer began to develop. The thickness of the black layer was inversely related to the infiltration rate, but was not a cause of reduced flow. The major cause of the initial reduction in flow rate was clogging of the surface by suspended soilds. Clogging of the outlets during run 2 created water table conditions throughout the length of the treated columns which created anaerobic conditions and, consequently, the black layer. There was an average reduction in total nitrogen of 62.9 percent for the first run and 15.9 percent for the second run. The mechanisms of removal for run 1 were predominately adsorption and denitrification, whereas the predominate removal mechanism in run 2 was filtering of organic nitrogen with adsorption and denitrification also playing an important role.

Development of the black layer was not a cause of reduced infiltration rates. However, lower infiltration rates appeared to be an indirect cause of a thicker black layer within a given soil type. There was no apparent relationship between black layer development and reduction in total nitrogen, but the majority of the nitrogen was in the wrong form for denitrification, which means this part if the results is inconclusive. The percent of total nitrogen removal was greater for lower infiltration rates.

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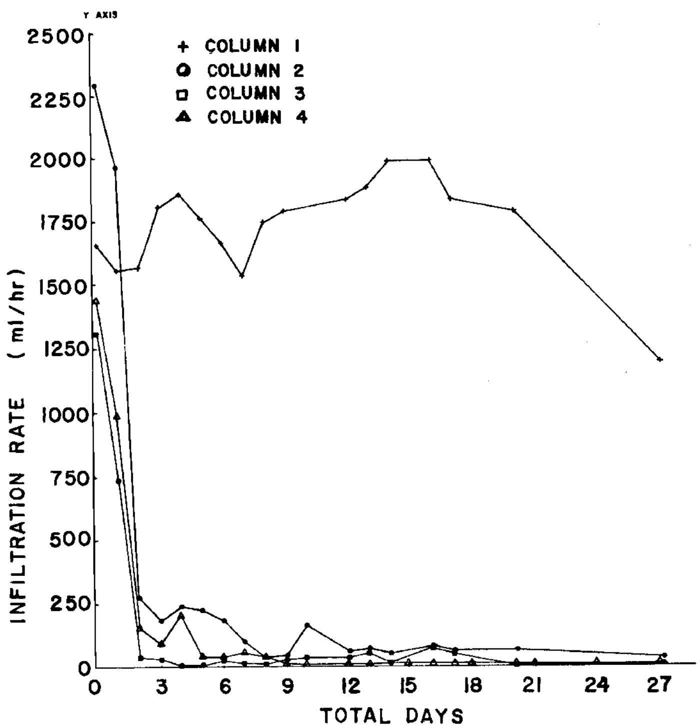

Figure 1. Infiltration Rates for 28 Days of Continuous Flooding during Run 1.

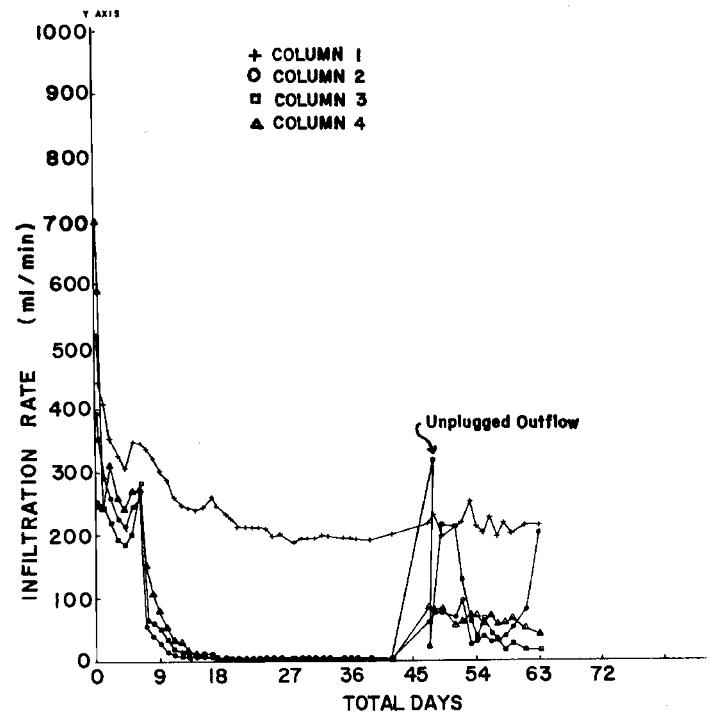

Figure 2. Infiltration Rates for 64 Days of Continuous Flooding during Run 2.

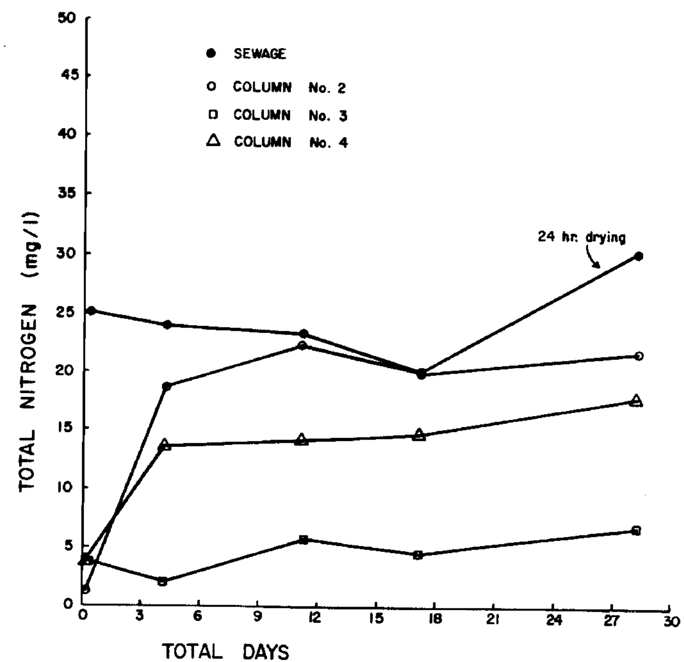

Figure 3. Total N for the Sewage and Treated Columns (Run 1).

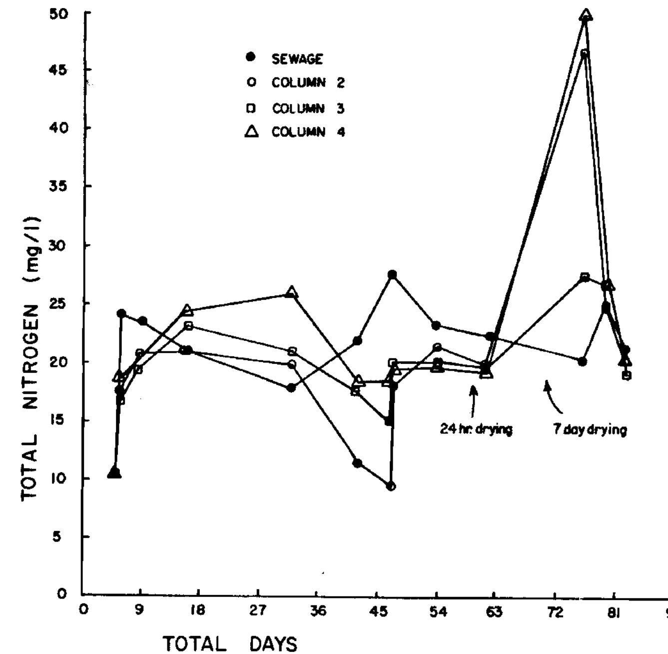

Figure 4. Total N for the Sewage and Treated Columns (Run 2).

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STABLE ISOTOPES OF OXYGEN IN PLANTS: A POSSIBLE PALEOHYGROMETER

by

A.M. Ferhi[1], A. Long[2], and J.C. Lerman[2]

ABSTRACT

Ratios of oxygen-18 to oxygen-16 in cellulose of dated rings from trees grown in nature and from plants grown in controlled environments have significance for retrieving information about the environment in which they grew. Phaseolus vulgaris was grown under varying conditions of controlled temperature, humidity and $^{18}O/^{16}O$ of irrigation water. The $^{18}O/^{16}O$ in plant tissue responds mostly to different environmental relative humidity; plant tissue grown under conditions of low relative humidity produce tissue relatively high in oxygen-18. Reasons for this response are not clear to us, but the relationship may prove a useful complement to established dendroclimatologic techniques.

INTRODUCTION

The study of paleoclimates has attained a new prominence lately, especially since the winter of 1977. The knowledge and understanding of past climates should eventually enable us to predict future climates, perhaps even better than did the "Old Farmer's Almanac" for this past winter[3].

One need only glance over some recent book titles to realize that our climatic future is becoming the concern of many thoughtful people these days. "Genesis Strategy" (Schneider and Mesirow, 1976) and "The Cooling" (Ponte, 1976) are examples. The latter chillingly ominous title implies precognition, and of course, if we already knew the future climate, there would be less interest in pursuing research into proxy indicators of past climate.

ISOTOPE PALEOCLIMATE STUDIES

We have begun testing natural stable isotopes of carbon, hydrogen and oxygen in tree rings as retrospective climate indicators. The present paper focuses primarily on oxygen isotopes.

Oxygen isotopes are certainly nothing new to paleoclimate research. Their study in ice cores and marine cores over the past couple of decades have contributed enormously to our knowledge of Holocene and Pleistocene climates. Tree rings may not give us such long continuous records as ice and ocean cores, but their time resolution of a year or less simply cannot be beat.

Several papers have been published in the last couple of years (see, for example: Libby and Pandolfi, 1974; Gray and Thompson, 1976). They show empirical relationships giving a positive correlation between temperature and increasing oxygen-18 content in tree rings. But empirical relationships can be tricky, and clearly we need a better understanding of why the isotope compositions change, before confidently interpreting these values in terms of climate. There has been no satisfactory explanation of what chemical or physical step or process causes the variations in the ratio of the heavier to the lighter isotopes in plants. (Hydrogen isotopes in plant and tree-ring material have been recently discussed. See, for example: Schiegl, 1974; Epstein and Yapp, 1976.)

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[3]The present edition correctly predicted extreme cold in the Northeast and drought in the Central and Western Great Plains.

EXPERIMENTS ON PHASEOLUS VULGARIS

To try to sort out the causes of oxygen isotope variations in plants, we grew common bean plants (*Phaseolus vulgaris*) under controlled conditions, and analyzed the plant tissue consisting mainly of cellulose when they are young (Bonner, 1950).

The technique for extracting oxygen from dried plant tissue and placing it in carbon dioxide molecules was modified from that of Hardcastle and Friedman (1974). A few milligrams of plant matter are dried and placed in the vacuum pyrolysis tube illustrated in Figure 1. Heating to 1250°C for 1/2 hour produced a mixture of carbon

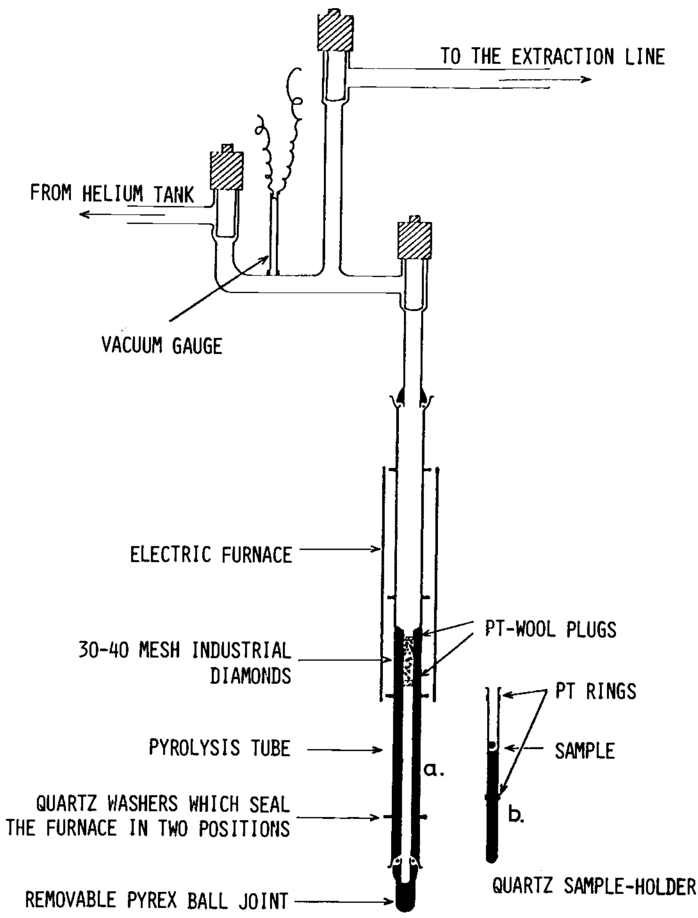

Figure 1. Scheme of the pyrolysis tube (A) used for the present experiments with detail of the sample holder (B). Further details of the extraction line and procedures have been described by Ferhi *et al*. (1975).

dioxide (CO_2) and carbon monoxide (CO). The CO is then converted to CO_2 in an electric discharge tube, and the combined CO_2 is thus completely labeled with the natural oxygen from plant tissue. A mass spectrometer especially designed for isotope ratio determination precisely compares the oxygen-18/oxygen-16 ratio in the sample with that in a reference CO_2 gas.

The sample's oxygen isotope value is represented by a "$\delta^{18}O$" value in per mil ($^o/oo$) with respect to an international standard known as SMOW[4]. All values referred to here are in reference to this standard. Positive values thus contain more oxygen-18 with respect to oxygen-16 than SMOW, and negative values less.

Differences in $^{18}O/^{16}O$ from one chemical or physical phase to another arise as a result of slight differences in thermodynamic properties between, for example, $H_2{}^{16}O$ and $H_2{}^{18}O$, and between $C^{16}O_2$ and $C^{16}O^{18}O$. Reactions between phases may occur under equilibrium conditions or under non-equilibrium (kinetic) conditions. Fractionation, (enrichment or depletion of ^{18}O) is the rule rather than the exception in natural processes. Our experiments were designed to quantify the relationships between environmental conditions in plants and the $^{18}O/^{16}O$ of their photosynthetic products.

In three sets of experiments, we evaluated the effect on $\delta^{18}O$ in tissue of each of these three variables while holding the other two constant: temperature, humidity, and $\delta^{18}O$ of irrigation water. The results of the three sets are shown respectively in Figures 2a, b and c. The experiments indicate, surprisingly, that at least in very high humidity, temperature does not affect the $\delta^{18}O$ of tissue grown between 15 and 30°C. But at constant temperature, $\delta^{18}O$ is a linear function of relative humidity. Finally, if both temperature and relative humidity are kept constant and only the $\delta^{18}O$ of irrigation water is varied, the $\delta^{18}O$ in plant tissue is only slightly affected.

STABLE OXYGEN ISOTOPES IN PLANTS

Unfortunately, we know of no mechanism that satisfactorily explains all experiments. Some of the factors probably affecting the $\delta^{18}O$ values have been listed by Ferhi and Letolle (1977). Two models which may be partially operative will be discussed in this section. Water and/or carbon dioxide seem to be the most likely sources of oxygen in plant tissue. A "ruling hypothesis" in plant physiology states that the CO_2 molecule is the source of oxygen.

A dominant fact to be dealt with when considering stable isotope experiments is that CO_2 isotopically equilibrates with H_2O in a matter of hours at normal temperatures. When CO_2 is in isotopic equilibrium with water, the oxygen in CO_2 is about 40°/oo more positive than that in H_2O (O'Neil and Epstein, 1966). Thus, in a very simple model, if: (1) a plant is living in water of $\delta^{18}O$ = 0°/oo; (2) uses only oxygen from CO_2 (which is in equilibrium with environmental water) in tissue manufacture; and (3) does not fractionate isotopic species in any step, then the tissue would have a $\delta^{18}O$ of about +40°/oo. In fact, our measurements indicate that plant tissue is about 26°/oo more positive than irrigation water, if grown at near 100% relative humidity.

A reasonable modification to the oversimplified model above would be a consideration of possible isotope fractionation of CO_2 as it diffuses into the stomata. Craig (1954) has discussed diffusion of CO_2. Re-evaluating his diffusional parameters in terms of the oxygen isotopes, a depletion of about 9°/oo seems reasonable. Figure 3 shows a highly diagramatic stomatal opening with reasonable values for diffusional fractionation of the molecules of CO_2 and H_2O. Thus, in the model with CO_2 diffusional fractionation, experimental plants grown at near 100% relative humidity are irrigated with water of $\delta^{18}O$ = -7.6°/oo. CO_2 equilibrated with this has $\delta^{18}O$ = +32.8°/oo outside the leaf, but +23.7°/oo inside due to binary diffusional fractionation. Oxygen-18 levels in experimental tissue (the variable temperature experiment) averaged +20.2°/oo.

The experiment with variable $\delta^{18}O$ of irrigation water (Fig. 2c) indicates that the irrigation water does contribute a small part of the oxygen to the plant tissue. This may happen either by direct participation of the H_2O in the reaction, or by a partial exchange of oxygen between leaf water and CO_2 or some reaction intermediate. Either way, the effect of the $\delta^{18}O$ level of the leaf water is a small one, no more

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[4]An acronym for Standard Mean Ocean Water.

$$\delta^{18}O\ (^o/oo)_{SMOW} = \left(\frac{^{18}O/^{16}O_{sample}}{^{18}O/^{16}O_{SMOW}} - 1\right) \times 1000$$

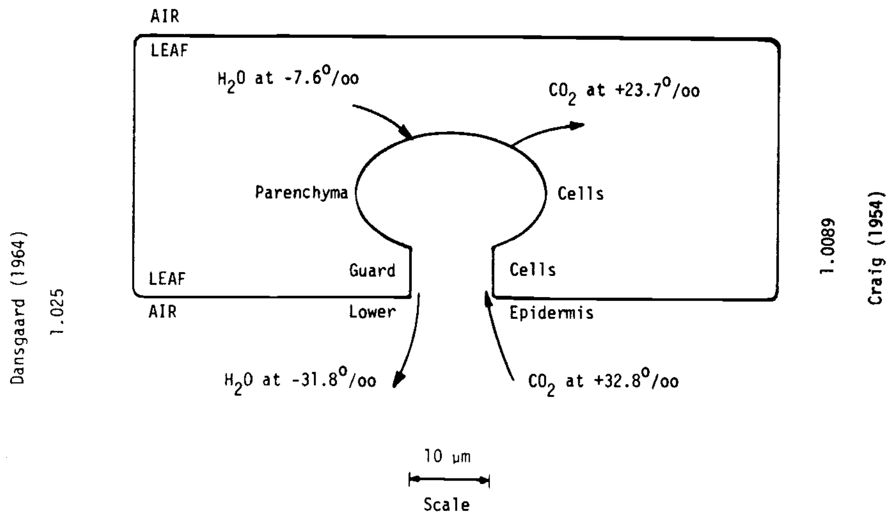

Figure 3. "Stomatal Model": It shows the $\delta^{18}O$ values of H_2O and CO_2 outside and inside the leaf and the diffusional fractionations.

than 15%, as indicated by the slope of 0.15 in Figure 2c.[5] Considering the leaf water effect to contribute 15% of the plant tissue $\delta^{18}O$, and the CO_2 the remaining 85%, the leaf tissue $\delta^{18}O$ would be:

$$(.15)\ (-7.6^{o}/oo) + (.85)\ (+23.7^{o}/oo) = 19.0^{o}/oo.$$

The result from this model is tantalizingly close to the observed average of 20.2°/oo in the temperature experiment. Agreement between calculated and measured values using the above diffusional fractionation model is almost exact for the "98 to 100% humidity" point in Figure 2b.

Unfortunately, this diffusion model is unable to explain the humidity effect. The $\delta^{18}O$ in plant tissue ranges from +18.6°/oo near 100% relative humidity to +34.2°/oo near 20% relative humidity. The extrapolated total range is 23°/oo, assuming linearity. Since the total diffusion effect is 9°/oo, the range of 23°/oo cannot be explained by this model.

The range can be explained, however, by an "internal equilibration" model, which allows CO_2 to equilibrate isotopically with the water inside the leaf before contributing its oxygen to plant tissue. Water in the photosynthesizing cells in leaves is not necessarily of the same isotope composition as it was when drawn from the soil into the roots. The transpiration process may enrich the leaf in water molecules composed of heavy isotopes because water vapor is isotopically lighter than the liquid from which it evaporated. This is because the lighter isotope has a higher vapor pressure. Thus, the heavier water molecules are more likely to remain in the leaf water. The extent of fractionation during evaporation depends on whether the evaporation took place by a kinetic process or an equilibrium process. Experimental values of the fractionation effects during evaporation (see, for example: Dansgaard, 1964) tell us that vapor is 10°/oo isotopically lighter if in equilibrium with liquid, but may be as much as 25°/oo lighter if kinetically evaporated and the vapor has no chance to re-equilibrate with liquid. These fractionation values are temperature dependent. Moreover, if the hydrogen isotopes of water are measured, it is found that the $HD^{16}O$ molecules, containing one atom of deuterium, behave differently than the $H_2^{18}O$ molecules in these two evaporation processes (Dansgaard, 1964). When δD (defined similarly to $\delta^{18}O$, and also using SMOW as a reference) is plotted on the ordinate and $\delta^{18}O$ on the abcissa, liquid-vapor pairs formed by the two processes are distinctive.

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[5]Previous measurements (Ferhi and Letolle, 1977) show a larger slope due to isotope fractionation during evaporation of the irrigation water. The present experiment was performed on hydroponically grown plants, with an oil seal to avoid evaporation of the water.

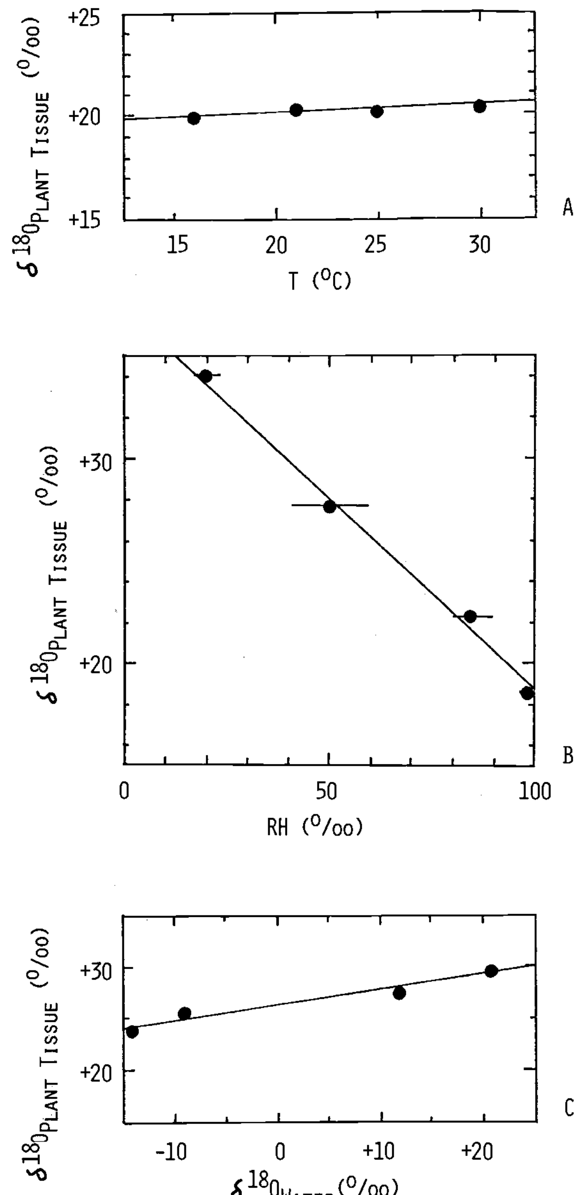

Figure 2. Results of the experiments on bean plants. (All δ-values are vs. SMOW).

a. Experiment with plants grown at constant relative humidity (90 to 100%) and varying temperatures. $\delta^{18}O$ of irrigation water = -7.6°/oo.

b. Experiment at constant temperature (21.5 ± 0.5°C) and varying relative humidity. $\delta^{18}O$ of irrigation water = -7.4°/oo.

c. Experiment at constant relative humidity (about 45%) and temperature (about 21°C) and varying isotope composition of the irrigation water.

Liquid and vapor in isotopic equilibrium fall on a line of slope 8, while liquid and vapor kinetically separated fall on a line of slope 3. Of course, a combination of the two processes would produce a slope between 3 and 8 (Dansgaard, 1964; Craig and Gordon, 1965). Measurements by Lesaint et al. (1974) of δD and $\delta^{18}O$ of water in leaves fall on a line of slope 2.9, and a maximum $\delta^{18}O$ difference between leaf water and stem water of 23°/oo. Thus, kinetic evaporation is evidently the process involved in transpiration.

This is entirely consistent with plant physiological experiments (see, for example: Zelitch, 1971) which strongly support diffusion of water vapor through stomatal openings as the dominant transpiration process. The rate of transpiration (in g cm^{-2} sec^{-2}) is thus related to humidity and diffusional resistance by "Ohm's law" (Zelitch, 1971):

$$\text{Transpiration} = \frac{X_i - X_a}{R_a + R_s}$$

where X_i = saturation water vapor concentration at the leaf temperature and X_a = vapor pressure in the surrounding air (both in g cm^{-3}); R_a and R_s are diffusional resistances of water vapor in air and stomatal openings, respectively (in sec cm^{-1}). The term $(X_i - X_a)$ is proportional to [1 - (relative humidity) x 10^{-2}] if leaf temperature equals air temperature. Therefore, the lower the relative humidity, the more rapidly a plant transpires. Note also that R_s will be a function of species, light intensity, temperature and availability of water, and that R_a is a function of wind velocity, especially below 0.5 meters per second (Devlin, 1975).

The leaf water $\delta^{18}O$ values observed by Lesaint et al. (1974) can be explained by a model with a steady-state system consisting simply of a single mixed reservoir (leaf or cell within a leaf). Water flows into the reservoir with a fixed $\delta^{18}O$ and out via transpiration with a $\delta^{18}O$ which is 25°/oo lower than in the reservoir. This is illustrated in Figure 4. Water in the leaf may also undergo photolysis, but in this

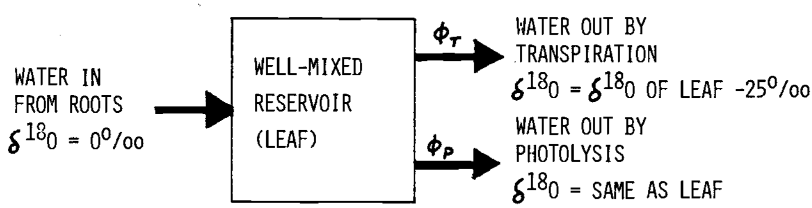

Figure 4. Scheme of the box model utilized to evaluate Figure 5 showing the dependence of $\delta^{18}O$ with ϕ_T (transpiration H_2O flux) and ϕ_P (photolysis H_2O flux).

model, we do not consider that isotope fractionation occurs in this step. The rate of transpiration is designated ϕ_T and the rate of photolysis ϕ_P. After transpiring an amount of water several times the weight of the reservoir, the system reaches an isotopic steady-state, i.e., the $\delta^{18}O$ of the reservoir water levels off. These steady-state $\delta^{18}O$ values given by the model are a function only of ϕ_T/ϕ_P, and are shown in Figure 5. Because of other variables, relative humidity cannot be placed on this scale, but the figure indicates where "high" and "low" humidity lie.

If CO_2 equilibrates isotopically with leaf H_2O, this model explains the range and direction of the humidity effect, but not its linearity. More importantly, it is not consistent with the experiments in Figure 2c which indicate little effect of irrigation H_2O and by implication leaf H_2O on the $\delta^{18}O$ of plant tissue.

We have here some laboratory empirical results in apparent contradiction with field evidence, and we are left with partial explanations, none of which may be correct. Clearly, more controlled growth experiments should be done, and they have been planned.

RELEVANCE TO PALEOCLIMATIC RESEARCH

These experiments wave a caution sign that $\delta^{18}O$ in plant tissue may be responding to temperature only in-as-much as temperature affects relative humidity. It is a long and tenuous thread that connects laboratory results obtained from plants grown under controlled conditions and field results from plants grown under the vicissitudes of nature. In nature there are diurnal variations of the temperature and humidity.

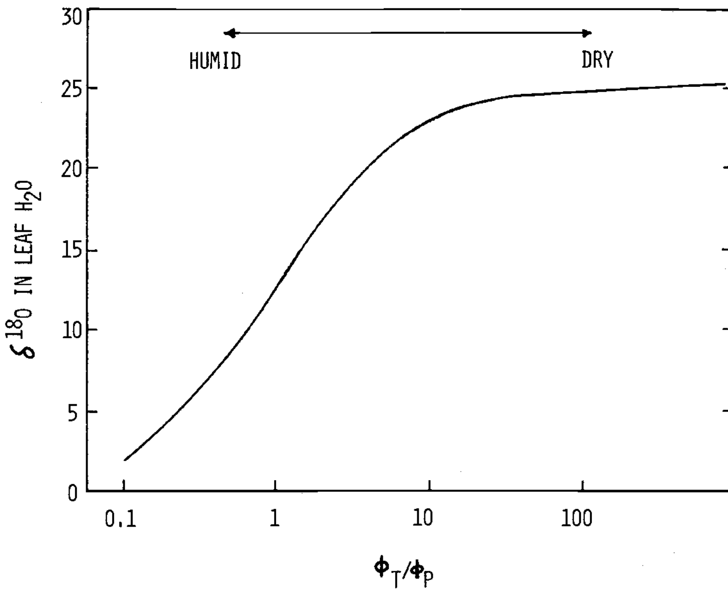

Figure 5. Calculated isotope fractionations of sap water as a function of relative humidity and of ϕ_T/ϕ_P (= transpiration flux/photolysis flux) from the model described in the text.

Also, with each precipitation event, $\delta^{18}O$ of irrigation water varies (Dansgaard, 1964; Mook, 1970). The stomata in leaf surfaces through which CO_2, O_2 and H_2O pass, open only when sufficient light and water are available. It is reasonable to assume, therefore, for paleoclimate investigations, that the $\delta^{18}O$ in total tissue or in cellulose from tree-ring specimens will have recorded both a temperature and a humidity component. Recent evidence on cellulose from Pinus radiata (Wilson and Grinsted, 1977), and on whole wood tissue from King Billy pine (Arthrotaxis selaginoides) (Pearman et al., 1976) indicate that $\delta^{13}C$ in wood is temperature dependent. Gray and Thompson (1976) have shown that the $\delta^{18}O$ of cellulose from white fir correlates well with annual average temperatures. Thus, the combination of $\delta^{18}O$ and $\delta^{13}O$ measurements on tree-ring sequences should be a useful probe into past climates. Moreover, when isotope data from trees in a continental wide network of sample points are coupled with dendroclimatological results from the same or nearby moisture-sensitive trees, a very powerful and comprehensive paleoclimatic tool may result.

HOW DO THESE RESULTS RELATE TO PLANT SCIENCE RESEARCH?

The modelized relationship between the $\delta^{18}O$ observed in plant tissue and the ratio between transpiration and photosynthesis signals to us one of the obviously possible applications to plant science. This isotope method would offer the possibility of a fast and cheap method for screening a large population of different plant species or different varieties or different individuals for water use efficiency. Thus, the same technique would be useful to retrieve/predict climate and to screen for better crops for the climates to come.

SUMMARY

We have discussed two models to attempt an explanation of the stable oxygen isotope ratios observed in plant tissue and the implications for two types of research: paleoclimate reconstruction, and plant science research. A computer model now seems feasible which would generate possible temperature and humidity conditions from $\delta^{18}O$

data stored in plant cellulose, perhaps ultimately from dendrochronologically dated tree rings, and such a model might provide us with a simple and cheap tool to gain insight into the physiology of modern plants.

ACKNOWLEDGEMENTS

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RESIDUAL WAXES FOR WATER HARVESTING

by

Dwayne H. Fink

INTRODUCTION

Refined paraffin wax has now been field tested for 5 years as a soil treatment for water-harvesting catchments at our Granite Reef test site, with no significant loss of runoff efficiency (still near 90%) or visible deterioration (Fink et al. 1973). Furthermore, the paraffin treatment is being accepted for use on catchments for watering livestock and wildlife (Cooley et al. 1976), and for establishing vegetation on mine spoil (Alden and Springfield 1975) and rangeland (Schreiber and Frasier 1977).

I elected to extend the wax-treatment studies to include laboratory testing of several of the numerous residual waxes produced by the various oil companies. There were several reasons for including residual waxes: (1) switching to residual waxes would constitute an "energy" savings, simply because they are byproducts; (2) they are slightly cheaper than refined paraffin (approximately 19¢ vs. 20¢ per lb., respectively, at source); (3) the literature suggests that many of the residual waxes are more adhesive and less brittle than paraffins (both factors could be important under certain soil-climate conditions).

Unfortunately, several inherent factors tend to frustrate any attempt at establishing a rational research approach to studying these residual waxes. The first is the formidable industry-predicated lingo used to describe the waxes. One encounters terms like slack wax, scale wax, petrolatum and crude petrolatums, amorphous and microcrystalline wax, road oil, tank bottoms, etc. The petroleum industry usually delineates waxes according to their production history, whereas chemists would prefer to delineate them according to the chemical structures of the constituents. Since residual waxes encompass such a wide range of properties, the name given a particular wax is not definitive. Some of these petroleum waxes are categorized in Table 1.

There are other frustrations. Whereas paraffin waxes are extremely uniform in their physical-chemical properties throughout the industry (refined paraffin waxes vary in grading primarily only by melting point), the residual waxes have practically no uniformity at all. Residual waxes vary according to both the crude source and the refining process. The latter includes both the refinery type and adjustments to the refining process used to maximize the yield and quality of those petroleum products having greatest economic return, a factor that can change daily. "Residual" means that the waxes are not the sought-after product. This results in tremendous differences both between and within the various wax types, and probably even within lots having identical designations from the same producer. As an example (Meyer 1968), crude petrolatum may contain from 5% to 50% oil, depending on how much the residual distillates have been dewaxed; the content of normal (straight-chain) or slightly branched paraffins may vary from 10% to 90%; and to complicate the matter further, content and type of saturated and unsaturated cyclic molecules vary tremendously -- as does content of certain coloring agents and other impurities.

From a water-harvesting-user standpoint, this variability and the concomitant unreliability of supply source result in the biggest disadvantage of all; namely, each material (and lot) probably must be individually tested for each proposed water-harvesting application. Needed is some "characterization index" of these residual waxes, based on easily obtainable physical-chemical properties, by which their potential for water-harvesting purposes can be evaluated.

In this report, the water-harvesting potential of several residual waxes is compared with that of refined paraffin, using laboratory tests designed to predict actual field performance of water-repellent soil treatments. These results were gleaned from several studies; thus, experimental conditions and tests were somewhat variable.

METHODS AND MATERIALS

Most of the laboratory procedures and tests used here have been described (Fink 1976a, b). Briefly, < 2 mm of soil was uniformly packed in petri dishes, air dried, then treated with the various wax materials by brushing them on as hot melts and further melting them in with heat lamps. Two soils were used: Granite Reef (sandy loam) from our laboratory's water-harvesting test site, and Superstition

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sand. Repellents studied were seven residual waxes (one also in emulsified form), a dust-suppressant oil, common 128-130 AMP refined paraffin, and several dust-suppressant oil-wax mixtures. Physical-chemical properties of the repellents per se were not evaluated.

The testing sequence is shown in Figure 1. It differs from that shown previously (Fink 1976a, b) in that samples which pass 500 hours' exposure to either ozone or ultraviolet (UV) radiation are now structurally destroyed by subjecting them to the freeze-thaw (FT) cycling sequence. As in the previous studies, the "relative repellency test" (L/L_n) quantitatively measures water repellency of the topical, exposed, treated-soil surface; the "4-hour hydration test" primarily qualitatively measures water repellency and/or waterproofing throughout the treated soil zone, but also detects structural failure of soils that hydrate excessively and then crack upon drying; the "brushing test" detects and removes loose and inadequately stabilized soil, thereby simulating water and wind erosive forces; the "dripolator test" utilizes the erosive force of water droplets to detect structural instability of the samples after their exposure to weathering by freeze-thaw cycling, concentrated ozone, or high-intensity UV radiation. The FT chamber cycled between $\pm$ 20 C at about 10 cycles per day. The UV weatherometer is designed so that 100 hours' exposure should equal that accumulated in 1 year in the midcontinent area. Ozone concentration in the ozone weatherometer was approximately ten times atmospheric.

This report represents four separate laboratory experiments carried out over several years' duration. Only the first experiment reported here used the complete testing procedure of Figure 1; the others used only selected parts of it.

EXPERIMENTS AND RESULTS

SLACK WAXES -- Experiment 1.

In this study (Table 2), Granite Reef soil was treated with four different residual waxes and a refined paraffin as standard, each at three application rates, for laboratory evaluation with the complete testing sequence outlined in Figure 1.

All treatments passed the initial, preweathering, water-repellency, and structural stability evaluations.

In Table 2, an (R) or an (S) signifies the sample failed either the 4-hr-hydration test or the erosion test, respectively, after exposure to ozone or UV radiation for the exposure time listed. Data are omitted for the relative-repellency test (L/L_n) after each 100 hrs' exposure, because degree of topical repellency after weathering begins has little or no effect on whether water will infiltrate the sample.

All samples resisted ozone attack. UV radiation did gradually reduce water repellency of the paraffin-treated samples, but was quite ineffective against the slack waxes, except for the low application rate of the Phillips 10 petrolatum. Samples exposed to ozone and UV withstood more FT cycling than did those not exposed to these two weathering elements. The cause of this added resistance is unknown, but may be related to the longer equilibration time for the ozone- and UV-weathered samples.

The Hawaiian crude was the most effective treatment overall in the laboratory and was particularly resistant to damage from FT cycling. The Bakersfield slack wax and Phillips 20 petrolatum withstood FT cycling somewhat better than did the paraffin, thus they could be effective treatments where such cycling is not excessive. Increasing the application rate of these two residual waxes slightly improved resistance to degradation by FT cycling. Unfortunately, random variability of the FT cycles was rather large. Generally, differences of less than 50 cycles between treatments were not considered significant. As reported previously (Fink 1976b), the petri disk samples always degraded under the centrally located water drop in the FT weatherometer -- never at the dry periphery. All samples, except those few which failed because of UV exposure, also passed the final dripolator test.

The four residual waxes performed as well as, or better than, paraffin. Results suggest that all these waxes should perform satisfactorily as water-harvesting treatments where FT cycling under moist conditions is not a big factor. Where it is a factor, the Hawaiian crude should be satisfactory. These waxes are now being laboratory evaluated on different soils to evaluate effects of soil textural variation.

SLACK WAXES -- Experiment 2.

In this study (Table 3), two soils were treated with three residual waxes, an emulsion of one wax, and an emulsified refined paraffin at application rates of 0.5 and 1.0 kg/m^2. Samples then were laboratory evaluated for initial water repellency (relative repellency and 4-hr-hydration test) and structural stability (brush test), for resistance to weathering by FT cycling, and to resistance to water erosion by the dripolator test.

Relative repellencies of most treatments were either borderline ($1.0 < L/L_n < 1.30$) or unacceptable ($L/L_n \leq 1.0$). Nevertheless, all passed the 4-hr-hydration test except emulsified paraffin applied at the low rate to Granite Reef soil. This suggests either that relative repellencies of 1.2 or greater are adequate, since most fell in this range, or that the waxes plugged the soil pores enough to prevent water infiltration (impermeable barrier). These samples also were given the brush test before weathering in the FT chamber. Samples treated with the Chevron 110 petrolatum (melt or emulsified, high or low rate) were most resistant to such simulated erosion; however, soils treated with the higher rate of either Chevron 140 slack wax or the paraffin emulsion also passed this test. Granite Reef soil treated with Mobile P42 failed both the brush and dripolator tests.

The Chevron 110-treated samples (both wax forms, both rates, and both soils) also consistently performed well in the FT chamber. In general, the sand samples outperformed the silt-loam soil in the FT chamber, but 172 cycles for the 1-kg/m^2 rate of 110 on Granite Reef soil was satisfactory. It seems that sandy soils could be safely treated with any of these residual waxes provided that the application rate was 1.0 kg/m^2 or greater. Results for the paraffin emulsion treatment were quite inconsistent and need further study.

The primary advantage of being able to use commercially-prepared wax emulsions is that less sophisticated equipment and technology would be required to treat soil catchments. A disadvantage is that it costs just to transport water; furthermore, if the waxes must be emulsified on site by the applicator, special equipment, chemicals, and technology are required anyway.

WAX-DUST SUPPRESSANT MIXTURES

In this study (Table 4), a dust-suppressant oil (DS) and several mixtures of the DS with three waxes were laboratory screened for effects of weathering by FT cycling, ozone, or UV radiation on water repellency and structural stability. The dust suppressant (a residual petroleum resin) contained an antioxidant; the waxes were a 128-130 AMP refined paraffin, Bakersfield slack wax, and Phillips 10 petrolatum.

All treated samples, which were prepared in triplicate, passed the initial relative water-repellency (L/L_n) and the 4-hr-hydration tests. Samples were then weathered in one of the three weatherometers. The 100% DS-treated soil was quite resistant to degradation by FT-cycling and ozone, but was vulnerable to attack by UV radiation (failed 4-hr-hydration test after 250 hours of weathering). All the DS-wax mixtures withstood the 500 hours of ozone and UV weathering without failing the definitive 4-hr-hydration, brush, or final dripolator tests (the mixtures complement each other). As in the first study, samples treated with 100% paraffin and Phillips 10 petrolatum were quite vulnerable to attack by ozone and UV radiation. Adding small amounts (5%) of paraffin or Bakersfield slack wax markedly improved the performance of the dust suppressant in the FT chamber; e.g., the number of FT cycles tolerated increased from 200 to 300 for DS only, to over 600 for the mixtures (three of the four samples are still being cycled). However, FT tolerance rapidly decreased as the proportion of wax increased above 5%. As in the first study, Granite Reef soil treated with 100% paraffin or 100% Bakersfield slack wax was quite vulnerable to degradation by FT cycling.

Adding dust suppressant did improve the FT tolerance of the Phillips 10 petrolatum, but not nearly as dramatically as those of the other two waxes. The results of this study suggest that DS-wax mixtures should weather better than any of the materials used singly.

WAXES ON STABILIZED SOIL

In this study (Table 5), packed Granite Reef soil was prestabilized using Terralock stabilizer at two dilutions and two rates. After the stabilized soil had air dried, Chevron 140 slack wax or paraffin was applied at 0.5 and 2 kg/m^2. Results were rather disappointing. Neither the stabilizer, the wax rate, nor the wax type significantly affected tolerance to FT cycling. No treatment withstood even 100 FT cycles. Stabilizers, however, may have potential for reducing water erosion of wax-treated, coarse-textured soil.

SUMMARY

ADVANTAGES OF RESIDUAL WAXES FOR WATER HARVESTING

1. Use of residual waxes instead of paraffin for preparing water-harvesting catchments would constitute an "energy" savings, since residual waxes are byproducts of the petroleum industry.
2. Several of the residual waxes outperformed the standard refined paraffin in these laboratory tests: Treated soils were initially water-repellent and structurally stable against erosion; they also better withstood the ravaging weathering effects of freeze-thaw cycling, ozone, and ultraviolet radiation.
3. Mixtures of certain waxes and a dust-suppressant oil outperformed either alone.
4. Residual waxes generally are slightly cheaper than refined paraffin.

DISADVANTAGES

1. Unlike the refined paraffins, which have remarkable uniformity throughout the industry, properties of residual waxes cannot be determined adequately from their industry-assigned names: a particular residual wax type encompasses a wide variation of physical-chemical properties, and there may even be considerable variation between lots of a particular wax.
2. Presently, each material (possibly each lot) must be individually tested for each proposed water-harvesting application.
3. No quickly and easily obtainable "characterization index" of these products presently exists.
4. None of the waxes has yet been successfully field tested.

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Table 1. Petroleum waxes and properties. 1/

Refined paraffin:	A narrow-range, reproducible distillate petroleum cut consisting of macrocrystals of normal (straight-chained) hydrocarbons and some isoparaffins (branched-chain); low in oil content (< 0.5%) and other impurities; melting point generally lower than that for residual waxes (120-160°F); brittle; very low adhesive strength.
Slack wax:	Paraffinic wax which still retains considerable (35%) oil (dewaxed but not deoiled).
Scale wax - or crude scale wax:	Similar to paraffin wax, but less highly refined and slightly higher in oil content (1-5%); (deoiled slack wax).
Semirefined wax:	Quality and properties range between crude scale and refined paraffin.
Reclaimed paraffin wax:	Wax salvaged from treated paper; textiles, etc.; varies in quality; generally cheaper than refined grades.
Cerels:	"Waxes" having melting points between that of common refined paraffin and low-pour oil (100 - 0°F).
Semicrystalline or semimicro waxes:	Waxes having properties midway between paraffin and microcrystalline wax.
Microcrystalline wax:	Wax extracted from heavy petroleum distillates and residues (residual petrolatum cut); normally consists largely of microcrystals of isoparaffins (branched) and naphthenes (saturated ring) along with small amounts of aromatic hydrocarbons and other impurities but may contain up to 90% of normal or slightly branched paraffin; oil content should be less than 5%; melting point is generally higher than the paraffin waxes (130-200°F); they vary from soft and plastic to hard and brittle; generally, they are more adhesive and resistant to moisture than paraffin. In essence, the range of physical-chemical properties of microcrystalline waxes is extremely large compared to the paraffin waxes.

Table 1. Petroleum waxes and properties (continued).

Amorphous wax:	Early-industry synonym for microcrystalline wax.
Crude petrolatum:	An unctuous residual wax containing a considerable amount of oil; dewaxing heavy petroleum distillates to obtain motor oil yields petrolatum as residue; deoiling petrolatum further yields microcrystalline wax.
Black wax:	Wax obtained by blowing heated air through melted petrolatum or other petroleum waxes.
Rod wax and tank-bottom wax:	Precursors of what we now call crude petrolatum and microcrystalline wax.
Residual wax:	Includes all of the above listed waxes except the paraffins.
Asphalt:	Another residual product of crude oil, consisting of a complex colloidal mix of solid organics dispersed in a liquid oil phase.
Road oils:	Petroleum residues similar to asphalt but of lower viscosity; often sold as cutbacks.
Bottom settlings:	Sludge collected at the bottom of oil tanks which is an emulsified mixture of water, oil products, and mud.
Additives:	Materials added to petroleum products to change their physical-chemical properties; the list is innumerable.

1/ Material in this table was gleaned from the following references: Bennett, 1975; Guthrie, 1960; Hahn, 1970, Van der Hane and Verner, 1957; Meyer, 1968; and Anglo-Iranian Oil Co., Ltd., 1949.

Table 2. Accelerated laboratory weathering by ozone, ultraviolet radiation, and freeze-thaw cycling of wax-treated Granite Reef soil.

		Weathering element				
				Freeze-thaw cycling 2/		
Waxes	Rate	UV 1/	Ozone 1/	FT	UV	Ozone
	kg/m^2	hrs exposure		cycles		
Paraffin,	0.50	200(R)	500	7	0 4/	63
128-130 AMP	0.75	400(R)	500	16	0	84
	1.00	300(R)	500	17	0	45
Phillips 10	0.50	500(R,S)	500	16	0	24
petrolatum	0.75	500	500	16	29	57
	1.00	500	500	16	63	86
Phillips 20	0.50	500	500	16	48	52
petrolatum	0.75	500	500	33	67	147
	1.00	500	500	57	115	170
Bakersfield	0.50	500	500	30	48	86
slack	0.75	-- 3/	500	36	--	137
	1.00	500	500	58	173	189
Hawaiian	0.50	500	500	237	630	413
crude	0.75	500	500	352	788	796
	1.00	500	500	196	796	613

1/ Weathered up to 500 hrs, with testing for repellency (R) and stability (S) after each 100 hrs; R or S notation indicates failure from 4-hr-hydration or brush test, respectively.
2/ Number of cycles required to destroy treatment; FT (freeze-thaw only); UV (exposed first to 500 hrs of high intensity ultraviolet radiation; ozone (exposed first to 500 hrs of highly concentrated ozone).
3/ Sample accidentally destroyed prior to completion of testing.
4/ Zeroes denote that sample failed a previous critical test.

Table 3. Water repellency and structural stability of residual-wax-treated soils subjected to freeze-thaw cycling, as determined by the relative repellency, 4-hr-hydration, brush, and dripolator tests.

		Granite Reef soil					Superstition sand				
		pre-tests 1/					pre-tests 1/				
Wax	Application rate	L/L_n	4-hr hyd	brush test	freeze-thaw cycles	drip-olator	L/L_n	4-hr hyd	brush test	freeze-thaw cycles	drip-olator
	kg/m^2										
Mobile P42	0.5	1.23	+	-	0 2/	F	1.23	+	-	0	N
Prowax	1.0	1.31	+	-	0	F	1.27	+	+	329	*
Chevron 140	0.5	1.29	+	-	0	F	1.37	+	-	0	N
slack wax	1.0	1.36	+	+	22	N	1.34	+	+	264	M
Chevron 110	0.5	1.27	+	+	22	N	1.26	+	+	264*	*
Petrolatum	1.0	1.28	+	+	172	N	1.26	+	+	342*	*
Chevron 110	0.5	1.23	+	+	93	N	1.31	+	+	215*	*
emulsion	1.0	1.20	+	+	71	N	1.25	+	+	304*	*
Refined paraffin (128-130 AMP)	0.5	1.11	-	-	0	F	1.24	+	+	376*	*
cationic emulsion (3177)	1.0	0.99	+	+	109	N	0.80	+	+	2	N

1/ Initial tests run prior to freeze-thaw cycling; + denotes passing, - denotes failing test.
2/ Zero denotes failing a previous test, therefore not subjected to freeze-thaw cycling.
3/ Dripolator test erosion notation: N, none; M, pitting ≤ 3 mm; F, pitting through treated zone.
* Still under test.

Table 4. Water repellency and structural stability of Granite Reef soil samples treated with mixtures of wax and dust suppressant and exposed to freeze-thaw cycling, concentrated ozone, or ultraviolet radiation.

		Weathering element					
		Freeze-thaw		Ozone		Ultraviolet	
			Drip- 1/	hrs		hrs	
Repellent	Rate	Cycles	olator	250	500	250	500
	ℓ/m^2						
Dust suppressant (DS)							
(antioxidant)	0.5	336	N	Δ 3/	Δ	1,2	1,2
	1.0	268	N	Δ	Δ	1	1
DS + wax mixtures:							
5% paraffin	0.5	659 2/	-	Δ	Δ	1	1
	1.0	678	N	Δ	1	1	1
10% "	0.5	127	N	Δ	Δ	1	1
	1.0	663 2/	-	Δ	Δ	1	1
25% "	0.5	72	N	Δ	Δ	1	1
	1.0	197	N	Δ	Δ	1	1
100% "	0.5	4	N	Δ	1,2,3,4	3	0 4/
	1.0	4	N	Δ	Δ	Δ	Δ
5% Bakersfield	0.5	555 2/	-	Δ	Δ	1	1
slack wax	1.0	632 2/	-	Δ	Δ	1	1
10% "	0.5	173	N	Δ	Δ	1	1
	1.0	121	N	Δ	Δ	1	1
25% "	0.5	47	N	Δ	Δ	Δ	1
	1.0	172	N	Δ	Δ	1	1
100% "	0.5	22	N	Δ	Δ	Δ	Δ
	1.0	47	N	Δ	Δ	Δ	Δ
5% Phillips 10	0.5	147	N	Δ	Δ	1	1
petrolatum	1.0	127	N	Δ	Δ	1	1
10% "	0.5	47	N	Δ	Δ	1	1
	1.0	261	N	Δ	Δ	1	1
25% "	0.5	25	N	Δ	Δ	Δ	1
	1.0	141	N	Δ	Δ	1	1
100% "	0.5	4	N	1,2	1,2,3,4	Δ	1,2,3,4
	1.0	12	N	Δ	1	Δ	Δ

1/ Dripolator test: N denotes no detectable erosion; dash (-), not yet evaluated.
2/ Still being cycled in freeze-thaw chamber.
3/ Δ denotes passing all tests: (1) L/L_n, (2) 4-hr-hydration, (3) brush test, (4) the dripolator test after 500 hrs weathering; numerals denote which tests failed.
4/ Zero (0) means sample failed a previous critical test in the sequence.

Table 5. Resistance to structural destruction by freeze-thaw cycling of Granite Reef soil treated with Terralock stabilizer, then with either refined paraffin (128-130 AMP) or Chevron 140 slack wax.

Stabilizer Dilution	Stabilizer Rate	Wax Rate	Freeze-thaw cycles to destroy stability: Paraffin	Freeze-thaw cycles to destroy stability: Chevron 140
vol/vol	ℓ/m^2	kg/m^2	freeze-thaw cycles	
-- none --		0.5	12	0 1/
		2.0	16	50
1:20	1	0.5	4	21
		2.0	37	94
1:20	2	0.5	4	38
		2.0	16	38
1:5	1	0.5	18	52
		2.0	21	4
1:5	2	0.5	20	42
		2.0	65	51

1/ Failed initial brush test.

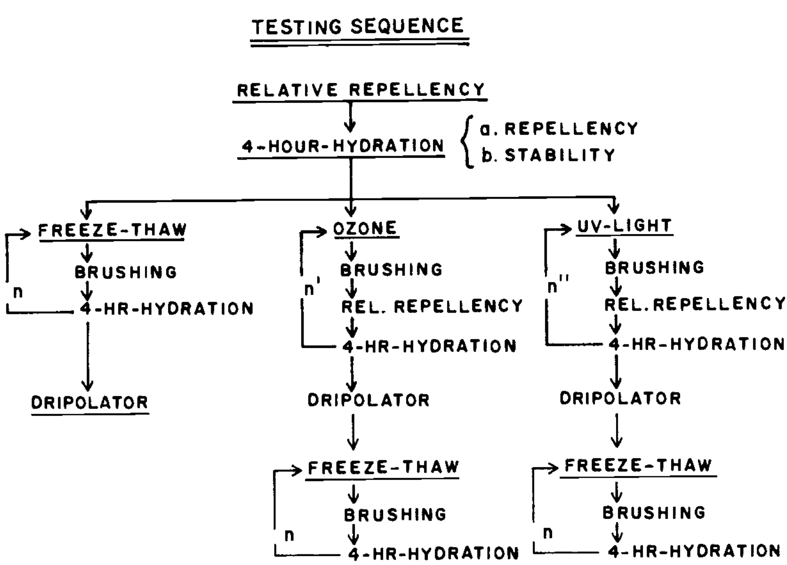

Figure 1. Laboratory testing sequence for evaluating water-repellent soil treatments for water harvesting.

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A UTILITY CRITERION FOR REAL-TIME RESERVOIR OPERATION

by

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ABSTRACT

A dual purpose reservoir control problem can logically be modelled as a game against nature. The first purpose of the reservoir is flood control under uncertain inflow, which corresponds to short-range operation (SRO); the second purpose, which the present model imbeds into the first one, is water supply after the flood has receded, and corresponds to long-range operation (LRO). The reservoir manager makes release decisions based on his SRO risk. The trade-offs involved in his decision are described by a utility function, which is constructed within the framework of Keeney's multiattribute utility theory. The underlying assumptions appear to be quite natural for the reservoir control problem. To test the model, an experiment assessing the utility criterion of individuals has been performed; the results tend to confirm the plausibility of the approach. In particular, most individuals appear to have a risk-averse attitude for small floods and a risk-taking attitude for large ones.

INTRODUCTION

The purpose of this paper is to present a development of a *utility criterion* for real-time reservoir operation under uncertainty. In recent years, intensive studies have been emerging concerning applications of statistical decision theory, subjective probabilities and utility theory. Real-time operation of a reservoir constitutes a scenario which exhibits all features needed to exemplify the above concepts in a direct and very natural manner.

In brief, the reservoir has a random input, the forecasting of which is provided by skillful meteorologists and hydrologists whose *subjective judgments* and *assessments of uncertainties* are indispensable in the present state-of-the-art in river forecasting. Next, there is a reservoir manager (also called the decision maker) whose experience provides *preferences* for making risky decisions and crucial trade-offs between operating objectives. The whole decision problem is, nevertheless, too complex to be analyzed directly by a human decision maker, so that the aid of a mathematical model is called for.

Despite a large research effort in the area of reservoir operation, there has been very little done to bridge the gap between river *forecasting* and *decision making* on the *operational level* - in the day-to-day, hour-to-hour operation. One way to link probabilistic forecasting (by and large subjective) with preferential reservoir operation is to resort to the decision theory. Bayesian approach offers a decision-making framework which accounts explicitly for uncertainty on reservoir inflow and for preferences over operational attributes.

In the context of a decision theoretic framework, this paper develops a utility criterion for real-time reservoir operation under uncertainty. Toward this aim, the decision problem is analyzed, and multiattribute utility theory (Keeney, 1974) is applied. It is shown that short-range reservoir operation may be modeled naturally as a game against nature, and, therefore, that a very realistic framework for assessing the reservoir manager's utility function can be obtained. Once the preferences of the manager are quantified in terms of the utility criterion, a decision model can be formally employed in solving complex operation problems in a real-time setting.

The paper is organized as follows. The next section defines the reservoir operation problem and presents a concept for imbedding short-range operation into long-range operation. In Section 3, short-range operation is viewed as a game against nature. The risk present in that game is described, and a need for a measure of the decision maker's preferences in the reservoir operation is exposed. In Section 4 a utility model is developed, and in the next Section the assessment procedure is discussed. Section 6 reports results of an experiment in assessing utility criterion.

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RESERVOIR OPERATION PROBLEM

TYPES OF RESERVOIR OPERATION

Consider a single, multi-purpose reservoir. Two types of operation are identified as follows. *Short-range operation* (SRO) is defined by purpose set

PS = {flood control}.

Long-range operation (LRO) is defined by a set of purposes

PL = {1. water supply (irrigational, industrial, municipal),
2. hydroelectric power generation,
3. low flow augmentation (navigation, fish and wildlife, recreation),
4. lake recreation}.

In a particular situation, the elements of PS and PL can be modified, but it is assumed that, always, $PS \cap PL = \emptyset$. Furthermore, it is assumed that SRO and LRO are performed over nonoverlapping finite time intervals (Figure 1). It follows that SRO is implemented during floods and that LRO is implemented between successive flood events. This fact is emphasized inasmuch as the definition of LRO bears on operational viewpoint and differs considerably from what planners usually mean by the long-range (seasonal) reservoir operation. The principal hydrologic and decision characteristics of both types of operation are summarized in Table 1. Although all of them are essential, attention is focused on characteristic number four to justify the definition of SRO and LRO over nonoverlapping intervals of the reservoir input.

To restate the approach, the analysis will concentrate on SRO; at the same time, through an appropriate imbedding of SRO into LRO, it will be guaranteed that, at any time, SRO is directed toward satisfying both sets of purposes PS and PL. The basic reason for imbedding is to assure that the operation explicitly considers the trade-offs between conflicting sets of purposes PS and PL. Thus, in the sequel, reservoir operation will always mean SRO which satisfies imbedding conditions into LRO.

IMBEDDING SRO INTO LRO

In this section, the decision problem in SRO is defined; then it is shown that the appropriate choice of the outcome space provides an easy imbedding of SRO into LRO.

The decision problem in SRO will be analyzed under the following assumptions: (1) SRO is initiated whenever the forecasted P[inflow rate > threshold value] >0, where it is understood that the forecast containing probability P is valid over a finite time interval, e.g., successive 24 hours. (2) Storage space at the beginning of SRO is a known parameter, and it results from the preceding LRO. (3) The decision maker can only make one decision for the entire period of SRO. Although this assumption may not be quite realistic, it is imposed here only to simplify the presentation. In fact, each decision in a sequential-decision operation is of the same nature. Therefore, for the purpose of encoding the decision maker's preferences, it is sufficient to analyze a single-decision problem; yet, the utility criterion developed in this way can be used in a sequential-decision operation, if needed.

The *decision problem* in SRO is now structured. Let the *state space* = {inflow hydrograph} be discrete and finite, and suppose that the nature chooses an inflow hydrograph in accordance with a known distribution law. The *decision space* = {rate of release from the reservoir}, and the *consequence space* (outcome space) = Z x Y, where

$z \in Z$ is the *maximum flood level* (flood crest) measured above initial damage level at a specified location below the reservoir, and
$y \in Y$ is the *storage space* (storage deficit) at the end of the flood.

With each of the sets PS, PL, and PS x PL, one associates a set of *measures of consequences* (effectiveness) $\{G_i:Z \times Y \to Re\}$ i = S, L, SL, with Re an abstract set. Examples of measures of consequences are stage-damage curve: $G_S:Z \to \$$, and a relation between storage deficit and dollar loss in irrigation: $G_L:Y \to \$$. The following two assumptions are introduced:

ASSUMPTION 1. *In reservoir operation problem defined by PS x PL, G_S is defined on Z, G_L is defined on Y, and $G_{SL} = f(G_S, G_L)$.*

Roughly speaking, Assumption 1 says that the measures of consequences for SRO and LRO are separable. Accordingly, the performance of LRO (SRO) can be adequately expressed as a univariate function defined on Y(Z). That is to say, for a given input over period of LRO, the performance of LRO depends only upon the initial storage space y. Since y is also the final storage space in SRO, it provides a means of *imbedding* SRO into LRO. The mere fact that a consequence of SRO constitutes an initial condition for LRO will be referred to as an *imbedding condition.*

ASSUMPTION 2. *With $\succ$ a binary preference relation on Z and Y, the decision maker possesses a preference which satisfies the property that for any $z_1 < z_2$ and $y_1 < y_2$, $z_i \in Z$, $y_i \in Y (i=1,2)$, $z_1 \succ z_2$ and $y_1 \succ y_2$. We shall denote by z_o and y_o the most desirable consequences; by definition $z_o = 0$ and $y_o=0$.*

RESERVOIR OPERATION AS A GAME AGAINST NATURE

The object of this section is to reveal the nature of the decision problem as defined in Section 2. Ultimately, it is to indicate the existence of a fair agreement between the mechanism of SRO and the mechanism of the von Neumann-Morgenstern (1947) scheme for utility assessment. First, let the SRO decision problem be analyzed within the framework of a game against nature (Luce and Raiffa, 1957).

Owing to Assumption 2, *pure decision* is defined as one which for a given inflow hydrograph yields minimal value of z and y_o. We introduce an intuitive notion of "small flood", MF, and "large flood", AF. A forecasting procedure specifies the probability of having either MF or AF as (p,1-p), $0 \leq p \leq 1$. The appropriate pure decisions will be denoted by M and A respectively. For short-hand, let $[(z,y);p;(z_1,y_1)]$ denote a game yielding either (z,y) with probability p or (z_1,y_1) with probability 1-p, $0 \leq p \leq 1$.

Now the decision problem may be presented as a game where the decision maker chooses one from among two *decisions* (M,A) and then nature takes on one of two *states* (MF, AF) with probabilities (p,1-p). The *consequences* of the game are shown in Table 2, a payoff table. The scheme of Figure 2 may help to visualize this game. For simplicity, let the flood level z be the rate of release from the reservoir.

Observe the following. By definition of the game, $z_{AM} = z_{AA} = z_A > z_o$, and $y_{MM} = y_{AA} = y_o = 0$. Also $y_{MA} = 0$ since the reservoir is overtopped due to too small release rate M. Finally, $z_{MM} \leq z_A < z_{MA}$, and $y_o < y_{AM}$. These observations yield to the modified game as presented in Table 3 in which the payoff table is given separately for each consequence for easy visualization.

Summing up, the decision maker is faced with the necessity of choosing between two decisions when the true magnitude of the oncoming flood is uncertain. To arrive at the choice, he must decide in his mind whether he prefers the game $[(z_{MM},y_o);\ p;\ (z_{MA},y_o)]$ to the game $[(z_A,y_{AM});\ p;\ (z_A,y_o)]$ or conversely. The choice of the decision M results in a certain value of the storage space y_o and in a gamble over maximum flood level (z_{MM} or z_{MA}). Conversely, the choice of the decision A results in a certain value of the flood crest z_A and in a gamble over storage space (y_{AM} or y_o).

The point is probably obvious that the disutility of flooding the plain or emptying the reservoir and the willingness to "take a chance" may play an important role in choosing the decision. That is to say, the consequence (z,y) is a psychological variable (Coombs and Beardslee, 1954) and in this case the criterion of minimizing expected monetary loss may not mirror the decision maker's risk behavior. Furthermore, it was recognized (Kates and White, 1961) that many man-made decisions concerning flood hazard result from an individual's attitude toward taking or toward averting risk rather than from pure evaluation of monetary consequences. We accept, thus, in this study a psychological hypothesis that in reservoir operation, the decision maker chooses that decision which minimizes his expected utility.

The von Neumann-Morgenstern (1947) scheme for utility assessment is based upon the expected utility hypothesis

$$u(c) = pu(a)+(1-p)u(b) \tag{1}$$

for an indifference relation $c \sim [a;p;b]$. Specifically, this relation implies that the individual is indifferent in the choice between the certain consequence c and the gamble yielding the consequence a with probability p and the consequence b with probability 1-p.

We are now in a position to indicate the direct equivalence between the risky situation in reservoir operation, as presented in the framework of the two-state flood game (Table 3), and the problem of choice, as imposed by relation (1). The von Neumann-Morgenstern scheme for utility assessment seems to be, in the case of reservoir operation, a very realistic procedure. Particularly, if the decision maker has some utility or disutility for risk (gambling) then this is exactly what we want to extract from him because the same personal characteristic may significantly influence the decision maker's perceptions of the real reservoir operation.

UTILITY MODEL

Under conditions induced by the von Neumann-Morgenstern axioms (1947), the utility function u is defined over attribute set Z x Y. We assume boundness of this set in the sense that there exists the most desirable attribute (z_o,y_o) and the least desirable attribute (z_e,y_e). To arrive at a functional form for u, heuristic assumption concerning the decision maker's preferences in SRO is made.

ASSUMPTION 3. *In SRO, Z and Y are mutually utility independent.* (For definition of utility independence the reader may wish to consult Keeney (1974)). Our heuristic support proceeds as follows. Although Z and Y are related physically to one another through basic laws of hydraulics, they are controls for independent sets of purposes PS and PL. Along with Assumption 1, this assures that the decision maker's preferences over any attribute induced by Z should be independent of the value of any other attribute induced by Y and vice versa. Particularly, this assertion holds if Z and Y are considered to be attributes themselves.

By virtue of Theorem 1 in Keeney (1972), Assumption 3 indicates a separable form for u(z,y) is appropriate. We selected

$$u(z,y) = u_1(z) + u_2(y) + f_1(z)\ f_2(y) \tag{2}$$

Theoretical development of this model, along with necessary and sufficient preference conditions and admissible transformation, is given by Fishburn (1974). Model (2) holds under the generalized utility independence condition which allows for reversals of preferences. Although under certain circumstances one could expect reversals in preferences over Z x Y, especially in the games with extreme values of the attributes, such situations will not be considered here. In most cases, more restrictive definition of the utility independence, as that of Keeney (1972), should be sufficient. Accordingly, (2) can be written operationally as

$$u(z,y) = k_z u_z(z) + k_y u_y(y) + k k_z k_y u_z(z)\, u_y(y), \tag{3}$$

with u_z, u_y, $u \varepsilon [0,1]$; $u_z(z_0) = u_y(y_0) = u(z_0,y_0) = 0$; $u_z(z_e) = u_y(y_e) = u(z_e,y_e) = 1$; and constants $k_z, k_y \varepsilon (0,1)$. The scaling constant k is determined by the relation

$$k = (1-k_z-k_y)/k_z k_y. \tag{4}$$

Strictly speaking, u as defined above is disutility function. Hence an appropriate decision criterion is minimization of the expected value of u.

Since the corner utilities in (3) are $u(z_e,y_0) = k_z$ and $u(z_0,y_e) = k_y$, from the estimates for k_z and k_y one can infer the decision maker's multivariate risk behavior as defined by Scott (1975). Accordingly, the decision maker is strictly multivariate risk averse (SMRA) if $k_z + k_y < 1$; strictly multivariate risk seeking (SMRS) if $k_z + k_y > 1$; and multivariate risk neutral (MRN) if $k_z + k_y = 1$.

ASSESSMENT PROCEDURES

PRINCIPLES

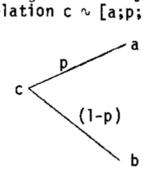
Derivations of utility functions from the decision maker's responses have been reported in the literature by many authors, such as Davidson et al. (1957); Schlaifer (1969); Halter and Dean (1971); Keeney (1975). Therefore, this section does not discuss details of the assessment schemes which already have been widely publicized. However, the procedures which to some extent are uncommon are thoroughly presented. They are based on the findings from present experiments in assessing the utility function in the specific context of reservoir operation. It is encouraging to find that these results concur with those of different experiments reported by behavioral scientists.

The development of the assessment procedures have been based on the following principles:

1. *Games with choices between extreme values of the attributes should be avoided.* It is a standard approach to begin the assessment of a single-attribute utility function u_z with a game $z_1 \sim [z_0;p;z_e]$. We found that the utility function obtained in this way may have a substantial bias for at least two reasons. First, it was indicated (Sheridan and Ferrell, 1974) that the more extreme, and thus usually the less likely to occur, the values of the attributes, the more likely anomalous behavior of the subject is to be observed. This can be especially so in reservoir operation because the necessity of making a compromised decision between a disastrous drought and a catastrophic flood is very unrealistic. Second, since the remaining subject's responses are quantified in relation to the first, even small bias in the first response may drastically affect the shape of the utility function. Thus a mistaken image of the decision maker's behavior can easily be produced. Such effects can be seen in Figure 3.

2. *The range and variance of the outcomes from the games should be realistic.* This is because, as found by Edwards (Sheridan and Ferrell, 1974), many subjects' preferences are apparently affected by the range and variance of the outcomes from a gamble; it is thus important that the utility function account for this type of preference. Then, for the purpose of encoding the preference structure which results from the subject's perception of the real decision situation, it is necessary that the range and variance of the games outcome be similar to those in reality. Also, the sequencing of games over various ranges of attributes should be carefully thought out to stimulate the subject to perceive the assessment process as a real-decision making situation in which he can fully use his managerial experience.

The assessment process reported herein is based upon the above principles in conjunction with the results of works by Becker et al.(1964) and Keeney (1975). It is conducted in a step-by-step manner and typically consists of a sequence of games satisfying the expected utility equation (1). Schematically, a game with an indifference relation $c \sim [a;p;b]$ will be represented as



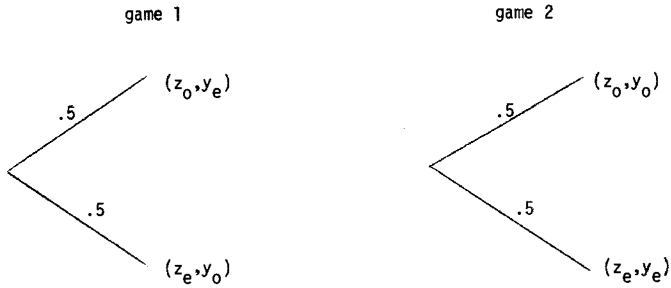
The subject's response may be in terms of the one attributed value (a,b, or c) for the two other given values and probability p, or in terms of the probability p for the given attribute values a,b, or c. For clarity, the value to be assessed by the subject will be marked by *.

The assessment process consists of three stages:

1. verification of the risk behavior,
2. assessment of single-attribute utility functions,
3. assessment of the corner utilities (trade-offs).

VERIFICATION OF THE RISK BEHAVIOR

To verify the type of multivariate risk behavior, the decision maker is presented with a choice between the two games:



The decision maker is SMRA if game 1 $\succ$ game 2; SMRS if game 2 $\succ$ game 1; and MRN if game 1 $\sim$ game 2.

ASSESSMENT OF SINGLE-ATTRIBUTE UTILITY FUNCTIONS

The assessment procedure is shown for attribute Z; assessment of u_y proceeds along the same way. The procedure consists of a sequence of games specified in Table 4 and explained as follows:

Step 1. Choose an arbitrary point z_n such that $z_o < z_n < z_e$.

Step 2. Assess utility function u_o for $z\varepsilon[z_o,z_n]$ on [0,1] scale, i.e., $u_o(z_o) = 0$, $u_o(z_n) = 1$. This can be accomplished by playing the games 1-3, but more games can be considered if needed for better accuracy or the consistency check.

Step 3. Assess utility function u_n for $z\varepsilon[z_n,z_e]$ on [0,1] scale, i.e., $u_n(z_n) = 0$, $u_n(z_e) = 1$ (games 4-6).

Step 4. Perform the game 7 (and 8 for the consistency check), and link the two utility functions u_o and u_n so as to obtain a function u_z defined on $[z_o,z_e]$ and scaled on [0,1]. This can be done as follows. By the fact that the utility function is unique up to a positive linear transformation, there exists a constant h>0 such that

$$u_o(z) = h\cdot u_n(z) + 1, \qquad \text{all } z\ \varepsilon[z_o,z_e].$$

Hence

$$h = (u_o(z)-1)\ /u_n(z). \tag{5}$$

If $z_7 < z_n$ then from the expected utility equation for the game 7

$$u_o(z_6) = 2u_o(z_7) = u_o(z_3)$$

and (5) can be evaluated in z_6 since $u_n(z_6)$ is known. If $z_7 > z_n$ then the expected utility equation for the game 7, written in terms of u_n, gives

$$u_n(z_3) = 2u_n(z_7) - u_n(z_6)$$

and (5) can be evaluated in z_3 since $u_o(z_3)$ is known. In the same manner h can be computed from the game 8, providing thus the consistency check.

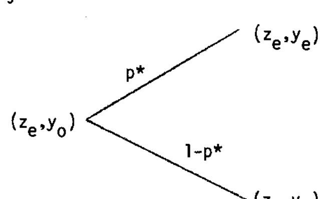
Now the utility function u_z can be defined on $[z_o,z_e]$ as follows

$$u_z(z) = \begin{cases} u_o(z)/(1+h) & \text{for } z_o \le z \le z_n \\ \\ [h\ u_n(z) + 1]/(1+h) & \text{for } z_n \le z \le z_e \end{cases} \tag{6}$$

where u_z is scaled on [0,1].

ASSESSMENT OF THE CORNER UTILITIES

From (3), the corner utilities are found to be $u(z_e,y_o) = k_z$, and $u(z_o,y_e) = k_y$. Assessment of k_z (and in a similar fashion of k_y) can easily be accomplished from the game



Expected utility equation for this game yields $u(z_e,y_o) = p$, and so $k_z = p$. This method of assessing corner utilities was used by Keeney (1975). Although this scheme is remarkably simple, it does not satisfy the first principle of avoiding games between extremes, discussed earlier. The alternative scheme proposed here was developed from that of Keeney by eliminating the games which included solely extreme values of attributes and responses in terms of probability.

Step 1. First the approach of Yntema and Torgerson (described in Sheridan and Ferrell, 1974) is used. The decision-maker is asked to locate the "corners" (z_e,y_o) and (z_o,y_e) directly on [0,1] interval scale of worth with 0 representing corner (z_o,y_o) and 1 representing corner (z_e,y_e). Inasmuch as such direct response may be subjected to a large perceptional error, in the next steps k_z and k_y are derived from a sequence of responses. Then the results from both methods can be compared for consistency.

Step 2. Assess indifference pairs.

For an arbitrary z_1, $z_o < z_1 < z_e$, assess $y_1{*}$ such that $(z_o,y_1{*}) \sim (z_1,y_o)$, which implies that $u(z_o,y_1) = u(z_1,y_o)$ and by (3) $k_y u_y(y_1) = k_z u_z(z_1)$. Consequently,

$$k_z = k_y \frac{u_y(y_1)}{u_z(z_1)} \tag{7}$$

To check the consistency, another indifference pair $(z_2{*},y_e) \sim (z_e,y_2)$ can be assessed for an arbitrary y_2, $y_o < y_2 < y_e$. In terms of (3) it implies that

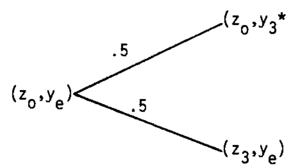
$$k_z u_z(z_2) + k_y + kk_z k_y u_z(z_2) = k_z + k_y u_y(y_2) + kk_z k_y u_y(y_2)$$

and substituting (4) for k

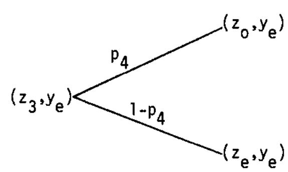
$$k_z = [k_y(1-u_z(z_2)) + u_z(z_2) - u_y(y_2)]/(1-u_y(y_2)). \tag{8}$$

Step 3. Find corner utilities.

For an arbitrary z_3, $z_o < z_3 < z_e$, conduct a game



and consider also a game



Solution of the expected utility equations for these games gives

$$k_y = (1-p_4)/(2-p_4-u_y(y_3)).$$

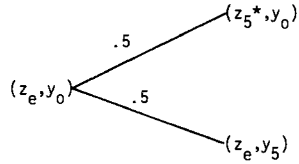
The second game need not be conducted with the decision-maker. Observe that the value of the attribute Y in this game is constant. Since Z is utility independent of Y, the expected utility equation for this game can be written as

$$u_z(z_3) = p_4 u_z(z_o) + (1-p_4)u_z(z_e).$$

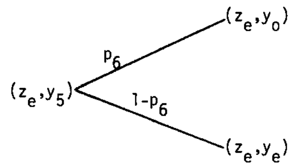
Since $u_z(z)$ has already been assessed, p_4 can be found directly from the relation $p_4 = 1-u_z(z_3)$. Hence the equation for k_y becomes

$$k_y = \frac{u_z(z_3)}{1 + u_z(z_3) - u_y(y_3)} . \tag{9}$$

In a similar manner k_z can be obtained by conducting, for an arbitrary y_5, $y_o < y_5 < y_e$, a game



and considering also a game



Solution of the expected utility equations yields

$$k_z = \frac{u_y(y_5)}{1 + u_y(y_5) - u_z(z_5)} \tag{10}$$

Inasmuch as Equations (7) and (9) uniquely determine the corner utilities, only responses y_1* and y_3* have to be obtained. If the responses z_2* and z_5* are also determined, then Equations (8) and (10) may serve as the consistency check.

EXPERIMENT IN UTILITY ASSESSMENT

The experimental assessment of the reservoir control utility function was conducted with five professional hydrologists. In a hypothetical operation problem, the reservoir was assumed to serve the following sets of purposes:

PS = {flood control},

PL = {power generation, navigation}.

The ranges of the attributes were $z \in [0,24]$ feet and $y \in [0,300] \times 10^3$ acre-feet. In addition to the description of the decision problem, the subjects were presented with engineering stimuli. For assessing u_z these were cross-sections and photomaps of the floodplain, pictures of the floodplain from the past floods, and the stage-damage function. In assessing u_y, the primary stimulus was a function relating storage deficit y to the expected monetary loss. Also, a description of nonmonetary consequences for various values of y was given.

After the assessment process had been completed, the results were discussed with each subject. Particularly, correct interpretations of doubtful responses, like inflection points on the utility curve, were being checked. The subject could then refine his responses if any inconsistencies became apparent.

The results are presented for three subjects out of five who participated in the experiment. Figure 3 shows single attribute utilities u_z and u_y. The values of the corner utilities k_z and k_y are given in Table 5.

RESULTS

1. An operational interpretation of the risk taking and risk averting behaviors is given first. Let two decision makers be faced with a necessity of choosing the operational rate of release from the reservoir. If the decision makers' behavior in this choice situation is consistent with their utility functions, then the release rate chosen by the risk averter should be greater than the release rate chosen by the risk taker.

2. The shape of u_z heavily depends upon location of various establishments in the floodplain. In this sense all subjects appeared to be risk takers (concave u_z) for some flood levels and at the same time risk averters (convex u_z) for other flood levels. For example, subject 4 shows the risk taking behavior for low flood levels. At level 10 (above which the residential and industrial area extends), he becomes very strongly a risk averter. That is, whenever the forecast indicates a positive probability of having a flood with $z > 10$, he easily decides on an advanced discharge up to level 10 in order to prepare the reservoir for the largest forecasted flood and thus reduce the chance of flooding the levels greater than 10. But when levels 10-13 become flooded, he prefers, again, gambling.

3. Utility functions of five subjects and the monetary loss function (which was used as a stimulus) rescaled to the interval [0,1], have been plotted in Figure 4 which gives an idea about the difference between individual perceptions of the same decision problem. Also the considerable diversity between criterion functions when utilities instead of monetary losses are considered is quite apparent.

4. The large bias which may be introduced into the subject's preference structure by the range of the games in the assessment process is illustrated in Figure 3 which shows the response obtained from the game over the entire range of an attribute (game [0;.5;24] for z, and game [0;.5;300] for y). When this inconsistency was pointed out to the subjects, they did not change their responses (or changed them only slightly), stating that it is hard to perceive such drastically diverse consequences, and that, therefore, their response is based upon an undefined feeling rather than upon a rational judgment. Interestingly, in most cases, the responses are biased in the direction of risk aversion. This example may well serve as a warning against unaware application of utility assessment schemes which require unrealistic judgments from the decision maker.

5. An intriguing dilemma emerged from verification of the multivariate risk behavior. In 3 cases out of 5, the subjects were found to be SMRA by application of the choice test. However, after assessing corner utilities, all subjects appeared to be SMRS. Reconsideration of the assessment process did not change the subjects' responses; moreover, they did not see any inconsistency in their answers. Although this result could cast doubt upon the adequacy of the utility concept as a decision behavior model of the subjects, we still think that the model can be very useful on the basis of hydrological considerations. First, the subjects' behavior, though inconsistent within the framework of the utility model, can still be considered as rational. The fact that $[(z_o,y_e);.5;(z_e,y_o)] \succ [(z_o,y_o);.5;(z_e,y_e)]$ does not preclude one's opinion that the "half-disastrous" consequences (z_o,y_e) and (z_e,y_o) are both closer, on the preference scale, to the worst consequences (z_e,y_e) than to the best consequence (z_o,y_o), and thus that $k_z + k_y > 1$. Secondly, there is a hope that the model may, nevertheless, perform satisfactorily provided the choices between extreme values of the attributes are excluded. Inasmuch as real-time reservoir operation satisfies, in general, this condition, this optimism is perhaps not without grounds.

CONCLUSIONS

1. It may be possible to predict the sequential behavior of a decision maker faced with a reservoir operation problem by assessing his utility for a single decision. For this purpose, the SRO should be imbedded in the LRO.

2. The reservoir operation problem may be modelled as a game against nature of the von Neumann-Morgenstern type.

3. The assumption that utility independence holds in SRO leads to a multiplicative utility function.

4. In the assessment of a multiattribute utility function, games between extremes are not acceptable because they bias the subject's response.

5. For similar reasons, the range and variance of state and decision variables in the experiments should be close to the range and variance in the real-life decision situations.

6. An algorithm compatible with the latter two points has been applied to assess the utility function of five hydrologists, who are all found to be risk averters for small floods and risk takers for large ones.

7. Results of the experiments lead to certain inconsistencies which may be explained in terms of the particular hydrological situation chosen for the tests.

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Table 1. Basic characteristics of short-range operation (SRO) and long-range operation (LRO)

SRO	LRO
1. Short operating horizon (measured in terms of hours or days).	1. Long operating horizon (measured in terms of weeks or months).
2. "Immediate" decisions are required (on an hourly basis).	2. Decision-making process can be extended in time (over days or even weeks).
3. High variability of the inflow rate.	3. Low variability of the inflow rate.
4. Input is forecasted in terms of rate of flow, and the operation concerns directly the rate of release from the reservoir.	4. Input is forecasted in terms of flow volumes over certain periods of time, so that the scheduling of releases concerns the volumes of outflow.
5. Usually the reservoir is refilled.	5. Usually the reservoir is drawn down.

Table 2. Two-state flood game

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">DECISION</td></tr>
<tr><td>M</td><td>A</td></tr>
<tr><td rowspan="2">STATE OF NATURE</td><td>MF</td><td>z_{MM}, y_{MM}</td><td>z_{AM}, y_{AM}</td></tr>
<tr><td>AF</td><td>z_{MA}, y_{MA}</td><td>z_{AA}, y_{AA}</td></tr>
</table>

Table 3. Modified two-state flood game

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">DECISION</td></tr>
<tr><td>M</td><td>A</td></tr>
<tr><td rowspan="2">STATE OF NATURE</td><td>MF</td><td>z_{MM}</td><td rowspan="2">z_A</td></tr>
<tr><td>AF</td><td>z_{MA}</td></tr>
</table>

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">DECISION</td></tr>
<tr><td>M</td><td>A</td></tr>
<tr><td rowspan="2">STATE OF NATURE</td><td>MF</td><td rowspan="2">y_o</td><td>y_{AM}</td></tr>
<tr><td>AF</td><td>y_o</td></tr>
</table>

Table 4. Example of a sequence of games for assessing u_z

STEP	Game i	a_i	b_i	c_i
2	1	z_o	z_n	z_1^*
	2	z_o	z_1	z_2^*
	3	z_1	z_n	z_3^*
3	4	z_n	z_e	z_4^*
	5	z_4	z_e	z_5^*
	6	z_n	z_4	z_6^*
4	7	z_3	z_6	z_7^*
	8	z_1	z_4	z_8^*

Table 5. Corner utilities and multivariate risk behavior

Subject		1	2	3	4	5
k_z		.94	.82	.76	.93	.78
k_y		.82	.52	.42	.62	.40
$k_z + k_y$		1.76	1.34	1.18	1.55	1.18
Multivariate risk behavior	From $k_z + k_y$	SMRS	SMRS	SMRS	SMRS	SMRS
	From choice test	SMRA	SMRS	SMRA	SMRA	SMRS

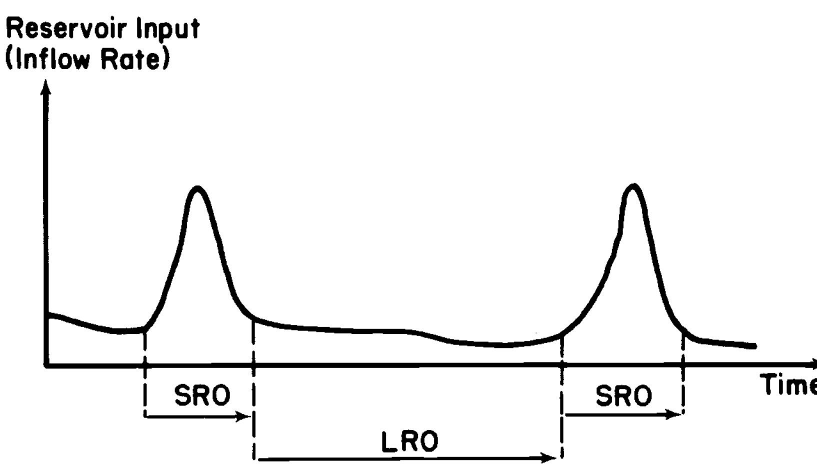


Figure 1. Input versus definition of short-range operation (SRO) and long-range operation (LRO)

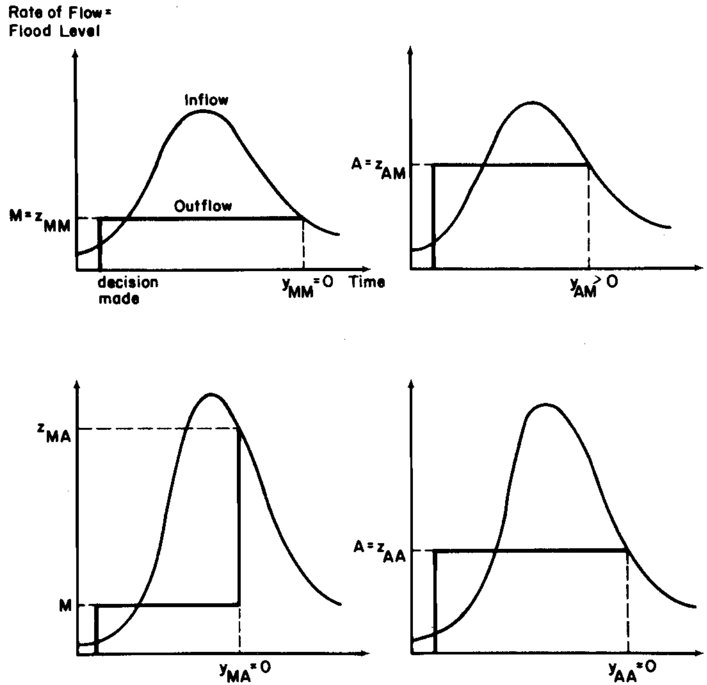
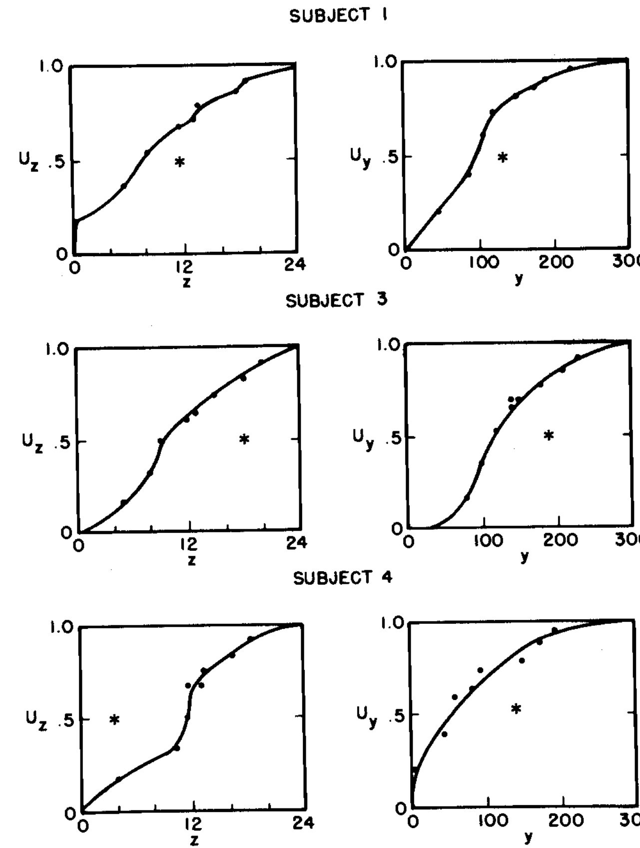


Figure 2. Schematic presentation of the outcomes of the two-state flood game



• Subject's response
* Subject's response from the game over the entire range of the attribute

Figure 3. Single-attribute utility functions

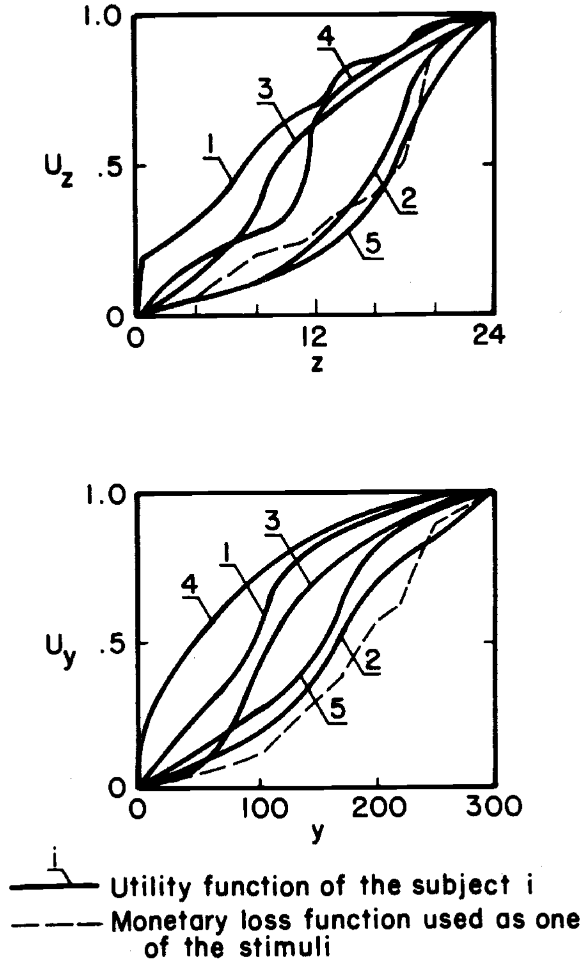


Figure 4. Single-attribute utility functions and economic loss functions

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Proceedings of the 1977 meetings of the Arizona Section of the American Water Resources Association and the Hydrology Section of the Arizona Academy of Science, held in Las Vegas, Nevada, April 15-16.

AN APPLICATION OF MULTIDISCIPLINARY WATER RESOURCES PLANNING AND MANAGEMENT FOR THE SAN CARLOS APACHE INDIAN RESERVATION: GILA RIVER CASE

by:

M.E. Norvelle, D.J. Percious, N.G. Wright

INTRODUCTION

The purpose of this paper is to briefly describe the formation and function of a new unit established at the University of Arizona, to provide technical assistance for natural resource development for southwestern Indian tribes; and the special institutional and cultural environment within which this function is to be carried out. The cost-effectiveness methodology is used to address a resource development problem on the San Carlos Apache Indian Reservation because of its general nature and rather special features.

PROBLEM SETTING

CULTURAL SETTING

The Laboratory of Native Development, Systems Analysis and Applied Technology (NADSAT) was established within the Office of Arid Lands Studies, University of Arizona, in June, 1976, to provide technical assistance to Southwestern Indian tribes to aid them in the development and economic utilization of their natural resources according to their goals and objectives. Imbedded within this committment is the obligation of technology transfer to assist the tribes in attaining an increased level of self determination. Current technology is to be applied to Indian resource development problems by NADSAT and transferred to the Tribes so that they can deal with similar problems in the future with a greatly reduced level of reliance upon outside assistance.

A primary consideration in this regard is the difference in cultural perception between the American Indian and the non-Indian analyst concerning the natural environment. Natural resource development and management is essentially a manipulative process whereby the planner and/or manager assesses a development problem in terms of its various elements and their interrelationships and in quantifiable terms whenever possible. Elements within are manipulated to enhance the output or value of the resultant product (s) sought over a particular time period depending upon the objectives.

However, Indian culture, with few exceptions, is essentially non-manipulative in its perception of the natural environment. Historically, the Indian has viewed himself as living in harmony with nature instead of being engaged in a contest with it, as has typified non-Indian society; however, it has become increasingly obvious to Indian societies that the economic development of their natural resources can yield considerable benefits. Development of their natural resources, consonant with the Indian desire of self determination, can not only provide sizeable social and economic advantages to individual tribes; but contribute to the gross national product as well. As was pointed out by Anderson, 1976, the three conditions necessary for economic development are, 1) jurisdictional control over tribal natural resources, 2) availability of capital, and 3) management assistance. Hence, there is a need for strengthening tribal resource ownership and sovereignty for if Indians lack control over their resources, they lack control over their economy.

NADSAT's role is assistance and technology transfer and therefore has adopted a passive, rather than an active role in decision making. The emphasis is on alternative formulation and performance analysis, relative to their costs and effectiveness in attaining tribal objectives, and a means to communicate the technological approach to

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tribal decision makers. The primary function of the technology transfer objective is to provide tribal decision makers and planning personnel with an appreciation for the non-Indian method of resource problem conceptualization, the factors to be considered in the analysis, and the formation of alternatives that a multidisciplinary analytical team perceives.

The cost-effectiveness methodology has been adopted for this study not only because it provides a systematic methodology for problem conceptualization and subsequent analysis, but it also is a coherent framework to interface various disciplines in a multi-criterion problem and affords a mechanism for technology transfer.

PHYSICAL SETTING

The San Carlos Apache Tribe has requested that NADSAT formulate possible alternatives for utilization of the land and water resources of the Gila River Basin portion of its reservation, emphasizing use of its decreed surface water allocation from the river.

The Gila River portion of the reservation lies in the Basin and Range Physiographic Province and is part of a northwest trending structural trough, bounded by volcanic mountains on the north and granitic and gneissic mountains on the south. Ground water occurs in a deep, basin-fill aquifer of low permeability, under semi-confined conditions and a shallow alluvial aquifer occupying the terrace and floodplain alluvium. The drainage area of the Gila upstream of the reservation gage is 11,470 square miles. Rainfall averages over 13 inches per year with precipitation dominated by winter frontal and summer cyclonic storms. Some 390 acres are currently being irrigated with pumped river water, and shallow ground water during the low river flow periods. Crops raised are alfafa, barley, and grain sorghum. Water quality of the Gila varies inversely with discharge exhibiting a very high sodium hazard during low flow periods. Ground water is pumped for irrigation from the alluvium; but is of poor quality presenting a high to very high sodium hazard to its use for irrigation. Numerous thermal springs discharge to the surface from the basin fill in close proximity to the river on the north, contributing to the salinity problem.

COST-EFFECTIVENESS (CE) METHODOLOGY

The CE methodology grew out of military applications and was standardized by Kazanowski, 1968, to comprise the following 10 steps:

1) Define the desired goals, objectives, or purposes that alternative systems are to meet or fulfill.
2) Identify the requirements essential for the attainment of the desired objectives.
3) Develop alternative system concepts for accomplishing the objectives.
4) Establish system evaluation criteria that relate system capabilities to re-requirements.
5) Select fixed cost or fixed effectiveness approach.
6) Determine capabilities of alternative systems in terms of the criteria.
7) Generate system versus criteria array (evaluation matrix).
8) Analyze merits of alternative systems.
9) Perform sensitivity analyses.
10) Document the rationale, assumptions, and analyses underlying the previous steps.

The methodology has been used to compare water resources systems in the Mekong Basin by Chaemsaithong, Duckstein, and Kisiel, 1974; in analyzing waste water reuse schemes by Ko and Duckstein, 1972; in the analysis of large scale water development alternatives in the Hungarian Great Plain by David and Duckstein, 1976; and for evaluation procedures for water quality control analysis in river basins by Duckstein and Kisiel, 1972. They also pointed out that the Water Resources Council guidelines for water resources development falls squarely within the cost-effectiveness methodology.

Bokhari, 1975, used CE to accomplish *ex post* evaluation of river basin development in Pakistan and Popovich, et al, 1973, used the methodology to evaluate various solid waste disposal alternatives. Kisiel and Duckstein, 1972, employed the methodology to evaluate the economics of hydrologic modelling.

Kazanowski, 1972, emphasized the major sources of uncertainty in the use of CE as being in the determination of the goals/objectives, the criteria, and the uncertainty surrounding cost estimates of alternatives.

The CE methodology is a general approach to resource development problems that seems to find significant differences in the costs or requirements of alternatives that are formulated to attain desired objectives (Duckstein, 1975). The methodology, as is illustrated in the above 10 steps, is a systematic framework that leads analysts and decision makers alike throughout the process of conceptualization, the formulation of alternatives, and analysis of a resource development problem. Opportunities for the interfacing of multidisciplinary team expertise are present in all the steps. Decision makers are offered the latitude of decisions based either on a fixed cost (budgeting constraints) or a fixed effectiveness standpoint. Sensitivity analyses on the steps provides an element of feedback for both analysts and decision makers, the latter being able to view how perturbations in system elements can affect alternative outcomes relative to their fixed cost or fixed effectiveness decision basis. Finally, by virtue of step 10, the methodology is an invaluable tool to examine the outcome of implemented decisions, in an ex post fashion, in the light of new data or decision making imperatives at some future time. As such, the methodology is akin to an adaptive control process on resource development; whereby the methodology can be used successively, whether for project updating or for new ventures, incorporating past mistakes at each juncture.

COST-EFFECTIVENESS APPLICATION

The application of CE to the San Carlos Apache Indian Reservation will be discussed in a general manner since the inclusion of specifics would detract from the thrust of this paper, that of its importance as a comprehensive and systematic methodology for resource development problem in general, and an effective framework for multidisciplinary teams and a mechanism of technology transfer in developing situations.

The ordering of the steps is not of upmost importance since each problem may present significant differences. The order that we are utilizing in this problem is 1, 2, 4, 5, 3, 6, 7, 8, 9, 10. The salient difference is the procedure of step 4 over step 3, to avoid possible bias towards formulating MOE to conform to alternatives.

OBJECTIVES

Agricultural production. Maximize irrigated agriculture production from the available land resources along the Gila River.

Water resources. Increase the utilization and economic development of the valley's water resources.

Resource utilization. The use of natural, social, economic resources to implement and operate alternative systems should be minimized but may be conditioned by tribal and non-tribal institutional and cultural imperatives.

Salinity. The salinity impact from resource development should be minimized.

Flood protection. Flood protection should be provided to lessen deterioration of the natural resources of the valley.

Flexibility. Alternative system development should be flexible enough to meet the needs of the future and avoid foreclosures of future options open to the Tribe.

It is important to note that the combined efforts of a multidisciplinary team can perform an important function here. Since the objectives condition the entire process, it is important that the tribal objectives reflect as much as possible, the "true" desires of the tribal decision makers. The input from team and tribe can complement one another so that important omissions may be neglected or that preference hierarchies can be ascertained. This is a difficult process in any resource development problem and may require several consultations to ensure their appropriateness.

SYSTEM SPECIFICATIONS

These should be specified as completely as possible and follow in one-to-one order with the objectives.

Agricultural production. As much of the available agricultural land along the Gila should be used as possible. Yield increases of 20% could be realized in the presently cultivated 390 acres with improvements in water deliveries and farm management practices. Agricultural lands can be categorized as presently irrigated; having high, medium and low potential; and improved pasture. Categories are based on accessibility, soil characteristics, and potential for inundation from specified flood return periods.

Potential crops are wheat, barley, grain sorghum, cotton, jojoba, and alfafa. Farm budgets can specify break-even production levels. Unit cost-production/acre curves will assist in defining management requirements and target yields. Production periods are a function of time (years) for jojoba and annually for the remaining crops.

Water resources. The San Carlos Tribe has a decreed allottment (Globe, Equity No. 59) to 6000 AF/year from the natural flow of the Gila for reclamation and irrigation of 1000 acres of land. The amount of withdrawals are further constrained as not exceeding 12.5 cfs at any one time or 1/80 cfs per irrigated acre. Use of the shallow ground water system should be minimized but conditioned by the objectives. This constraint can be released with potential of quality improvement under a given alternative. Different contingency pumping schedules can arise from different alternatives. Monthly crop water demand can be determined from consumptive use figures for various crops. Different farm management specifications can alter total crop deliveries, and diversion requirements can be determined from efficiency specifications.

Resource utilization. The resource categories are water, land, manpower, energy, capital, and environmental resources.

Water losses represent a valuable resource and should be minimized. Losses can be determined by specifying water use and conveyance efficiencies for sprinkler and flood irrigation, and leaching requirements, if any.

Land resources are specified through the results of a basin-wide soil survey and flood inundation potential.

Manpower requirements occur both in the implementation and the operational stage of development. The potential for manpower utilization may be considerable and should be maximized to increase personal income and social well being and other benefits.

Energy consumption should be minimized. The prospects of additional energy from the existing source is highly uncertain and additional power from any source will be expensive and uncertain in the light of the present energy situation. The current average monthly consumption for 1 existing irrigation well is 1,336 Kwh with a peak demand of 100 Kw, assuming a peaking load factor of 1.1. Estimated irrigation horsepower is 165, based on total power use per year of 208,416 Kwh at 1650 Kwh horsepower (Loftin and Associates, 1977).

Capital resources may be broken down into categories to assist decision makers (DM) and lending institutions in financial feasibility analyses. Categories are land development costs, equipment costs, production costs, and the cost of irrigation facilities. These costs may be tempered by considerable uncertainty. In general, one would tend to minimize initial capital investment.

Environmental resources should be protected from any deterioration as much as possible. It is likely that wildlife populations may be enhanced by relatively large scale farming in the valley since the available land will be in parcels spread through the valley, affording populations cover and food supplies.

Salinity. A plot of specific conduct vs. discharge and a plot of the sodium absorption ratio (SAR) vs. discharge allows specification of discharge thresholds to irrigation suitability.

Surface water irrigation suitability and SAR specifications are as follows: a) 35 cfs, SAR = 12.3, very high sodium hazard, b) 90 cfs, SAR = 8.7, high sodium hazard, and c) 260 cfs, SAR = 4.5, medium sodium hazard.

Ground water quality is specified as it bears on its use for irrigation purposes or its impact on river and/or alluvial aquifer quality. Ground water issuing from 10 thermal, limestone springs north of the river, indicated total dissolved solids (TDS) from 1,357 to 4,037 ppm and a SAR range of 7.86-25.37. Analyses of irrigation well water from the alluvial aquifer exhibited a TDS range from 2,107 to 3,409 ppm and SAR's from 7.02 to 12.46. These waters fall either in the C4-S4 or C4-S3 class.

Analyses from stock wells that penetrate the basin fill aquifer indicate low TDS, low SAR's, and irrigation classifications from C2-31 to C3-S1.

Return flows should be minimized to avoid downstream problems. Pesticide residue levels 15-20 miles downstream at San Carlos Reservoir is already near FDA standards (Arizona Water Quality Council Hearings, 1976). Flows should subscribe to Federal Standards. State standards specify only boron and turbidity limits for agricultural purposes.

Flood protection. Annual peak floods are distributed as log Pearson III. Basic descriptive statistics for 46 years of record are, mean of 10,400 cfs, standard deviation of 13,700 cfs, skew of 3.27, and a coefficient of variation of 1.32 for the unlogged data. Return periods of 2, 5, 10, 25, 50, and 100 years have been computed and will be processed through the Army Corps of Engineers' HEC-2 water surface profile program to yield flood inundation levels, validated by remote sensing techniques. This information will yield protective measures for irrigation facilities and assist in crop selections for flood prone areas. Some crops such as barley can suffer flooding while jojoba can suffer no loss at all, constituting a no risk decision.

The set of specifications should be defined as precisely as possible since they identify the specifications or requirements that formulated alternatives are to fulfill to approach objective attainment. The word approach is used since it is probable that no particular alternative will satisfy all the desired objectives exactly. In addition, objectives are usually specified to meet higher order goals that correspond to broad society needs, and these are transitory.

Uncertainties in the specifications can be encoded into probability distribution functions, if possible, and can be used later in the sensitivity analysis.

SYSTEM EVALUATION CRITERIA

The criteria or measures of effectiveness (MOE) are used to evaluate how well a given system performs with respect to meeting the specifications, and hence the objectives. Systems responses may be quantitative such as crop production, system water deliveries, volume of ground water pumped, and the level of flood protection required; or may be expressed qualitatively for system flexibility; likelihood of tribal acceptance, tribal employment potential, and potential for soil improvement. The criteria list should be complete but not exhaustive and should follow the specifications sequence. The following is only a partial list for brevity.

Agricultural production. The MOE for agricultural production is #/acre or #/acre-year, for a rate criteria.

Water resources. Use is source specific and to quantity used, a) surface water in AF/year, and b) ground water pumped in AF/year.

Resource utilization. Land MOE is acres in production per year. Capital MOE may be in terms of land development costs, rate-of-return, and total investment. Energy MOE may be expressed as Kwh/year. Water losses MOE are similar to water use in AF/year. Environmental impact may be very good, good, fair, and bad. Manpower MOE may be expressed in terms of high, medium, and low potential for employment.

Kazanowski, 1972 pointed out that a complete listing of MOE is critical since it not only relates directly to objective attainment but plays an important role in the next step. With a fixed cost approach, decisions among alternatives are based on the evaluation criteria or MOE.

SELECT FIXED COST OR FIXED EFFECTIVENESS

This step is of considerable importance in the decision making process and is not a trivial matter. The "true" preference hierarchy of the Tribe's goals and objectives may be imbedded in the selection process and will become more obvious once the final selection is made and implementation begins. Goals are high order statements and specific objectives may be difficult to vocalize, especially regarding natural resources development. Ill specified objectives are recognized as an important source of uncertainty in multiobjective-multicriterion problems, as pointed out previously.

In the fixed cost approach, a definite budgetary expenditure is given, and the alternatives are compared in terms of levels of effectiveness. On the other hand, the fixed effectiveness approach requires that the alternatives be compared through alternative implementation costs. Analysts cannot dictate which approach should be taken since each decision approach will really be based on value judgements of the decision makers. The role of cost uncertainties, inherent in any problem, takes on a special significance in this step. Kazanowski, 1972, emphasizes this point and considers costs as a major uncertainty source.

It should be added that, despite scarce financial resources, a fixed effectiveness approach is still feasible because there may be a viable effectiveness level due to the availability of funds from outside sources. In addition, it is illuminating to comment on the phrase "it is cost-effective" that can often be heard conversationally or in the literature. As discussed above the two words are not correlative but speak to two different approaches in decision making. The desire for maximum effectiveness for the least cost is fallacious since minimum cost (zero) corresponds to minimum effectiveness (zero).

DETERMINE ALTERNATIVE SYSTEMS

Various systems formulated to achieve specified objectives should be distinct so that their costs and measures of effectiveness (MOE) can be explicitly related to each.

Extremal alternatives will tend to broaden a decision makers satisfaction space within which he operates, whereas marginal alternatives (not too distinct) will narrow the space so that trade-offs may be difficult to evaluate. This should be tempered with practicality and a foreknowledge of what institutional and cultural frame the DM is situated in. For the purposes of discussion, three preliminary alternatives are discussed in general terms, since their inclusion is not really germane to the tenor of this paper.

System I considers planting the entire valley with jojoba to take advantage of the salt tolerant aspects of the plant. The plant is indigenous to the Southwest and thrives on lesser amounts of water, in addition, its long maturation period, economic future, and production capacity/acre can create spillover effects for farm management training, personal income, and tribal welfare by strengthening the existing Apache Tribal Marketing Co-operative. Raising jojoba commercially is a no risk decision, requiring considerable flood protection.

System II would continue irrigation of crops in the conventional manner using river pumping plants and ground water wells to augment river supplies during low flow periods. This alternative would entail improvement of existing facilities, including flood proofing and refurbishing of poor productive irrigation wells; and the installation of new systems.

System III could entail fixed river pumping plants at various points, with flood protection that can function as System II and also lift river water up to gravity distribution points for distant fields or to spreading basins with small retention structures built on highly permeable alluvial fan areas. The structures can also function as a retardant for tributary flood waters. Recharge from these spreading areas can promote the flushing of poor quality ground water in the shallow alluvium by steepening the gradient towards the river. Environmental effects may be both good and bad.

DETERMINE ALTERNATIVE SYSTEM CAPABILITIES

This step analyzes the capabilities of alternative systems in terms of various MOE. The methods employed can range from simulation processes, stochastic hydrology, to pilot plant studies, analogues, and economic analysis.

GENERATE SYSTEM VS. CRITERIA ARRAY

For this step, an array is constructed that assembles all the system capabilities, as they relate to the specifications through their measures of effectiveness (MOE). This allows the decision makers (DM) an alternative by alternative comparison regarding their individual cost requirements, water deliveries, energy consumption or requirements, manpower potential, management requirements, etc.

The usefulness of the array tableau is heightened by the inclusion of quantitative and qualitative MOE's avoiding the fallacy that everything important is quantifiable or that all measures can be lumped into a sole criterion (Chaemsaithong, 1973, and Kazanowski, 1968).

ANALYZE THE MERITS OF ALTERNATIVES

The merits of the alternative systems require ranking in order of importance and is largely a subjective process. Ranking is the responsibility of the Tribe; however, assistance can be offered in examining the problem with specified cost and effectiveness levels to illustrate the process and perhaps generate an appreciation of the nontriviality of the matter. It is also important to appreciate that all the information in the array is assumed correct at this juncture, and that the ranking is not determined by arbitrary weighting. Various ranking techniques can be employed if serious conflicts arise.

PERFORM SENSITIVITY ANALYSIS

Sensitivity analyses are performed on all the previous steps to introduce a feedback element into the procedure. Perturbations are introduced to the various MOE's specifications, parameters, approach, etc. to observe changes in the system/criteria array. The effect of uncertainty categories can be assessed in this manner, e.g., economic and strategic uncertainties.

DOCUMENTATION

The essential value of the standardized CE methodology lies in its ability to order ones thinking regarding water resources planning and development, both on the part of the analysts and the decision makers. The organized approach is not only valuable in evaluating alternative courses of action, prior to implementation, and expected results; but also holds considerable value in looking back on actions taken and evaluating the results in the light of current information. The methodology can be used successfully for project planning, and subsequent reevaluation before new projects or updating is required, thereby retaining control over development and retaining flexibility. To accomplish the foregoing it is essential that the assumptions, rationale, and methodology employed are fully documented.

CONCLUSIONS

The following concluding points may be drawn from the above discussion:

1) The CE methodology is a general method to approach natural resource development problems.

2) CE can avoid the common fallacies inherent in other approaches, e.g., sole criterion as in benefit-cost, the trade offs are determined in the fixed cost or fixed effectiveness approach.

3) The methodology offers a systematic approach for analysis of resource development problems, with a built in feed back element to avoid omissions of important factors.

4) The methodology is able to account for all categories of uncertainty, e.g., natural, model, parameter, economic, strategic and technological.

5) Cost effectiveness methodology provides an important mechanism for technology transfer in that the conceptualization, factors, and alternative formulation and analysis, are communicated to decision makers in an orderly framework; and the interrelationships among important factors are revealed through the entire process.

6) CE offers a means of *ex post* evaluation of decisions, can incorporate new data for subsequent planning and implementation, and allows decision makers to retrace their steps through the entire decision process.

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SNOWPACK DENSITY ON AN ARIZONA MIXED CONIFER FOREST WATERSHED

BY

Peter F. Ffolliott and J. R. Thompson[1/]

INTRODUCTION

Snow density is one useful index of the stage of "ripening" in a snowpack. Fresh snow often has a density of 0.10 gm cm^{-3} or less. As the snowpack undergoes metamorphosis and ripening, a density of 0.35 to 0.50 gm cm^{-3} is attained. Arizona snowpacks are usually "ripe" in this range. Additional energy input to the snowpack will cause runoff.

DESCRIPTION OF THE STUDY

The objective of this study was to obtain basic inventory data on the seasonal variations in snowpack density on an Arizona mixed conifer forest watershed and to relate these variations to hydrograph characteristics. Also, we attempted to determine how peak seasonal snowpack densities are affected by differences in forest density, elevation, and potential insolation.

The study was carried out on the 440-acre North Fork watershed of the Thomas Creek drainage in east-central Arizona. Seven coniferous and two deciduous overstory species are found on the watershed: Douglas-fir, white fir, corkbark fir, Engelmann spruce, blue spruce, ponderosa pine, southwestern white pine, quaking aspen, and Gambel oak. Topography varies, with the lower and middle portions of the watershed being quite steep. Soils are derived from basalt parent materials; and elevations range from 8,400 to 9,150 feet. Annual precipitation averages 27 inches, approximately one-third of which occurs during the snowfall season of November through April.

Estimates of snowpack density were obtained from total snow depth and water-equivalent measurements taken with a federal snow sampler and scale at 75 to 90 randomly located sample points throughout the winters of 1972-73, 1973-74, and 1974-75. Measurements were taken prior to peak seasonal snowpack accumulation, at the time of peak seasonal snowpack accumulation, and during the snowmelt-runoff period.

Watershed streamflow was measured at a water-stage gaging station and converted to discharge values using a rating curve.

Data required to develop expressions of forest density, elevation, and potential insolation were obtained at each sample point. Forest density was estimated by point sampling techniques (Avery 1975). The number of trees tallied with an angle gage corresponding to a basal area factor of 25 were determined at each sample point. This measurement represents an index of the amount of crown closure over the sample points.[2/] The elevation of each sample point was estimated from 7 1/2-minute USGS topographic maps with 20-foot contours. Potential insolation (gram calories cm^{-2}) received on an index date was obtained from slope and aspect measurements (Frank and Lee 1966).

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2. An unpublished study conducted on the North Fork of Thomas Creek showed percent of overhead crown closure estimated from canopy photographs (Brown 1962) to be correlated with basal area estimated by point sampling techniques.

RESULTS AND DISCUSSION

The source data for this study were obtained from a relatively large number of sample points located on the watershed studied. Therefore, the sampled population was considered to be the entire basin snowpack, not just localized snowpacks in the immediate vicinity of snow courses. In this respect, the study differs from most of the other investigations which have been less concerned with statistical characterization of the spatial variation in snow densities on entire watersheds.

An average snow density of between 0.35 and 0.40 gm cm^{-3} apparently represented ripe conditions for the North Fork of Thomas Creek, as the snowpack generally remained in this density range for most of the runoff period in each of the years of study (Figures 1, 2, and 3). Snow density did not drastically change in this period, although water-equivalents decreased. Occasionally, densities exceeded this range near the end of runoff, when only residual patches of snow remained on the watershed.

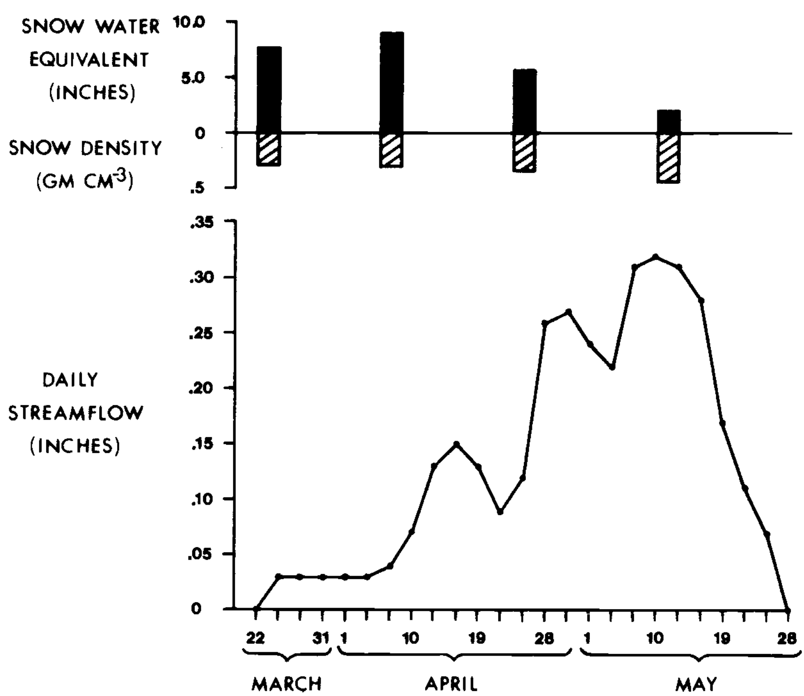

Fig. 1. Snowpack density, water equivalent, and daily streamflow for 1972-73.

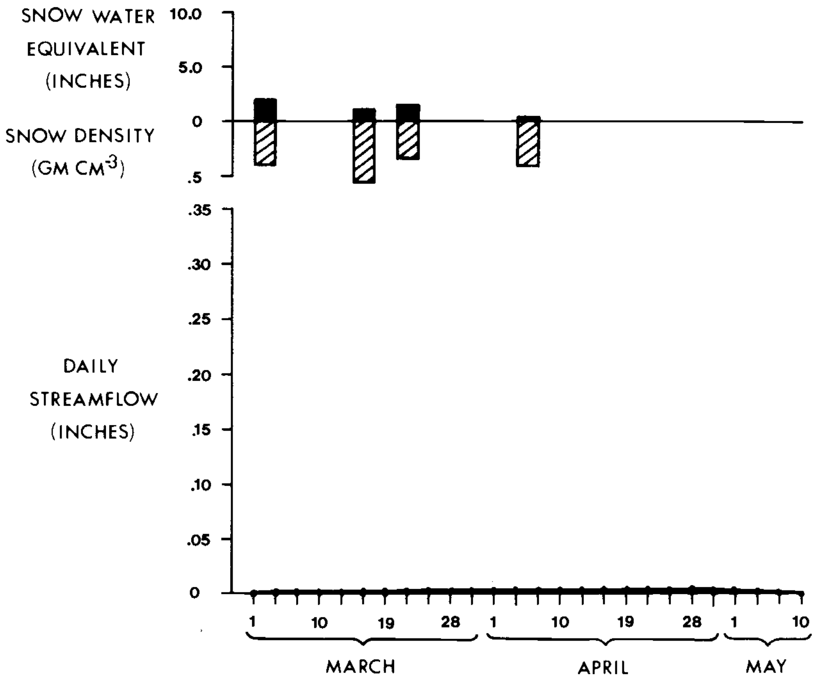

Fig. 2. Snowpack density, water equivalent, and daily streamflow for 1973-74.

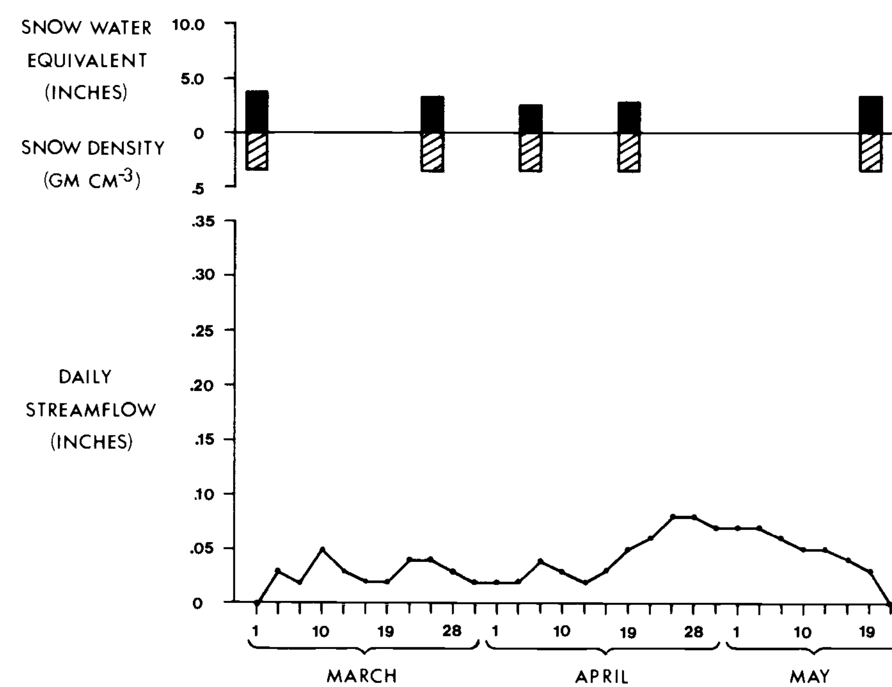

Fig. 3. Snowpack density, water equivalent, and daily streamflow for 1974-75.

The snow densities observed on the North Fork of Thomas Creek (Tables 1, 2, and 3) are comparable to those characterizing many snowpacks elsewhere in the West. For example, Ffolliott and Thorud (1969) found that an average density of 0.37 gm cm^{-3} represented ripe snow conditions on a small watershed in the ponderosa pine forests of north-central Arizona. Lejcher (1969) observed that the snowpack under a ponderosa pine stand in northern Arizona was ripe and had begun to yield melt water at a density between 0.36 and 0.38 gm cm^{-3}. Gary and Coltharp (1967) reported maximum snow densities of 0.35 to 0.40 gm cm^{-3} for aspen, grass, and Douglas-fir cover types in New Mexico. According to Kittredge (1953), snow densities between 0.40 and 0.50 gm cm^{-3} are necessary before water will drain from snowpacks under ponderosa-sugar pine and fir cover types in California. Work (1948) presented data for Crater Lake, Oregon, which indicated that the snowpack did not melt significantly until it had attained a density between 0.40 and 0.50 gm cm^{-3}.

Table 1. Average snowpack density, confidence interval[a/], and coefficient of variation, 1972-1973.

Date	Density (gm cm^{-3})	Coefficient of Variation
February 24	0.24 ± .01	0.08
March 10	.25 ± .02	.27
March 24	.30 ± .02	.20
April 7	.32 ± .01	.16
April 28	.34 ± .02	.17
May 12	.43 ± .03	.15

[a/] α = .05

Table 2. Average snowpack density, confidence interval[a/], and coefficient of variation, 1973-1974.

Date	Density (gm cm^{-3})	Coefficient of Variation
January 6	0.14 ± .01	0.34
January 12	.19 ± .01	.20
February 16	.35 ± .02	.23
March 2	.40 ± .03	.33
March 16	.55 ± .06	.34
March 22	.33 ± .03	.39
April 6	.42 ± .03	.20

[a/] α = .05

Table 3. Average snowpack density, confidence interval[a], and coefficient of variation, 1974-1975.

Date	Density ($gm\ cm^{-3}$)	Coefficient of Variation
February 16	0.21 ± .03	0.49
March 1	.33 ± .02	.26
March 25	.34 ± .03	.31
April 6	.32 ± .03	.31
April 19	.34 ± .05	.51
May 19	.34 ± .03	.29

a/ α = .05

The constancy of the coefficient of variation for snow density during the major portion of the runoff period in each of the study years indicates that the relative variation was homogeneous. Thus, a given sample size would have equal precision in estimating the average for this period. However, since sample size decreased throughout the period, the precision of the estimated average also decreased.[3]

Snow density values appeared to be normally distributed on the North Fork for the years of study (Figures 4, 5, and 6). Strong linear trends of cumulative frequency diagrams plotted on arithmetic probability paper indicated normality. Exceptions to normality occurred on sampling dates toward the end of runoff, when too few observations were available to characterize the distribution of high snow density levels.

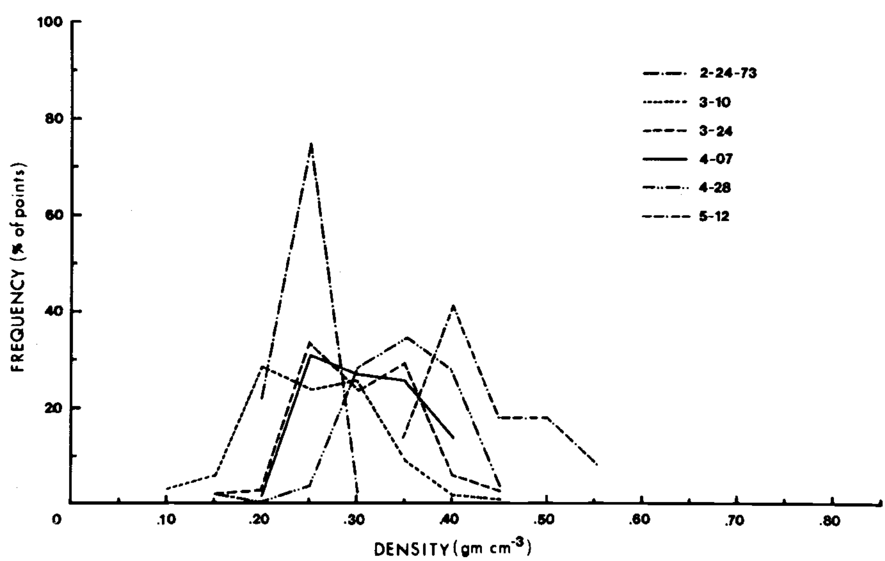

Fig. 4. Frequency distribution for snowpack density, 1972-73.

3. All statistical characterizations of density are based on sample points that had measurable snow. As the snowpack disappears, the number of sample points with measurable snow decreases.

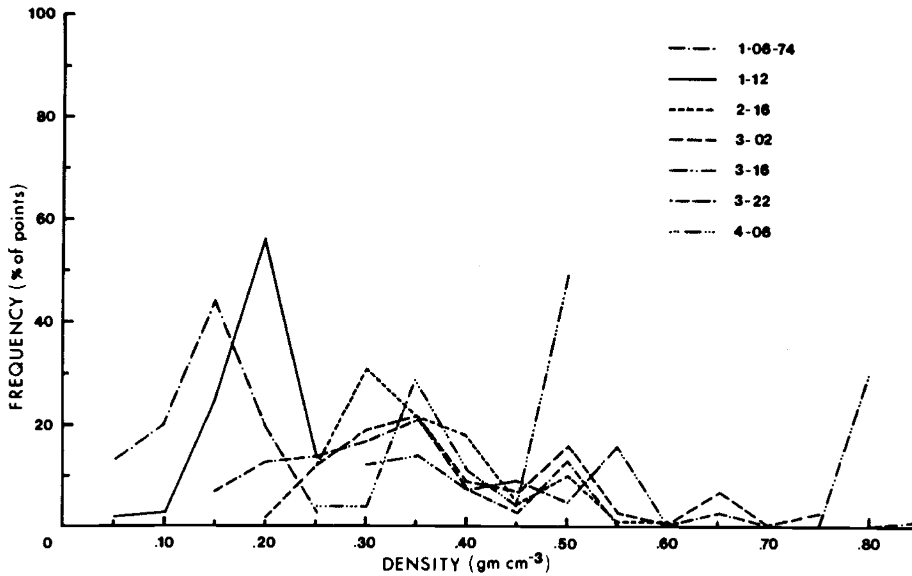

Fig. 5. Frequency distribution for snowpack density, 1973-74.

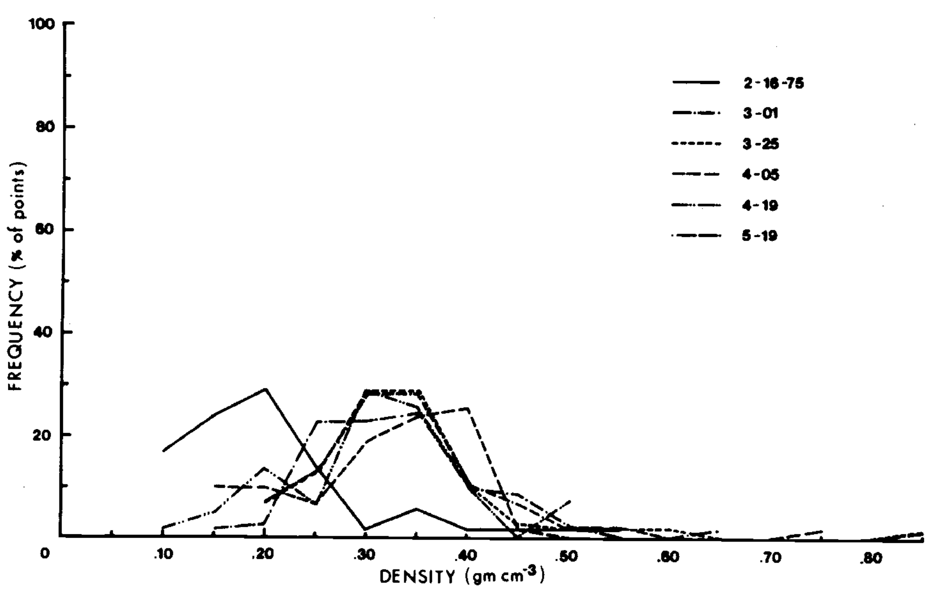

Fig. 6. Frequency distribution for snowpack density, 1974-75.

Similar frequency distributions of snow density have been observed on a small watershed supporting ponderosa pine forests in Arizona (Ffolliott and Thorud 1969).

Forest density, elevation, and potential insolation were subjected to linear correlation analysis to determine their individual associations with snow density at peak seasonal accumulation. In general, higher snow densities were observed under sparsely stocked than dense mixed conifer stands, although this correlation was not consistent in all years. Possibly, this pattern was the result of a greater proportion of "old" snow in the samples taken on sites with low forest density; more snow accumulates on these sites, therefore, the snow persists longer.

No significant correlations existed between snow density and elevation, nor between snow density and potential insolation, possibly due to the relatively limited range of values for these variables on the North Fork of Thomas Creek.

CONCLUSIONS AND SUMMARY

(1) An average snow density of between 0.35 and 0.40 gm cm^{-3} apparently represented ripe snowpack conditions on the North Fork of Thomas Creek, a mixed conifer forest watershed in east-central Arizona.

(2) The coefficient of variation for snow density remained relatively constant for a major portion of the runoff periods evaluated.

(3) Snow density appeared to be normally distributed on the 440-acre study area.

(4) Correlations between snow density and forest density were weak and inconsistent; no correlations were found between snow density and elevation and potential insolation.

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VARIATIONS IN SOIL MOISTURE UNDER NATURAL VEGETATION

by

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ABSTRACT

Soil water content was measured every two weeks during 1974-1975, using a neutron probe, at selected locations around the desert plant species creosote (Larria divaricata), bursage (Ambrosia deltoidea), and in an open space. The purpose of taking the measurements was to enable one to estimate the evapotranspiration rate of the desert plants by measuring soil moisture depletion. The sampling problem associated with measuring soil moisture, using neutron access tubes, is the number, location, and installation depth of the tubes. Analyses of the total soil moisture beneath the creosote plant showed greater variability between access tubes located near different plants the same distance from the crown of the plant than between tubes located around the same plant. Because of the size of the bursage plant, the variability in total soil moisture beneath the plant was greater among tubes around the same plant than between tubes at the same location at different plants.

INTRODUCTION

The evapotranspiration rates of both irrigated and natural vegetation are commonly determined from a water balance in which changes in soil moisture in and around the root zone of the vegetation are measured by either sampling galaviometrically or using a neutron probe. The number of neutron access tubes, their location, and the time between measurements must be determined for precise evapotranspiration calculations. Usually, sample numbers depend not upon estimated quality required, but upon the manpower, money, and physical constraints of the research project.

In agricultural crops, where the soils are more or less uniform, the irrigation is applied uniformly; and the vegetation is planted in a uniform stand. The soil-moisture variability is less than in a natural ecosystem, where the input is rainfall which varies with space and time and the vegetation is randomly located. The soil texture and structure is also more variable in a natural ecosystem. This paper has the objective of investigating the number and location of neutron access tubes to estimate with a specified precision the total available soil moisture and the evapotranspiration rate of the creosote plant (Larria divaricata), bursage plant (Ambrosia deltoidea), and the evaporation from an open area.

REVIEW OF PREVIOUS WORK

There is very little information in the literature as to the spatial variability of soil moisture measured with a neutron probe. Lawless and MacGillivray (1963) investigated the interface problem associated with using a neutron probe, and concluded that probe readings at three- and six-inch depth spacing gave six times more precise answers for computing the soil moisture content than readings at twelve-inch depth spacings, when abrupt soil-moisture content changes were encountered. However, if the measurements are concerned only with changes in soil moisture and not absolute values, then the spacing between probe readings is not as important. They gave no estimate of the sample size necessary to estimate the soil-moisture content with a given degree of precision.

Nielson and Biggar (1973) sampled soil moisture under a steady-state infiltration process, using uhland core soil samples. They found that 76 samples were necessary to estimate the mean to within 11 percent of the true mean-moisture content with the

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90 percent confidence. This sample size is probably larger than would be necessary using a neutron probe because the neutron probe integrates the measurement of soil moisture over a larger area than the uhland soil sampler.

Hammond, Prichett, and Chew (1958) sampled soil moisture using a sampling tube, and they required a sample size of 38 to be within 11 percent of the mean of the population sampled with 90 percent confidence. Again, this sample size would be larger than the expected sample size using the neutron probe.

METHODS

Soil-water content was measured with a neutron probe in a study area located 25 miles north of Tucson, Arizona. The study site was selected from a soils map of the area, which classified the soil series as a Tres Hermanos fine, gravelly-sandy loam. Four groups of creosote plants were randomly selected and neutron access tubes were installed around them to measure soil moisture content which ranged from 5 to 13 percent by volume. The location of the tubes around the plants is described by Table 1 and Figure 1. Four groups of bursage plants were also randomly selected and access neutron tubes were installed with the same pattern. Two bare soil sites were selected and a trench dug one meter deep around the plots and wrapped with two thicknesses of six-mil polyethylene plastic to isolate the area from all roots of the surrounding vegetation. Four neutron access tubes were installed two meters deep in each plot.

Table 1

Location 1.	One crown perimeter where crown of adjacent plant touches (zone of maximum root competition-concentration).
Location 2.	On crown perimeter facing adjacent plant whose crown edge is 2 m away for creosote and 1 m for the bursage.
Location 3.	On crown perimeter facing 4 m minimum opening for creosote and 2 m minimum for bursage.
Location 4.	In opening, 2 m from study plant crown, and with no other plant closer than 2 m for creosote and 1 m for bursage.
Location 5.	In "bare" area, isolated from all shrub roots by trenching and wrapping with two thicknesses of 6-mil polyethylene plastic to 1 m deep.

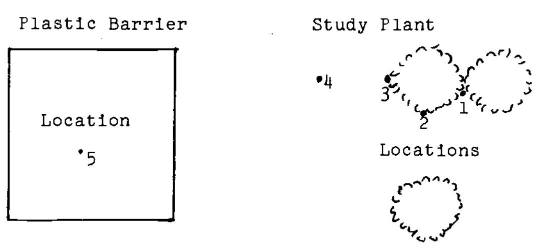

Figure 1. Location of access tubes near study plants.

Soil moisture content in all the plots was read at 25-centimeter intervals starting at the 25-centimeter depth. Measurements of soil moisture were taken every two weeks. Rainfall was measured with a standard 8-inch rain gage located next to the study plot. Measurements were started in June, 1974 and continued through December, 1975.

RESULTS AND DISCUSSION

Studies based on analyses of variance described by Kempthorne (1952) were conducted which investigated the relative size of various sources of variability. From these analyses, the following conclusions were drawn.

For the creosote plant, there was no evidence (p = .05) that the total soil moisture measured in the creosote plant rootzone was different at the four locations around the plant (Table 2). Evapotranspiration rates (ET were determined from a water balance:

$$ET = R \pm \Delta SM - D \quad (1)$$

where R = rainfall
D = deep drainage
ΔSM = change in soil moisture.

With the limited available moisture from rainfall, there was no measured deep drainage during the course of the project. Consequently, for analyses of variability, time periods were selected when there was no rainfall and the evapotranspiration equaled the measured change in soil moisture that occurred in all depths in the rootzone. Analysis of the mean change in soil moisture by depth indicated that evapotranspiration was predominantly occurring from the top meter, so this was selected to represent the rootzone depth. Twenty two-week time periods were used to compute evapotranspiration. The differences in location means, with regard to total changes in soil moisture, were statistically ($p = .05$) significant in 5 of the 20 time periods.

Table 2. Observed significance levels of the test that the total soil moisture at locations 1-4 were the same for the two different plants by time period.*

	Larria divaricata		*Ambrosia deltoidea*	
Month/Day	1974	1975	1974	1975
1-04		.54*		.07
1-18		.61		.10
2-01		.81		.14
2-16		.54		.14
3-01		.61		.09
3-15		.34		.14
3-31		.45		.16
4-12		.54		.07
4-26		.47		.09
5-10		.43		.08
5-24		.65		.08
6-07	.93	.47	.09	.13
6-20	.87	.50	.09	.10
7-05	.78	.65	.07	.04
7-18	.85	.57	.09	.07
8-01	.69	.75	.07	.05
8-15	.91	.83	.10	.05
8-31	.88	.74	.09	.09
9-14	.90	.72	.12	.03
9-28	.79	.68	.00	.03
10-12	.71	.84	.10	.09
10-26	.56	.28	.02	.08
11-09	.54	.80	.00	.08
11-24	.76	.85	.20	.05
12-07	.53	.85	.08	.09
12-20	.60	.67	.16	.10

* If the four-location means were in fact equal 54 percent of the time, the observed means would exhibit more variability than that observed. The smaller the significance level the greater the evidence is that the four locations' means are not equal.

The conclusion which may be drawn is that the location of soil-moisture content measurements, using a neutron probe, to determine both total moisture in the rootzone (1 m deep) and the evapotranspiration rate by the creosote plant is not dependent upon the location of the neutron access tubes. An explanation of this conclusion is that the creosote plant has an extensive root system and the roots extract moisture as readily from the bare spaces between the creosote plants within distances specified in Table 1 as they do from the area beneath and around the crowns of the plant.

The soil moisture data collected around the bursage plant was analyzed in a similar manner. The total soil moisture in the rootzone 50 cm deep at the four locations was not generally significant at the 5 percent level. However, for the different time periods there was a consistent trend showing that the total soil moisture was statistically different at the four locations between the 5 and 10 percent level. The location of the neutron access tubes to measure changes in soil moisture was significant ($p = .05$) in 5 out of 20 time periods. At the 10 percent level of significance, there were 8 periods out of 20 that were significant. The conclusion drawn from this is that, around a bursage plant, the location of soil moisture measurements, using a neutron probe, may be important for both available soil moisture and evapotranspiration rates in the rootzone. The reason is that the root system of the bursage plant is shallow and does not extend more than 50 cm laterally from beneath the crown of the plant. Consequently, tubes located more than 50 cm from the crown are probably not measuring extraction of moisture by the bursage plant but only evaporation from the soil surface.

The bare soil plot (Location 5, Table 1) was divided into two sections: the bare area around the creosote plants in the open and the bare area around the bursage plants. There was no significant differences between these two bare-soil plots. This was to be expected because the tubes were in the same soil type in areas isolated by plastic barriers from roots of other plants. Thus they should have represented the same evaporation rate. Analyses of the mean moisture content by depth indicated that the evaporation was predominantly from the top 25 cm of the profile. Analysis of the mean change in soil moisture to measured evaporation rate, with the neutron probe, indicated that the access tubes should be placed randomly in the bare soil plot. However care should be taken to isolate the plots from any roots of surrounding plants.

SAMPLE SIZE:

The yearly evapotranspiration rate of a plant is determined by measuring the change in soil moisture, which is equal to the evapotranspiration rate where deep drainage is negligible. For the time periods before and after a rainfall event, the summations of the changes in soil moisture represents the total evapotranspiration for the year. The variance in the estimated evapotranspiration for the year is the sum of the variances of the individual components. Consequently, the larger the number of individual samples used to estimate the total, the larger the sample size will be required to maintain the same precision at the same confidence level. Table 3 presents the number of neutron access tubes to estimate the evapotranspiration rate for a specified number of time periods to have an associated absolute error of 2.5 cm, 1.25 cm, .625 cm, .312 cm, .156 cm, .078 cm, and .039 cm. The table was computed from eq. 2.

$$N = \left[\frac{1.96\ \sqrt{k}\ \mathrm{ESD}\ \sqrt{d}}{q}\right]^2$$

where
- q = absolute error
- N = number of tubes needed to be installed to achieve the desired precision
- k = number of time periods sampled during a year to determine ET
- d = number of depths sampled in the soil profile
- ESD = estimated standard deviation of a single measurement
- 1.96 = a factor which is associated with being 95% confident that this sample site will achieve the specified result.

The standard deviation of the measurements to calculate the change in soil moisture is .083 cm for Larria divaricata, .097 cm for Ambrosia deltoidea, and .097 cm for the bare soil. The number of depths (d) used to calculate the evapotranspiration and, consequently, the sample size to have a 95 percent confidence in the computed average evapotranspiration is 4 for Larria divaricata, 1 for Ambrosia deltoidea, and 1 for the bare soil. The time period of 1 represents the error associated with one computation in order to obtain the evapotranspiration for 1 time period.

An example of how Table 3 may be used is: if the evapotranspiration for the creosote plant was measured for a 12-month period by measuring the soil moisture at the beginning and end of the year and at four depths (25 cm, 50 cm, 75 cm, 100 cm), then the time period would be 1. To have an absolute error of .312 cm (k = 1), assuming the rainfall and deep drainage error during that time period was negligible, would require a sample size (N) of 2.

If four measurements (k = 4) of evapotranspiration were made during the 12 months and summed to determine the total evapotranspiration during the year, then a sample size of 5 would be required to have an absolute error of .312 cm.

If monthly measurements (k = 12) were made and summed for the year to determine the evapotranspiration, then a sample size of 14 would be necessary to have an absolute error of .312 cm.

The evapotranspiration rate or the change of soil moisture for a time period changes, depending upon the time of the year and available moisture which depends upon the rainfall distribution. Consequently, although the absolute error is constant, the percentage error associated with a sample size changes. Table 3 gives the percentage error based on either a yearly evapotranspiration rate of 20 cm, or a two-week maximum evapotranspiration rate of 1.4 cm, or a two-week minimum evapotranspiration rate of .14 cm. Longer time periods between readings would increase the precision of estimating the yearly evapotranspiration. However, if a rainfall event occurs between soil moisture measurements, then a measurement of the rainfall with its associated error must be made to compute evapotranspiration from equation 1.

The sample size associated with a plot species is applicable to only one site. The site-to-site component of variability could not be estimated from the data. Samples should be taken at other sites and inter-site variability estimated.

Table 3. Sample size associated with evapotranspiration measurement determined from changes in soil moisture using a neutron probe, for several sizes of absolute errors with 95% confidence.

Absolute Error cm of moisture	Percentage Error Associated with a Calculated ET Rate			Creosote Bush *Larria divaricata* 1 meter depth					Bursage *Ambrosia deltoidea* (25 cm depth)					Bare Soil (25 cm depth)				
				Number of Time Periods to Determine the Evapotranspiration Rate (k)														
	1/	2/	3/	52	26	12	4	1	52	26	12	4	1	52	26	12	4	1
				Sample Size (N)					Sample Size (N)					Sample Size (N)				
2.50	(12.5)	(178)	(1785)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1.25	(6.2)	(89)	(892)	4	2	1	1	1	1	1	1	1	1	1	1	1	1	1
.625	(3.1)	(44)	(446)	15	8	4	2	1	5	3	2	1	1	5	3	2	1	1
.3125	(1.5)	(22)	(222)	57	29	14	5	2	20	10	5	2	1	20	10	5	2	1
.156	(.7)	(11)	(111)	226	113	53	18	5	77	39	18	6	2	77	39	18	6	2
.078	(.39)	(5)	(55)	902	451	209	70	18	308	154	72	24	6	308	154	72	24	6
.039	(.19)	(3)	(27)	3608	1804	833	278	70	1232	616	285	95	24	1232	616	285	95	24

1/ Percent error in terms of 20 cm average yearly evapotranspiration.

2/ Percent error in terms of 1.4 cm maximum 2-week evapotranspiration.

3/ Percent error in terms of 0.14 cm minimum 2-week evapotranspiration.

CONCLUSIONS

In measurements of both available moisture and evapotranspiration determined from changes in soil moisture for Larria divaricata, the location of the tubes is not important. In measurements of changes in soil moisture and evapotranspiration rates for Ambrosia deltoidea, the location of the tubes may be important and they should be installed as close to the plants as possible. The sample size necessary to have a specified precision, in order to measure evapotranspiration rates for time periods, depends upon the total evaporation amount that occurred during that time period. The absolute error is independent of the measured change in soil moisture. The variability associated with a change in soil moisture for any given depth is similar for the three types of plots when the variability of location is removed. However, the total variability is dependent upon the number of individual depths that must be measured to compute the evapotranspiration rate.

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ROOT SYSTEM OF SHRUB LIVE OAK IN RELATION TO WATER YIELD BY CHAPARRAL

by

Edwin A. Davis

ABSTRACT

The root system of shrub live oak (Quercus turbinella) was studied in an initial effort to classify the major Arizona chaparral shrubs as potential users of soil water based on root system characteristics. The root system was of the generalized type with a taproot, many deeply penetrating roots, and a strong lateral root system. Roots penetrated 21 feet to bedrock through cracks and fractures in the rocky regolith. A dense network of small surface laterals radiated from the root crown and permeated the upper foot of soil. Because of its root system, shrub live oak is well adapted to utilize both ephemeral surface soil moisture as well as deeply stored moisture. Emphasis is placed on the importance of a knowledge of the root systems of chaparral shrubs and depth of the regolith in planning vegetation conversions to increase water yield.

INTRODUCTION

Research in Arizona has shown that, under certain conditions, water yield from experimental chaparral watersheds can be increased by converting from brush to grass (Hibbert, et al. 1974). Similar vegetation conversions in California chaparral have also resulted in increased runoff (Rowe and Reimann 1961, Hill and Rice 1963). The usual explanation for the results of such conversion is that the deep-rooted brush is able to obtain more water from deeper soil layers than the shallow-rooted grasses, thus reducing the amount available for water yield.

Dense stands of chaparral frequently consist of a mixture of shrub species. Increased water yields obtained by converting these areas to grass must, therefore, be attributed to the average effect of controlling a mixture of brush species. Water use differences among species go undetected.

Knowledge of the root habits of chaparral shrubs and depth of the regolith occupied by chaparral is prerequisite to improved treatments for increasing water, wildlife, grazing, and recreational values of chaparral. Such knowledge is also basic to problems of plant establishment, adaptation, distribution, ecesis, competition, drought tolerance, soil stability, and succession following fire, herbicide treatments, or root plowing. In brush control, the relationship between rooting depth and movement and persistence of herbicides in the soil may help to explain species response differences and aid in the development of improved brush control methods.

Since the early work of Cannon (1911) with desert plants near Tucson, Arizona, little information has been added to our knowledge of the root habits of native woody plants in Arizona. Phillips (1963) reported finding what appeared to be living mesquite roots 175 feet below the original ground surface of an open pit mine in Arizona. Except for limited observations on shrub live oak (Quercus turbinella Greene) very little is known about the root systems of chaparral shrubs of Arizona. This did not limit research in water yield improvement since yield comparisons were made between mixed chaparral and grass. But a lack of knowledge concerning root systems and water use of the dominant chaparral shrubs could limit the scope of future research and management projects concerning water yield and wildlife habitat.

Shrub live oak is the dominant shrub species in much of Arizona chaparral. The root system of a typical plant was thoroughly studied by means of a quantitative determination of root mass distribution vertically and laterally, followed by further excavation and examination of a central section of the root system. Results are then interpreted as they relate to watershed management practices.

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STUDY AREA

The shrub live oak bush was excavated in central Arizona on the Three Bar Wildlife Area, at 3300-feet elevation on the easterly face of the Mazatzal Mountain Range west of Lake Roosevelt. Chaparral at the study area consisted of a mixture of sclerophyllous woody shrubs dominated by shrub live oak. Other species included birchleaf mountainmahogany (*Cercocarpus betuloides* Nutt.), yellowleaf silktassel (*Garrya flavescens* S. Wats.), sugar sumac (*Rhus ovata* S. Wats.), and hollyleaf buckthorn (*Rhamnus crocea* Nutt.). These shrubs comprise a postfire complex of sprouting and nonsprouting shrubs that regrew following a wildfire in 1959.

The climate of chaparral zones in Arizona has a biseasonal precipitation pattern characterized by summer rainfall, fall drought, winter precipitation and spring drought. Annual precipitation at the study area averaged 25.7 inches over the past 18 years, with about 61% occurring as rain or snow from November through April.

Soil at the root excavation pit was typical of that on nearby experimental watersheds. It is classified in the Barkerville series. The soil is a very gravelly sandy loam derived from granitic parent material; it is slightly acid and has an A, C, R, horizon sequence. It is well drained and has infrequent surface runoff. Permeability is moderately rapid. Seismic exploration on the watersheds indicated that the coarse-grained granite is weathered and fractured 20-40 feet deep. The presence of such a deep regolith has significant hydrologic and ecologic implications.

The excavated bush, located on a 40% east-facing slope, was a vigorous, mature specimen typical of shrub live oak in the area. Charred snags indicated that it had burned in the 1959 wildfire; judging from the size and appearance of the root crown it also may have burned in previous wildfires. The 8 foot-tall bush had canopy dimensions of 18.5 x 19.0 feet. Its canopy consisted of 12-year-old regrowth stems which sprouted from the root crown following the wildfire. Sprouts came from an almost circular area 5 feet in diameter.

METHODS

The first phase of the study consisted of a quantitative determination of root mass. A trench was cut along the north side of the bush with a bulldozer. The trench was 11 feet deep at the upslope end, 21 feet long, and 19 feet wide, with the bottom nearly level. The face exposed for sampling was about 3 feet out from the edge of the bush's root crown. Samples were taken to determine root mass distribution in four, 1-foot-thick transections (slices) of the regolith starting at the trench face and moving in toward the bush. Pattern of root distribution was determined by removing 1-cubic-foot blocks from each transection by means of picks and a pneumatic chipping hammer, separating roots from soil by passing the soil through a 1/4-inch mesh sieve, and subsequently weighing the ovendried roots. The two inner transections included parts of the root crown, but its weight was not included with the weight of roots. In constructing lateral and vertical distribution patterns only data to the 6-foot depth were used, because the number of lateral blocks varied below this depth.

In the second phase of the study, a backhoe was used to dig a 6-foot-wide pit in the bottom of the trench. At the upslope end of the pit, at a depth of approximately 20-feet, hard rock was reached that could not be broken. Roots broken during digging were identified with those protruding from the face of the pit, tagged, and later reconnected. The root system in a 1-2 foot transection of soil beneath the center of the bush was then exposed by careful excavation and reconstruction. Roots in this excavation were allowed to hang against the face of the pit. Next, a portion of the surface lateral root system was exposed in a semicircular trench, 18 inches wide and 1 foot deep, about 2 feet out from the base of the bush. Exposed roots were painted white with vinyl latex paint for photographic documentation.

RESULTS

QUANTITATIVE RESULTS

Roots were found in every cubic foot of soil in spite of the rocky regolith. Root weights per cubic foot block varied from less than 1 g to 2804 g. Because of the hardness of the regolith, many roots penetrated crevices, fractures, and seams of weathered material. The greatest accumulation of root mass was centered beneath the root crown, the zone occupied by the taproot. Distribution of root mass in the other transections followed the same trend; root mass decreased, in general, with lateral and vertical distance from the root crown.

Lateral distribution of root mass was determined from the two inner transections of the regolith to a depth of 6 feet. Each transection was made up of 66, 1-cubic-foot blocks. Weight of roots at each lateral location was based on 12, 1-cubic-foot blocks.

Forty-seven percent of the root mass was located in a 4-square-foot (2 x 2) column beneath the root crown; 73% was located within an 8-square-foot (2 x 4) central column. Although there was a marked decrease in root mass beyond the central 4-square-foot column of the transection, root mass did not steadily decline with distance downslope due to the lack of uniform penetrability of the regolith and the irregular distribution of large roots.

Vertical distribution of root mass to a depth of 6 feet was determined by combining data for the four transections according to depth. Weight of roots for each depth was based on 30, 1-cubic-foot blocks of soil. Vertical distribution of root weight from the soil surface downward in 1-foot increments was as follows: 26, 29, 18, 12, 9, and 6 percent. The greatest accumulation of root mass was in the top 2 feet of soil. Below 2 feet there was a gradual decrease in root mass with depth.

A gross estimate of the root/top ratio of the excavated bush was made by estimating total weight of the root system based on 63.8 pounds ovendry roots in the 239 cubic feet of soil sampled. Assuming that the weighed roots represented 1/3 of the entire root system, which is a probable maximum, then the total ovendry weight of roots was 191.4 pounds, excluding the root crown. Ovendry weight of the clipped top at the start of excavation was 101.6 pounds. Thus, at this stage in the life of the plant, the weight of the root system exceeded that of the top; the estimated root/top ratio was 1.9. If the massive root crown is included in the weight of the root system, then its estimated weight is 321.8 pounds, and the root/top ratio would be 3.2.

DESCRIPTION OF THE ROOT SYSTEM

Following the quantitative phase of the study, a central portion of the root system beneath the root crown of the bush was excavated and displayed to nearly its full extent (Figure 1). The taproot had already been removed for weighing in the quantitative transections. It consisted of a network of main roots that fused into a single, rapidly tapering root with numerous branches. The taproot was attached to the base of a massive root crown; some of its branch roots penetrated 21 feet to bedrock. The horizontal spread of vertically penetrating roots was 16 feet. A long surface lateral root extended downslope 22.7 feet before turning sharply downward. This root was only partially excavated when figure 1 was taken. A lateral growing diagonally upslope extended 11 feet before it turned downward. Downslope main laterals were more abundant than upslope laterals.

A dense network of fine surface laterals that radiated from the root crown completely permeated the upper foot of soil (Figure 2). Abundance of these roots was greater from the downslope half of the bush than from the upslope half. Diameters of roots excavated in the surface trench ranged from 1 mm or less up to 1 cm; the majority of roots were less than 2 mm in diameter.

A unique feature of this particular root system was a long, thin, dense network of intertwining roots that extended downward as a vertical plate, oriented crosswise to the direction of the slope of the hillside (Figure 3). The plate was about 10 feet long, 3.5 feet wide, and 3 inches thick; it was extremely dense, especially near the soil surface. At 8-10 feet some of the larger roots were flattened into irregularly shaped belt-like strips by their confined growth along fracture planes in the rock. These roots were 2-5 cm wide and 0.4-1.0 cm thick. The plate followed a narrow seam of highly weathered granite and sandy clay that penetrated the rocky regolith. Root grafts were common where roots were rigidly confined. Moisture, nutrient, and aeration conditions in the seam were apparently ideal for extensive root development.

The presence of bedrock at approximately 21 feet prevented further extensive root penetration; roots were forced to turn in a more or less horizontal direction and grow along a gently sloping surface of the bedrock. Diameters of these terminal roots were 1.5 to 5.0 mm. A few roots penetrated small cracks in the bedrock and may have extended a few feet deeper. Unsuberized fine roots were found growing in thin layers of soil between plates of rock at the 20- to 21-foot depth.

DISCUSSION

Shrub live oak is well adapted to the chaparral environment in Arizona. Its vigorous capacity to sprout from the root crown allows it to thrive under a natural regimen of periodic wildfires. The root crown gradually enlarges and the number of stems increases following top removal by fire. Pond and Cable (1960) found that there were nearly six times as many live stems a year after burning than originally. Even after four annual burns the number of stems was still greater than pretreatment counts. This prodigious regenerative capacity is supported by stored energy reserves in the root crown and roots, and by supplies of water and nutrients made available by an extensive root system.

Figure 1. Midsection of the root system of shrub live oak to a depth of 21 feet. After the quantitative phase of the study a central portion of the root system beneath the root crown of the bush was excavated and displayed to nearly its full extent.

Figure 2. Downslope side of the surface lateral root system showing the dense layer of small roots radiating from the root crown, and some shallow main laterals.

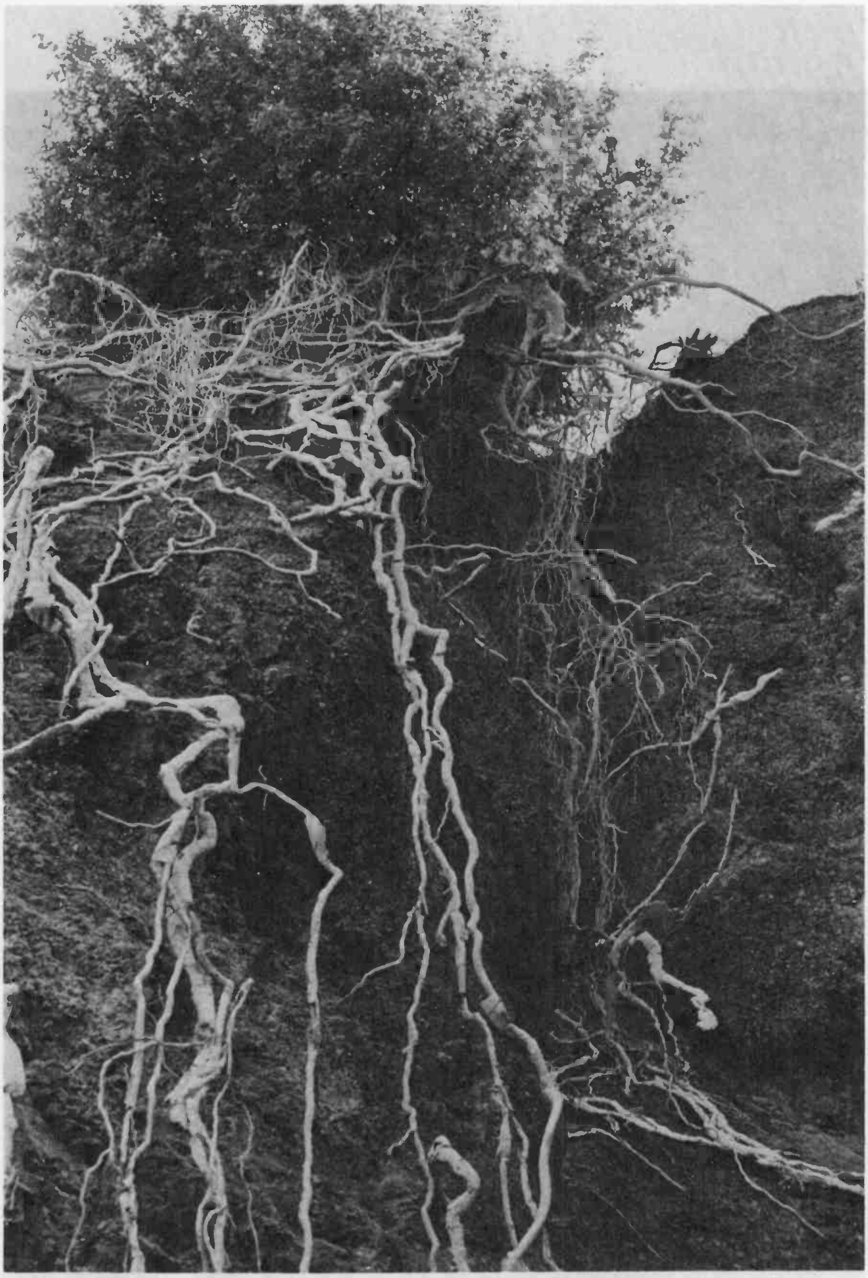

Figure 3. Roots penetrated fractures in the rocky regolith forming plates of roots along fracture planes. Some roots were flattened into irregularly shaped belt-like strips. Numerous self-grafts occurred where roots grew in the rigid confines of cracks and fractures.

In accordance with the terminology used for classifying root systems (Cannon 1911, 1949; Weaver and Clements 1938) shrub live oak is of the generalized type in which both taproot and laterals are well developed. Its extensive, deeply penetrating root system allows it to draw upon deep soil moisture during periods of drought. Thus, it can maintain an active physiological state for a longer period of time than less extensively rooted plants. Shrub live oak also has a highly developed surface root system to utilize ephemeral surface soil moisture. A dense layer of surface roots gives it a competitive advantage over grasses, and may explain the difficulty in establishing and maintaining perennial grasses in stands of burned shrub live oak in which regrowth is not suppressed. Dominance of the oak in stands of mixed chaparral may also be explicable in terms of competitive advantages associated with its extensive root system.

Self-grafts of shrub live oak roots were common. Grafting occurred when roots grew in the restrictive confines of fractures. Saunier and Wagle (1965) observed self-grafts of shrub live oak as well as intraspecific grafts. Of several California chaparral shrubs observed by Hellmers et al. (1955), Quercus dumosa (California scrub oak), a close relative of shrub live oak, was the only species in which root-grafting was observed. Root grafts have also been reported for several other oak species (Graham and Bormann 1966).

Most of the observed roots of the excavated oak, including the surface laterals, were suberized. Since the plant responds rapidly to soil moisture following drought and to soil-applied herbicides following rain, it is possible that the suberized roots are active absorbers of water. Direct measurements by Chung and Kramer (1975) clearly indicate that suberized roots usually constitute the major absorbing system of woody plants.

The wide lateral spread of surface laterals has important hydrologic and ecologic implications. What may be a fairly open stand of shrub live oak above ground, depending on the length of time following a wildfire, may actually be a relatively closed one from the standpoint of overlapping root systems.

Final root pattern and growth potential are genetically determined when soil factors are favorable but may be profoundly modified by soil structure, water content, and aeration (Weaver and Clements 1938, Pearson 1974). Roots of shrub live oak are capable of penetrating deeply either in a highly weathered regolith or in fractured and jointed rock underlying the solum. When downward growth is prevented by an impenetrable layer, however, the roots are necessarily restricted to the upper soil layer. Shrub live oak bushes have been observed growing in 6 to 10 inches of soil overlying highly indurated sediments (Saunier and Wagle 1967). This indicates that its distribution is not restricted to deep soils or weathered and fractured subsoils.

Quercus dumosa was reported by Hellmers et al. (1955) to have the deepest root penetration of the California chaparral shrubs they observed. In roadcut observations its roots were found penetrating fractured rock to a depth of 28 feet below ground surface. Unlike the shrub live oak in this study, Q. dumosa had few feeder roots in the top 6 inches of soil.

Present vegetation manipulation practices for the conversion from brush to grass for water yield improvement are not intentionally selective from the standpoint of brush species. Some selective hand applications of pelleted herbicides have been made in which desirable browse species were not treated (Davis and Pase 1969). Since differences in water use by chaparral shrubs have not been defined, treatment selectivity on this basis has not been possible. The deeper and more extensive a plant's root system the longer the plant can remain active and transpire during dry seasons. In well-aerated soils deep-rooted species can remove water from considerable depths. Deep-rooted shrubs are potentially much heavier water users than shallow-rooted species in areas with deep soils and limited rainfall. Although the greatest differences in rooting depth occur between grasses and trees or shrubs, considerable variation may occur within each group. Possible differences among chaparral shrubs may provide a partial basis for identifying low and high water users.

The sprouting ability of a shrub can have a bearing on the extent of its root system. Sprouting species have the potential for developing deeper and wider spreading root systems than nonsprouters. In areas that have wildfires, sprouting species are older than nonsprouters since they survive the effects of fire. Consequently, they should have more extensive root systems. Differences in root systems may occur among sprouting species due to hereditary factors. Plants in arid and semiarid regions are adapted by virtue of a variety of morphological, anatomical, and physiological characteristics, and may or may not be deep rooted. Many desert plants do not have deep root systems (Barbour 1973), but have other attributes that aid their survival (Gindel 1973). It is possible, therefore, that differences exist in the root habits of Arizona chaparral shrubs. Striking differences in root systems were found to occur among California chaparral species (Hellmers, et al. 1955). Differences were also noted in the abilities of various species to penetrate rock crevices.

A more detailed knowledge of characteristics of the major Arizona chaparral shrubs would allow for more effective management for multiple use objectives, assuming the availability of a suitable, registered brush control herbicide for chaparral conversions. Needed is a classification of chaparral shrubs which includes water-use characteristics, type and depth of root system, susceptibility to single and repeated burns, response to herbicides, sprouting ability, and browse value. In some of these categories considerable information is already available; but for others there is little or no information. This study of shrub live oak represents an initial effort to increase our knowledge of the root systems of chaparral shrubs.

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EFFECTS OF BRUSH TO GRASS CONVERSION ON THE HYDROLOGY AND EROSION OF A SEMIARID SOUTHWESTERN RANGELAND WATERSHED

by

J. R. Simanton, H. B. Osborn, and K. G. Renard

INTRODUCTION

Grass forage on Western U. S. rangelands is a renewable natural resource utilized in red meat production. Increased nutritional and economic demands for agricultural products from the U. S. have dictated the need for greater and more efficient use of this and other natural resources. The Western U. S., excluding Alaska and Hawaii, contains 40% of the total U. S. land area (USDA, 1976). Of this, 243 million acres is pasture or rangeland, and only about 50 million acres of this is classified as good or better condition rangeland (USDA, 1974). Because of the large land area involved, a small increase in production per unit area would mean a large increase in production from the total area. Methods to increase agricultural output in the form of forage for increased grazing include mechanical treatments, vegetation manipulation, fertilization, and improved grazing and cattle management practices.

Vegetation manipulation, usually chemical or mechanical, is the quickest and, perhaps, the most economical method of increasing forage and consequent agricultural production of an area. Often, these manipulations or conversions are made without much concern for, or understanding of, the hydrologic consequences. These consequences can lead to a post-conversion condition that is more unproductive than the original condition and, often, downstream damage may be extensive.

This paper reports and discusses the hydrologic and erosion changes measured from a 110-acre semiarid watershed, which was converted from brush to grass cover by root-plowing and seeding. Data analyses include considerations of changes resulting from the vegetation conversion on the rainfall-runoff relationships, sediment yield, Universal Soil Loss Equation (USLE) factors, vegetation composition and trends, and forage and grazing capacity.

DESCRIPTION OF EXPERIMENTAL AREA

The watershed studied is located in southeastern Arizona near Tombstone, Arizona, and is part of the Walnut Gulch Experimental Watershed operated by the Agricultural Research Service. Before treatment, the watershed (designated No. 63.201) was typical of many thousands of acres of deteriorated semiarid rangeland found throughout southern Arizona, New Mexico and northern Mexico. The desert shrub vegetation was dominated by whitethorn (Acacia constricta), creosote bush (Larrea divaricata), and tarbush (Flourensia cernua) (Table 1). Soil of the watershed is a Rillito-Karro gravelly loam which is of the Typic and Ustic Calciorthids subgroups. This soil complex is deep (55 inches), well-drained, medium and moderately coarse textured, and formed in calcareous old alluvium (Gelderman, 1970).

Precipitation, runoff, and sediment yield data were collected from the watershed from 1966 through 1976. Precipitation, measured in the area since 1955 with a 24-hour recording raingage, averaged about 13.5 inches annually, about 2/3 of which occurred from June through September. Storm runoff was estimated from recorded water level changes in a stock pond at the watershed outlet. Stock pond depth-volume curves were developed from annual topographic survey data, which were also used to determine sediment accumulation (Simanton and Osborn, 1973). Average annual runoff was about 7% of the annual precipitation, and occured only during the summer thunderstorm season.

WATERSHED TREATMENT

The watershed was fenced to exclude grazing, then root-plowed on the contour in June, 1971. Root-plowing consists of pulling a large, fixed cutting blade at the 12-to 18-inch depth beneath the soil surface to cut the brush roots below the plant crown. Eighty percent of the watershed was rangeland drilled to side-oats grama (Bouteloua curtipendula) in July, 1972. The remaining area was broadcast seeded to blue grama (Bouteloua gracilis) in August, 1972. Seeding dates were determined from soil-water availability curves developed for these semiarid rangelands (Tromble, 1974). Although optimum seeding time is usually immediately after brush removal because of the eliminated moisture competition

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from other vegetation; the 1 year's delay before seeding, caused by seed unavailability, did not seem to hinder grass establishment. The seeding was successful, and grass now dominates the watershed vegetative cover (Figure 1, Table 1).

TABLE 1. Vegetation of Watershed No. 63.201

Pretreatment Species	Pretreatment % of Total Crown Cover	Post-treatment Species	Post-treatment % of Total Crown Cover
Acacia constricta	39.4	Bouteloua curtipendula	35.4
Larrea divaricata	23.1	Tridens pulchellus	13.0
Flourensia cernua	20.2	Bouteloua gracilis	12.2
Parthenium incanum	11.0	Eragrostis Lehmanniana	8.5
Zinnia pumila	3.4	Sporobolus contractus	3.8
Muhlenbergia Porteri	2.9	Zinnia pumila	3.7
Total	100.0	Acacia constricta	3.6
		Larrea divaricata	3.3
		Muhlenbergia Porteri	2.8
		Tridens muticus	2.3
		Aristida species	2.3
		Flourensia cernua	2.3
		All Forbs	1.6
		6 Remaining Grass Species	3.7
		2 Remaining Shrub Species	1.5
		Total	100.0

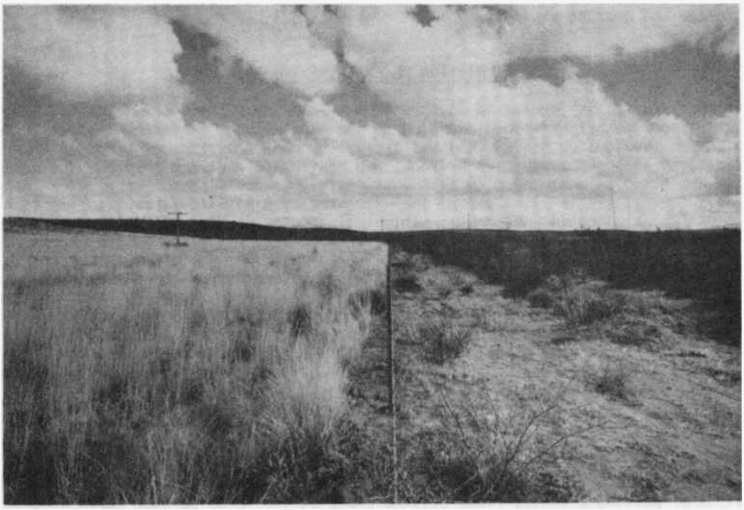

Figure 1 - Fence line contrast showing root-plowed, seeded area on the left and the brush dominated pretreatment condition on the right.

DISCUSSION OF RESULTS

RAINFALL - RUNOFF

Rainfall variability and storm size should be included in any hydrologic studies where thunderstorm precipitation dominates the hydrologic input. Thunderstorm variability has long been recognized as the most influential factor in hydrologic and watershed studies in the southwestern United States (Osborn and Reynolds, 1963; Renard and Brakensiek, 1976). Associated with the rainfall variability is the variability of the USLE's rainfall factor (R) (Renard and Simanton, 1975). The R value is the number of erosion-index (EI) units (ft-tons/acre) in a normal year's rain and is a measure of the rainfall's erosive force. EI is the product of the total kinetic energy and the maximum 30-minute intensity of a storm (Wischmeier and Smith, 1958). Each storm's EI value is accumulated to obtain a yearly R factor. Log-normal probability distributions for summer rainfall and annual R of the treated watershed are presented in Figure 2. These distributions represent the 22 years of precipitation data from 1955 through 1976, and are useful in explaining some of the changes in the rainfall-runoff relationships associated with watershed treatment. From Figure 2, the summer rainfall expected 1 year out of two is about 7 inches. The average rainfall for the post-treatment period was 6.8 inches (Table 2), slightly less than the 50% probability. The average rainfall for the transition period was 9.3 inches. However, during the second year of the transition period (1972) there were 12 inches of summer precipitation. Based on Figure 2, this amount would be expected to occur on the average of once in 10 years. The gross effects of this rainfall variability set limitations on the conclusions regarding rainfall-runoff relationship changes. However, for the precipitation observed, there were significant changes in the rainfall-runoff relationships (Table 2).

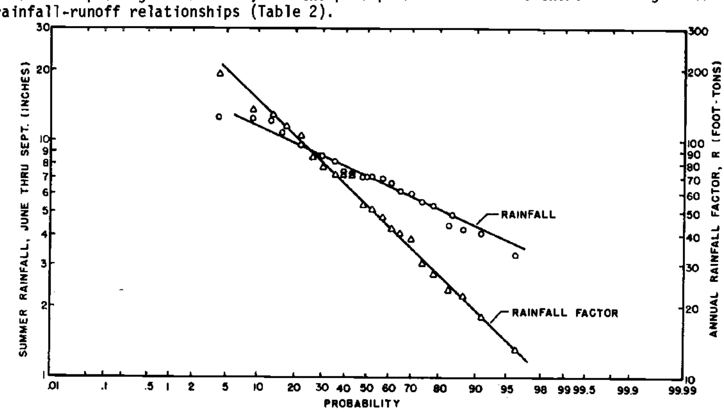

FIGURE 2. LOG-NORMAL PROBABILITY CURVES OF SUMMER RAINFALL AND ANNUAL RAINFALL FACTOR. RAINGAGE 63.002. 1955-1976.

TABLE 2. Runoff and Sediment Yields During 3 Periods of Watershed Change.

63.201
(1966 - 1976)

Period	AVG SUMMER PRECIP		AVG SUMMER RUNOFF Observed		AVG SUMMER RUNOFF Predicted (Per 1 in Runoff)		SEDIMENT YIELD Observed		SEDIMENT YIELD Predicted (Per 1 in Runoff)	
	in	(mm)	in	(mm)	in	(mm)	Tons ac/yr	Tonnes ha/yr	Tons ac/yr	Tonnes ha/yr
Pretreatment (Brush Vegetation) 1966 - 1970	9.43	(240)	0.904	(23.0)	0.096	(2.44)	1.67	(3.746)	1.85	(4.150)
Transition 1971 - 1973	9.32	(237)	1.329	(33.8)	0.143	(3.63)	1.14	(2.557)	0.86	(1.929)
Post-treatment (Grass cover) 1974 - 1976	6.84	(174)	0.131	(3.3)	0.019	(0.48)	0.13	(0.292)	0.99	(2.221)

Runoff differences may be attributed to factors other than precipitation. Type and amount of vegetative cover are very important in determining watershed runoff amounts because of their role in affecting infiltration (Kincaid et al., 1966; Kincaid and Williams, 1966; Dixon, 1975). The relationship between vegetation and runoff can be implied from data presented in Figure 3. Until the root-plowing in 1971, the cumulative rainfall-runoff relationship was fairly constant. Just after root-plowing, the treatment effects (surface disturbances) apparently counteracted the loss in vegetation effects (the rainfall-runoff relationship remained constant). After 1 season's rainfall reestablished a watershed drainage network, the lack of vegetation contributed to a discernable runoff increase. After seeding and grass establishment, the effects of vegetation were reflected in a significant decrease in runoff rate. The combined effect of the root-plowing and revegetation for the combined transition and post-treatment 6 year period produced the same end point on the rainfall-runoff curve that would have been expected with no treatment (assuming the rainfall-runoff curve for the pretreatment condition remained constant).

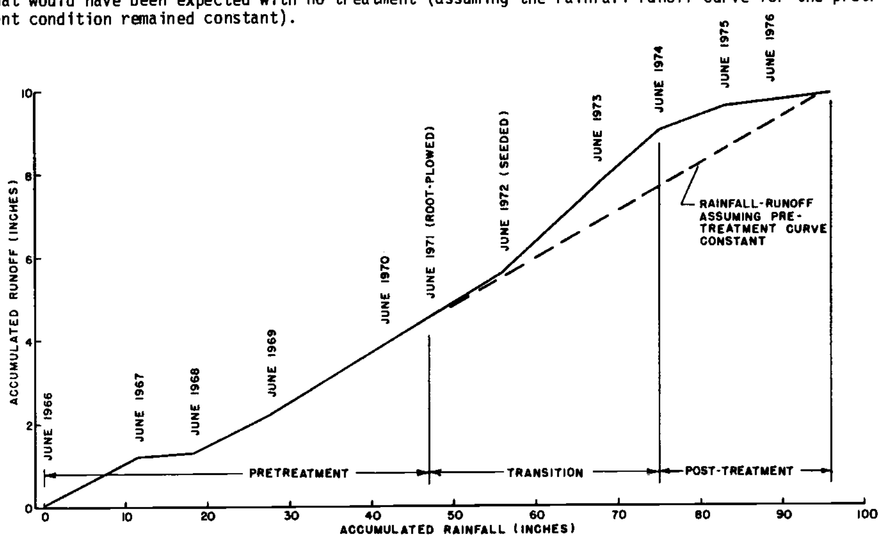

FIGURE 3. MASS RAINFALL-RUNOFF CURVES. WATERSHED 63.201, 1966-1976.

Figures 4a and 4b illustrate changes in runoff for a given precipitation event when all the storms are considered individually. The curve number method used in Figure 4a was developed from the Soil Conservation Service National Engineering Handbook (SCS, 1971). The modified linear regression technique (Diskin, 1970) was developed specifically to treat data where some of the independent data (precipitation) produced zero data (runoff) in the dependent variable (Figure 4b).

From Figure 4a, the pretreatment curve number (CN) for the watershed is 78, which converts to about 0.06 inch of runoff from a 1-inch rainfall. The transition period CN is 84, or 0.15 inch of runoff from a 1-inch rainfall. The post-treatment CN is 77, or 0.05 inch of runoff from a 1-inch rainfall. The differences in runoff between the pretreatment and transition periods and between the transition and post-treatment periods are more and less, respectively, but there is very little difference in runoff between the pre- and post-treatment periods.

Figure 4b represents the curves developed from a modified linear regression technique developed to interpret rainfall-runoff relationships when many of the runoff values are zero. Two findings are significant in this figure. The first is a considerable decrease in runoff associated with the post-treatment as compared to the pre-treatment and transition periods. The second finding is that the rainfall threshold for runoff initiation is about 20% greater during the transition period than during the pre- and post-treatment periods. Also, the rainfall thresholds of the pre- and post-treatment periods are equal. These rainfall threshold changes indicate that the watershed surface storage and drainage network, disturbed by root-plowing, held water during the smaller rainfall events. However, this disturbance was not enough to compensate for the loss of vegetative cover which caused the runoff increase from the larger events. The fact that the pre- and post-treatment periods' rainfall threshold was the same but the post-treatment period runoff was much less once this threshold was passed is again consistant with the results from Figure 2, where the flatness of the post-treatment curve associated with an increase in grass vegetation represents a decrease in runoff.

Although the results from the curves of Figure 4a and 4b are consistant, there was no significant difference in runoff between the pre- and post-treatment when the data were fitted by the curve number method, but there was a significant difference (95 percent level) when the modified linear regression was used. This was probably because of the very low coefficient of determination associated with the post-treatment data fit of Figure 4a using the curve number method. The low coefficient of determination for the post-treatment rainfall-runoff relationship may indicate that a new equilibrium watershed

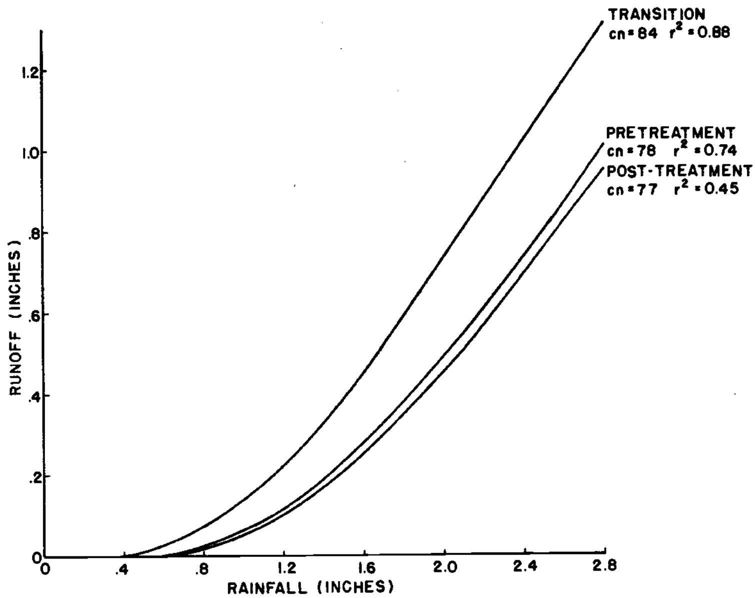

FIGURE 4a. RAINFALL VS. RUNOFF. SCS CURVE NUMBER.

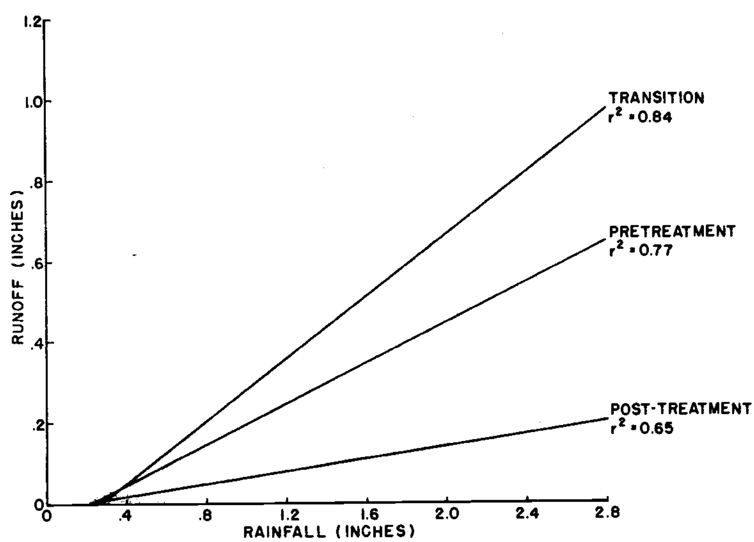

FIGURE 4b. RAINFALL VS. RUNOFF. MODIFIED LINEAR REGRESSION.

condition had not been established by the arbitrarily selected post-treatment date of June, 1974.

SEDIMENT

Average annual sediment yields during the three study periods are shown in Table 2. Measurement difficulties in determining pond volume changes, sediment bulk density, sediment delivery ratios, and unrecorded sediment removal made our actual results uncertain. Also, time-related changes in watershed roughness, drainage patterns, and erosion pavement all made the sediment yield analyses difficult. The time and environmental dependent changes and their effect on sediment yield can be hypothesized, but not until detailed and better controlled studies are made can they be adequately qualified or quantified.

One explanation for the uncertainty in the results could be changes in the erosion pavement and drainage network formation processes. Before treatment, the watershed probably had reached an equilibrium between rainfall and erosion pavement. That is, the erosion pavement had reached an amount governed by the most intense rainstorm experienced on the watershed. Also, the watershed drainage patterns, both rill and interrill, were similarly stabilized. After treatment, both the erosion pavement and drainage patterns had to reestablish according to the new watershed surface and most severe rainstorm experienced. This establishment did not occur at equal rates; thus, there are anomalies between runoff and sediment yields throughout the study period. Topographic conditions on the watershed immediately after root-plowing resembled those on a contoured plowed or terraced watershed. The vegetation was knocked down, the soil surface loosened, and small ridges formed parallel with the contour. The terrace effect produced by the contour ridges apparently reduced the sediment transport capacity of the runoff as it moved more slowly downslope. The reduced energy associated with this type runoff decreased the particle size of sediment moved, causing mostly finer sediment to move into the stock pond. Changes in stock pond volume due to the suspended sediment accumulation are difficult to determine from topographic surveys.

To help quantify sediment yield changes associated with treatment, the Universal Soil Loss Equation (USLE) parameters were evaluated for conditions pre- and post-treatment. These parameters include a rainfall factor (R), soil erodibility (K), cover (C), slope-length (SL), and erosion control practice (P). The applicability of the USLE to semiarid rangeland conditions seems possible for certain watershed conditions (Renard, Simanton, and Osborn, 1974). Values for the five USLE parameters for pre- and post-treatment periods are listed in Table 3. The USLE parameter values for the pretreatment period were measured immediately outside the treated watershed and were assumed to reflect the pretreatment watershed condition. USLE parameters were not determined for the watershed during the transition period.

TABLE 3. USLE Parameters and Sediment Yield

Condition	R	K	C^1	SL^2	P	Sediment Predicted (Tons/Acre/yr)	Yield Measured (Tons/Acre/yr)
	(Average)						
Brush (1966 → 1970)	88	.20	.08	.90	1	1.28	1.67
Grass (1974 → 1976)	47	.16	.15	.90	1	1.02	0.13

1 From SCS TR #51 (1972), Table 1: Brush - 50% Canopy Cover, Type W
60% Ground Cover (erosion pavement).

Grass - 0% Canopy Cover, Type G
30% Ground Cover (erosion pavement).

Variability in the R factor is more pronounced than the rainfall variability because the term not only includes rainfall depth, but also rainfall intensity. Although the summer R value constituted at least 95% of the annual total, the annual value was used because annual R is most commonly used in the USLE. The annual R 50% probability, from Figure 2, is around 52, with a 22 year range of 13 to 190. The average R for the post-treatment period was 47. The average R for the pretreatment period was 88 and the transition period had an average R of 96. In fact, the transition period had the largest annual R value of the 22 year period.

The soil erodibility (K), cover (C), and erosion control practice (P) were the parameters changed by the treatment. These changes were expected because of the disturbance of the soil surface and plant cover. The K term was determined from a nomograph procedure utilizing five soil properties--organic matter, very fine sand and silt, sand, structure, and permeability (Wischmeier et al., 1971). Of these, organic matter was the only one measureably changed because of treatment. The percent organic matter increased from 1.1 pretreatment to 2.2 post-treatment. With these organic matter changes, the K term changed from 0.20 pretreatment to 0.16 post-treatment, a 20% decrease.

The C term, reflecting vegetation type and density, was determined from specially prepared tables (SCS TR 51, 1972). The C term was expected to decrease because of the increase in ground cover associated with grass. However, because erosion pavement was assumed to be part of the ground cover, as suggested by Osborn et al. (1976), and this cover decreased from 60 to 30% between the pre- and post-treatment periods, the C term increased from 0.08 to 0.15, or nearly 90%.

Using the best estimates available for the five USLE parameters, the predicted sediment yield for the pretreatment period was within 30% of the measured yield. However, the predicted yield for the post-treatment period was almost 8 times that measured; probably because of the watershed change caused by the root-plowing. This watershed change should be reflected in the erosion control practice (P) term. Because no values are available for the root-plowing, seeding practice, the P term can only be estimated by solving the USLE using the known sediment yield and the other USLE parameters for the post-treatment period. Solving for P using the 0.13 tons/acre/yr, measured during the post-treatment period, gave a P value of 0.13. This value is less than the 0.50 recommended by Wischmeier and Smith (1965) for a contouring practice, but near the value of 0.15 that they recommended for contour listing. This type of analysis is limited because the effects of the root-plowing, seeding treatment are dynamic.

VEGETATION

The primary purpose of the brush to grass conversion was to relate the changes in vegetation to changes in forage production or animal carrying capacity. Before treatment, the watershed was dominated by low forage-value brush which comprised about 97% of the total vegetative cover (Table 1), and had a grazing capacity of about 2-3 animal units (AU)/section/yr. After root-plowing and seeding, the dominant vegetation was grass, comprising about 85% of the total cover. A grazing study was initiated in the early spring of 1975 to determine the effect of brush to grass conversion on the area's grazing capacity. Twenty-two Hereford cattle grazed 80 acres of the root-plowed area for 2 months in the early spring of 1975. This was equivalent to 29 AU/section/yr., and was almost 3 times greater than the pretreatment carrying capacity. Twenty-four cattle grazed the same 80-acre area for two months in the early spring of 1976. This was equivalent to 32 AU/section/yr., over 3 times the pretreatment carrying capacity. Vegetation measurements made before each of these grazing periods indicated no significant change in either vegetation composition or percent crown cover. However, different grazing systems using this large number of AU may have a detrimental effect on the vegetation composition and crown cover.

SUMMARY

Brush to grass conversion of a semiarid rangeland watershed can have pronounced effects on the hydrology, erosion, and animal carrying capacity of the treated watershed. The extent and direction of these effects depends mainly on the rainfall characteristics after the conversion. Data from this study indicated runoff increased during the transition period and decreased once grass became established. There was a decrease in sediment yield from the watershed following the vegetation conversion.

Because of the many factors involved and the variabilities of these factors, many years of observations are needed to accurately describe the hydrologic effects of watershed conversion. The conversion effects on the erosion or sediment yield from a watershed are even more difficult to describe because of the difficulty in measuring sediment yield. Also, the many complicated interactions involved in the erosion and sedimentation processes make short-term analysis difficult. Erosion pavement formation is only one interaction in a semiarid environment that may take years to stabilize. Limited water and a relatively short growing season make the vegetative component of the conversion another time-dependent variable. Although the brush to grass conversion was successful, the full benefit will only be realized if the new vegetative condition can withstand the rigors of climatic extremes and grazing pressure. The new condition must also show a positive effect in the conservation of the soil and water resource, upon which it and man depends.

The large increases in carrying capacity caused by the conversion are very encouraging. Considering the large amount of semiarid rangeland areas of the world, of which the pretreatment area was typical, such rangeland conversion can have a tremendous impact on the agricultural and economic output.

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