GROUND-WATER RECHARGE FROM URBAN RUNOFF AND IRRIGATION RETURNS

K. J. DeCook and L. G. Wilson [1/]

ABSTRACT

Preliminary information on urban runoff from selected small watersheds in the Tucson area indicates that average annual runoff from the urbanized areas is more than four times as much as that of a comparable undeveloped desert area, and may be ten times as much in some individual years. The urban runoff contains relatively high concentrations of bacterial loading and dissolved organics; although it is not now known to be a seriously hazardous source of pollutants in ground water, urban runoff should be monitored with increasing urban growth, especially for content of organics, microorganisms, and trace metals. Additional study also should be given to the travel-time regime of runoff from the small tributary urban watershed to the major stream channels where recharge mainly occurs.

Deep percolation from irrigation return flows was evaluated during a one-year study for the U.S. Geological Survey's "Southwest Alluvial Basin, Regional Aquifer System Assessment Program". Objectives of the study included (1) identifying sources of recharge information, (2) collecting and summarizing available recharge information, (3) identifying methods for interbasin transference of recharge values, (4) characterizing deep percolation models, and (5) itemizing methods for overcoming data gaps. Apparently there is a difference in opinion among irrigation experts on the extent to which recharge from deep percolation occurs. One reason for the difference of opinion is that field measurements of the flux and velocity components of deep percolation through the vadose zone are scarce, particularly for deep alluvial basins. Similarly, there is a need for a simple, theoretically-based model of deep percolation/recharge. Many of the data deficiencies could be overcome by conducting lumped and site-specific field studies. Such studies, although expensive, would be timely in light of the current interest in ground-water management.

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ground water in place, and the mechanisms of its arrival in the subsurface, are being examined by others; but gaps exist in our knowledge of the changes undergone en route from the urban source to the aquifer destination.

URBAN RUNOFF CHARACTERISTICS AT SOURCE

The University of Arizona Water Resources Research Center has collected rainfall/runoff data on several urban and suburban watersheds in Tucson since 1968, and also maintains a data file on Atterbury Experimental Watershed (Figure 1), until recently an undeveloped desert area, dating from 1957. The Atterbury data provide a baseline for conditions without urbanization, and the data for High School and Arcadia Watersheds are cited as examples of urbanized areas in the Tucson region. Figure 2 shows the delineation of watersheds in the urbanized valley region. Figure 3 illustrates the configuration and topography of High School and Arcadia Watersheds, which are 0.9 and 3.5 square miles in area, respectively. Also shown are the location of raingages and streamflow gaging stations (critical-depth flumes with continuous recorders). The character of land use in these two watersheds, as reflected by percentage of types of surface area, is illustrated in Table 1.

Distributed samples of runoff quality from the various land-use surfaces would be highly useful in identifying and isolating specific pollutant sources; distributed sampling has been undertaken, but results are not as yet available in sufficient detail to be conclusive. Lumped samples of runoff from each watershed have been collected and analyzed for a number of storm events, and an indication of results is shown in Table 2. The water quality parameters that consistently show relatively high values are suspended solids, chemical oxygen demand (COD), and bacterial density. By comparison, runoff samples collected from the undeveloped desert area in Atterbury Experimental Watershed show suspended solids content even higher than that in the urban area (about 5,200 mg/l), while COD was roughly equivalent (223 mg/l), but bacterial counts (total coliform) were much lower, only 13 percent of the concentrations found in the urban runoff.

The Pima Association of Governments (1978) has stated that urban runoff in the Tucson region "...is considered a low level immediate health hazard, but a high level long-range problem", and has recommended a continuing monitoring program to determine the impact of urban runoff on area ground-water supplies.

The amount of loading of these constituents arriving as inflow to the major streams and attributable to the tributary urban watershed depends of course upon the amount of runoff generated on that watershed. Table 3 indicates the volume runoff and peak flows measured as outflow from High School and Arcadia Watersheds in Tucson, for the period 1968-79. As may be expected in a semiarid region, the year-to-year variation in both volume runoff and peak flows is rather large, and within each year the peak flow in summer months commonly exceeds that of the winter season. As compared with undeveloped areas in the desert watershed, runoff values are generally much higher in the urbanized area; whereas the

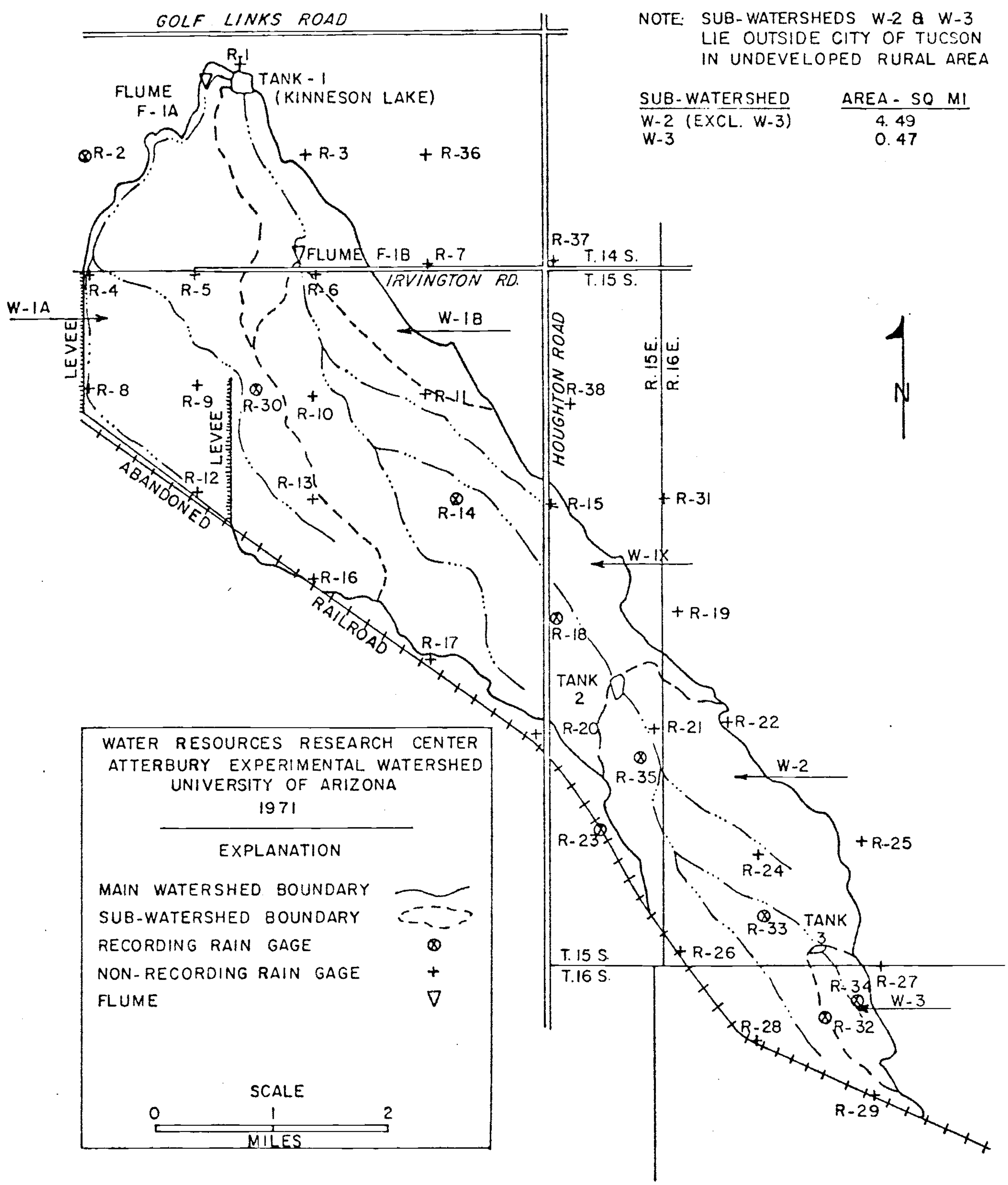

NOTE: SUB-WATERSHEDS W-2 & W-3 LIE OUTSIDE CITY OF TUCSON IN UNDEVELOPED RURAL AREA
SUB-WATERSHED
AREA - SQ MI
W-2 (EXCL. W-3)
4.49
W-3
0.47
GOLF LINKS ROAD
R-1
TANK - 1 (KINNESON LAKE)
FLUME F-1A
R-2
R-3
R-36
FLUME F-1B
R-7
R-37
T. 14 S.
T. 15 S.
IRVINGTON RD.
R-4
R-5
R-6
W-1A
W-1B
LEVEE
R-8
R-9
R-30
R-10
R-1L
HOUGHTON ROAD
R-38
R. 15 E.
R. 16 E.
N
R-12
R-13
R-14
R-15
R-31
ABANDONED
RAILROAD
R-16
W-1X
R-19
R-18
R-17
TANK 2
R-20
R-21
R-22
R-35
W-2
R-23
R-24
R-25
R-33
TANK 3
T. 15 S.
T. 16 S.
R-26
R-27
R-34
W-3
R-28
R-32
R-29
WATER RESOURCES RESEARCH CENTER
ATTERBURY EXPERIMENTAL WATERSHED
UNIVERSITY OF ARIZONA
1971
EXPLANATION
MAIN WATERSHED BOUNDARY
SUB-WATERSHED BOUNDARY
RECORDING RAIN GAGE
NON-RECORDING RAIN GAGE
FLUME
SCALE
0
1
2
MILES

FIGURE 1.

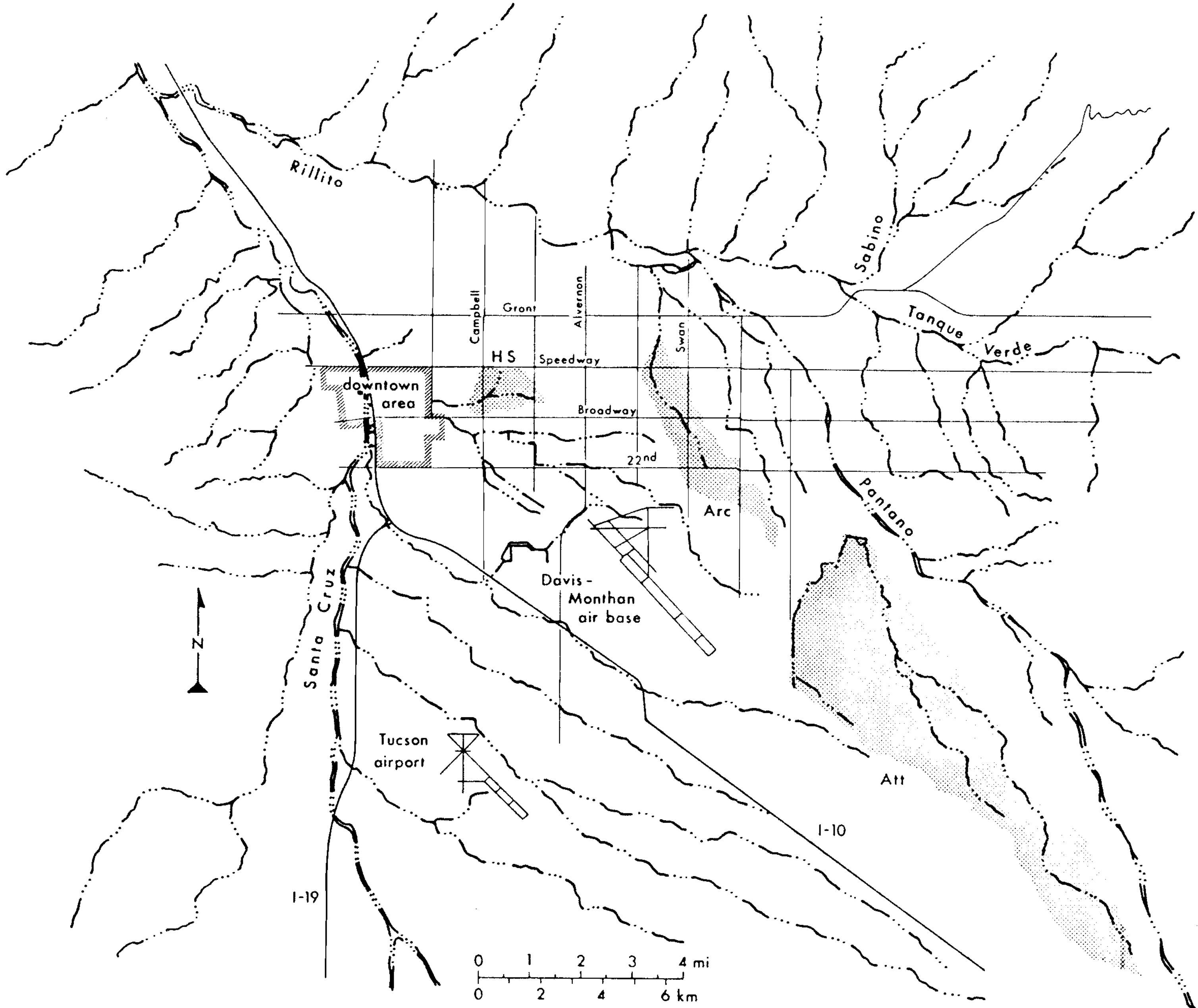
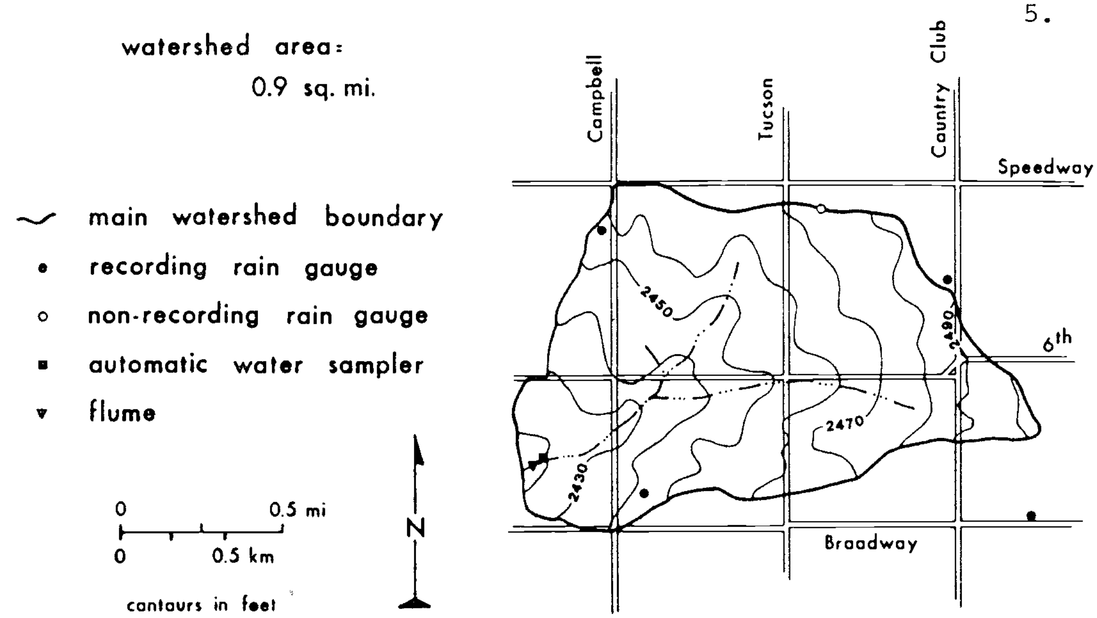


FIGURE 2. Tucson Urban Area

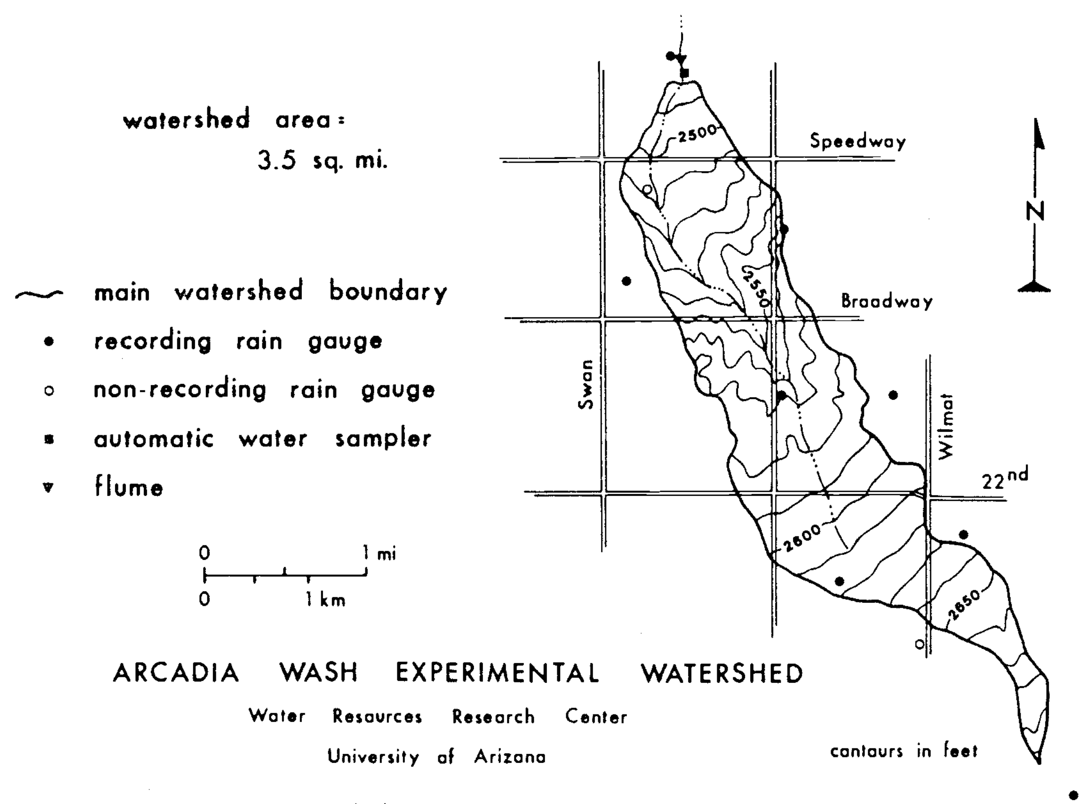


HIGH SCHOOL WASH EXPERIMENTAL WATERSHED

Water Resources Research Center

University of Arizona

Note: watershed lies in fully-developed residential area



ARCADIA WASH EXPERIMENTAL WATERSHED

Water Resources Research Center

University of Arizona

Note: watershed lies in suburban area

FIGURE 3.

Table 1. Land-use Characteristics of the Experimental Urban Watersheds

Land Use (Percent of time)	High School	Arcadia
Residential	65.5	60.4
Commercial	3.5	6.1
Industrial	0.0	0.0
Paved	19.9	13.3
Open, undeveloped	5.1	15.6
Parks, grassed	0.6	2.1
Unpaved roads	3.4	1.7
Institutions	2.0	0.8
Population density, people/acre	7.06	6.98

Table 2. Summary of Mean Values of Urban Runoff Analyses, Tucson Region*

	Watershed			
	High School		Arcadia	
Physical or Chemical Quality Indicator**	Summer Storms	Winter Storms	Summer Storms	Winter Storms
Suspended Solids (mg/l)	923	630	1768	1019
pH	7.3	6.9	7.4	7.1
Total Dissolved Solids (mg/l)	212	166	208	138
Chemical Oxygen Demand (mg/l)	227	248	200	170
Nutrient or Biological Quality Indicator**				
Nitrate, NO_3^- (mg/l)	3.1	--	2.0	0.4
Phosphate, $PO_4^{\equiv}$ (mg/l)	0.59	0.36	0.33	0.21
Total Coliform (Density per 100 ml)	$>98x10^5$	$19x10^5$	$67x10^5$	$17x10^5$
Fecal Coliform (Density per 100 ml)	$>20x10^5$	$6x10^4$	$16x10^5$	$4x10^4$
Fecal Streptococci (Density per 100 ml)	$>21x10^4$	$48x10^3$	$>10x10^4$	$45x10^4$

*Source: Dharmadhikari, 1970.
**For comparison, standards for recreational waters (partial body contact) in Arizona specify the following:

pH.. 6.5 - 8.6

Fecal Coliform:

1. Geometric mean.................................. $1x10^3$
2. 10% of samples for 30-day period shall not exceed $2x10^3$
3. Single sample shall not exceed.................. $4x10^3$

Standards for suspended solids and chemical oxygen demand have not been set. Total dissolved solids content is acceptable for all uses.

Table 3. Streamflow Data[1] for Urban Watersheds in Tucson, Arizona

High School Wash at Cherry Avenue[3]

Calendar Year	Volume Runoff (ac-ft) Summer[2]	Winter[2]	Annual	Maximum Summer Peak (cfs)	Maximum Winter Peak (cfs)
1968				486	74
1969	38	20	58	341	50
1970	93	15	109	409	43
1971	102	41	144	664	40
1972	59	71	130	*800	110
1973	20	31	51	204	52
1974	42	16	58	126	45
1975	44	19	62	195	27
1976	30	30	60	129	62
1977	9	69	78	129	178
1978	23	92	115	111	99
1979***	27	27	54	346	51
Range	9-102	15-92	51-144	111-800	27-178
Average	44	39	83	328	69
Average/mi^2	49	43	92	364	77

Arcadia Wash at Pima Street[3]

Calendar Year	Volume Runoff (ac-ft) Summer[2]	Winter[2]	Annual	Maximum Summer Peak (cfs)	Maximum Winter Peak (cfs)
**1968				213	310
1969	32	13	45	265	93
1970	205	32	237	594	124
1971	363	94	456	1207	313
1972	159	184	343	940	254
1973	15	57	72	121	74
1974	38	50	87	264	104
1975	21	11	32	133	75
***1976	68	17	86	347	37
1977	17	48	65	213	191
***1978	87	177	264	724	343
1979	136	34	170	647	70
Range	15-363	11-184	32-456	121-1207	37-343
Average	104	65	169	472	166
Average/mi^2	30	19	49	135	47

*Peak Computer - Overflowed Flume.
**No records prior to 3-19-68.
***Estimated values for some storm events because of equipment failure.

[1]Measurements by critical-depth flume.

[2]Summer rainy season is June through September; winter season is October-December and January-May.

[3]Preliminary data, as calculated; subject to revision.

long-term average runoff from Atterbury Watershed is 2-1/2 to 3 percent of rainfall or about 15 acre-feet per square mile per year (ac-ft/mi^2/yr), the volume runoff from Arcadia Watershed is more than three times as much, approaching 50 ac-ft/mi^2/yr, and that of High School Watershed shows a six-fold increase or more than 90 ac-ft/mi^2/yr. This factor can be even greater, of course, for individual storm events.

According to figures published by Pima Association of Governments (1978) in reference to specific categories of watershed surface type, annual runoff may range from 3 ac-ft/mi^2/yr for horticultural plots to 130 ac-ft/mi^2/yr for paved streets. For multiple watersheds containing a mixture of seventeen land-use categories and excluding undeveloped desert areas, the average volume of runoff from the Tucson urban area is approximately 65 ac-ft/mi^2/yr.

Peak discharges, especially for summer storm events, also may be increased in the urbanized watersheds. A comparison with the undeveloped Atterbury drainage would be difficult, as it is much larger and because its flow is regulated in part by several stock tanks. Nonetheless, the record for the suburban Arcadia Watershed shows an average peak summer (and annual) flow of 135 cubic feet per second per square mile (cfs/mi^2), and that for High School Watershed, the smaller and more intensively developed area, shows 364 cfs/mi^2.

DISPOSITION OF URBAN RUNOFF

To dispose of urban runoff in a humid region, the traditional storm sewer system is commonly used, but in desert regions such as southern Arizona, such systems may not be economically justified, and various other means are employed to dispose of storm waters. In Los Angeles and Fresno, California, for instance, storm runoff is controlled through collection systems and recharged artificially through spreading basins and pits. In Phoenix, runoff from shopping centers and parking lots is collected within those areas and injected underground into "dry wells" which do not penetrate the zone of saturation.

In Tucson, storm runoff is largely uncontrolled. A notable exception is the system constructed by the Corps of Engineers, by which runoff from Davis-Monthan Air Force Base is diverted, routed through Ajo Road Detention Basin, and discharged through Julian Wash to the Santa Cruz River. Elsewhere, city streets and natural arroyos are the principal channels of discharge to the major watercourses.

Surface Inflow

Inflow to the major streams in the Tucson basin is a principal source of recharge water, and the main channels are rather efficient natural recharge mechanisms. Burkham (1970) has estimated that about 70 percent of the average annual inflow to selected reaches of these channels is depleted by infiltration. To what extent this natural flow and recharge system is affected by urbanization remains to be determined.

First, does deep percolation occur during or following rainfall/runoff events, within the small, urban tributary watersheds? It is generally believed that recharge in the valley floor is negligible, and it would appear that recharge in the small collector channels is insignificant, also. Some basic requirements for recharge would be a permeable medium for infiltration and deep percolation; a significant wetted surface area; sufficient head to force infiltration; and sufficient duration of flow or ponding to cause substantial downward movement of water. Generally, these factors are not favorably assembled in the urban area. Much of the surface consists of impermeable roofs and paving, the near-surface strata include caliche and thin beds of silt or clay, and flow duration is measured in hours for each runoff event, of which there are only perhaps twenty per year. The head of surface water imposed on possible infiltration surfaces then may be visualized as an occasional "pulse", which over time may be so attenuated with depth that its effect on the zone of saturation a few hundred feet below may be undetectable. In any event, the net effect of conditions in the urbanized area is such that deep percolation there is relatively very small, and runoff to the main stream channels is relatively large, as seen in Table 3.

The effect of such discharge on existing flow and recharge in the main channel depends heavily upon timing of the urban tributary flow. In terms of individual runoff events, if the urban flow arrives at a time when the main channel is carrying little or no flow (quite possible, especially in the summer rainy season), the urban discharge may be spread upon a receiving channel surface which is quite favorable to recharge; if it arrives, however, when mainstream flow is already at high stage and channel materials are largely saturated, the influence of the realtively small pulse of tributary inflow may be negligible.

The same idea can be carried to seasonal timing. As shown in Table 3, somewhat more than half the annual discharge and most of the larger peak flows occur in summer on the urban watersheds. The relation of these factors to the flow regime in the main channels depends upon which main channels are receiving the urban tributary inflow. As shown by Keith (1980), the Rillito receives flow from mountain streams such as Sabino, Agua Caliente and Tanque Verde Creeks, in which approximately 70 percent of annual discharge occurs during the winter (November-April) season. Arcadia Watershed and several others in the northern and eastern urban or suburban area of Tucson also discharge into the Rillito, but their heavy summer flow contributions would be seasonally out of phase with these major mountain-stream runoff events. High School Watershed, on the other hand, represents numerous small drainages which are tributary to the Santa Cruz River, a piedmont stream wherein 70 percent or more of the annual flow occurs in the summer season (May through October). These flows coincide with the predominant summer urban runoff input, so that conditions for recharge of the urban flows may be less favorable. These relationships deserve further study.

This line of investigation becomes important also in evaluating the quality (or pollutant potential) of urban runoff. It is readily apparent that at times of high flow in the mainstream, a discharge of urban runoff with high contaminant concentration but short duration may become highly diluted by mixing, whereas such a discharge at times of no flow in the main channel may enter the recharge zone in relatively concentrated form.

Subsurface Movement

Once an increment of urban storm runoff has reached a potential recharge location such as a major stream channel -- having undergone various forms of abstraction, tranformation, and dilution/concentration under surface-flow conditions -- the next in-transit flow movement is in the subsurface, from the infiltration surface to the zone of saturation, where it will encounter further mixing and other changes. During its downward percolation from the surface to the aquifer, the recharged water may undergo a complex sequence of changes in quality through adsorption, solution/precipitation, or filtering. Empirical sampling in the aquifer can show the end result of all these processes, but the results are *ex post facto*. In order to avoid undesirable changes (ground-water pollution), prior evaluation and prediction must be made, based on knowledge of the quality parameters of the recharging waters at the surface as well as the quality of ambient subsurface waters and the lithochemistry of the intervening soil/rock strata. The cost of such information is high, but methods for control are being studied by agencies such as the Arizona Department of Health Services, in order to set standards for subsurface disposal of surface waters and develop procedures for protection of ground-water quality.

COMMENTS AND RECOMMENDATIONS

1. Two small urbanized watersheds in the Tucson area yield an average annual runoff of about 50 to 90 ac-ft/mi^2/yr. For the larger Tucson "urban window", excluding undeveloped desert areas, it appears that approximately 220 square miles of urbanized area yield an average of about 65 ac-ft/mi^2/yr or a total of 14,300 acre-feet per year (Pima Association of Governments, 1978, p. 58). In the unurbanized state, these same areas evidently would yield about 15 ac-ft/mi^2/yr or 3,300 acre-feet in total. Therefore, urbanization appears to have effected a net increase of 11,000 acre-feet of runoff per year to the main stream channels in the basin, during the 1970's.

2. The observed quality of urban runoff in Tucson does not clearly indicate a presently high pollution potential for ground water. The urbanization process, however, is both intensifying and expanding, so that future pollutant loadings will be rapidly growing without a corresponding increase in assimilative capacity or dilution potential in the natural stream system. Accordingly, the following recommendations by Mooradian (1980) are endorsed: (1) Analyses of urban runoff samples should be continued; (2) an extensive research program should be implemented to document the movement of urban runoff in the surface and subsurface, using techniques such as tracers; (3) studies should be continued on the soil attenuating capabilities of the riverwash sediments; and (4) water samples should be collected and analyzed, from monitor

wells along the linear sinks for urban runoff such as the Rillito and Santa Cruz Rivers. Distributed sampling within specific urban land-use areas also would be useful, for isolating "hot spots" of pollutant contribution.

3. The travel-time/flow regime of the urban watershed should be investigated, in terms of the relationship of arrival times of urban tributary inflows to those of mainstream inflows.

4. Where it appears desirable to modify the flow time of urban runoff or where high pollutant level is found, it is recommended that systems be devised for off-channel detention of increments of the urban runoff in upstream areas, where it could be clarified for use as in park areas, or released at controlled rates for more compatible recharge downstream.

AGRICULTURAL RETURN FLOWS AS A SOURCE OF RECHARGE

In the course of a one-year study, initiated on June 1, 1979, the Water Resources Research Center has been assisting the U.S. Geological Survey in the Southwest Alluvial Basin, Regional Aquifer System Analysis (SWAB/RASA) program. This program is one of several RASA projects initiated since 1976 to systematically study the regional ground-water systems in the U.S. General goals of all RASA studies (Anderson, 1979) are (1) to describe the hydraulic and geochemical properties of developed and undeveloped ground-water systems, (2) to determine changes resulting from development, (3) to interrelate results from previous studies, and (4) to provide predictive models to facilitate further management projects. The area of the SWAB/RASA project comprises about 84,000 square miles in southern and central Arizona, and smaller portions of California, Nevada, and New Mexico. The project area is divided into 71 hydrological basins.

The general purpose of the study undertaken by the Water Resources Research Center for the SWAB/RASA effort is to assess the recharge component of alluvial basin hydrological systems. Both natural and "culturally modified" components of recharge are included. Natural recharge consists of recharge from streamflow depletion and from mountain front infiltration. "Culturally modified" recharge sources include irrigation return flows, (i.e., deep percolation), canal seepage, leakage from pits, ponds and lagoons, artificial recharge, and streamflow depletion of sewage effluent discharged into ephemeral channels. (Urban runoff, an additional "culturally modified" recharge sources was discussed in the first major section of this paper.) The five specific objectives of the recharge study are as follows: (1) to identify sources of recharge information, (2) to collect and summarize recharge values (including identifying data gaps), (3) to identify approaches for transferring recharge values from basins with extensive values to basins with poor data bases, (4) to evaluate recharge models, and (5) to identify methods for overcoming data gaps. In this section of this paper we will review the progress to date in achieving these goals for the deep percolation component of irrigation return flows. General observations are also briefly discussed.

APPROACHES

Project activities during the first six months of the project comprised collecting available recharge data and deep percolation models. This information collection effort was not restricted to the SWAB/RASA project area but included other arid and semiarid regions of the U.S. and elsewhere in the world. Consequently, a widespread search was conducted for agencies and individuals with recharge information. Similarly, an intensive literature search for recharge values was conducted. The potential of several data management systems for storing and retrieving the assembled recharge values was examined.

Although the collection of information was continued into the second half of the project the major emphasis was on using the information to satisfy the last three objectives of the project, i.e., transferring results, evaluation of models, and developing alternative methods for offsetting data gaps.

RESULTS

Sources of Information and Initial Observations

A complete listing of information sources will be included in the final report for the project. In summary, information was obtained from individuals within the following types of agencies: federal, state and local water resources divisions, academic and professional institutions, and private consultants. From personal discussions with individuals in these agencies it was found that there is a dichotomy of opinion on whether or not deep percolation in fact exists. Evidence for the existence of deep percolation includes the following:

a) Water budget calculations require the input of substantial values of deep percolation to permit closure. For example, in a water budget analysis for the Salt River Valley for normalized 1970 conditions, the Arizona Water Commission (1975) estimated that recharge from irrigation was 949,000 acre-feet.

b) Cascading water from perched ground-water zones has been observed in wells within irrigated areas of the state, such as the Lower Harquahala Valley (Graf, 1980), and the Avra Valley (Robertson, 1979). Chemical analysis of samples of cascading water indicates the presence of high nitrates, which may have originated from applied fertilizers.

c) Pesticides have been found in ground-water samples within the Salt River Valley. Whether pesticide residues arrive as a result of flux across the water table from deep percolation of irrigation water, or as a result of leakage through faulty wells is uncertain at this time.

The evidence against the existence of deep percolation is based on field observations by authorities on irrigation water management, who were contacted during the project. These individuals have taken large numbers of soil samples in irrigated fields during the growth of various crops, either for determination of consumptive use curves, or for irrigation scheduling. Aside from the wetting of soil profiles during preirrigation, movement of water past the predominant rooting depths is not observed. In fact, several of the individuals contacted felt that in some areas (such as in Pinal County) the farmers do not apply enough water to offset moisture deficits, and that crop yields would be improved by adding more water.

Collection of Data

Hard data on deep percolation of irrigation water are virtually absent because very few on-site studies have been made. The deep percolation values in the majority of reports were calculated as the residuals in water balance calculations for entire basins. Consequently, the errors in estimating the other parameters of the water balance equation accumulate in the deep percolation values.

As it turned out, useful, site-specific information on deep percolation was available primarily for the Yuma area. Extensive, on-farm water balance studies using field measurements of input-output values have been conducted on irrigated areas at Yuma since the early 70's. These studies are part of a program to improve irrigation efficiencies and reduce the salt load of drainage water discharged into Mexico. The program was conducted under the aegis of an Advisory Committee on Irrigation Efficiency, including members from the following agencies: The Water and Power Resources Service (formerly U.S. Bureau of Reclamation), the Soil Conservation Service, and the U.S. Environmental Protection Agency. A summary of the water budget analyses from the Wellton-Mohawk Irrigation and Drainage District for the year 1970 through 1977 is shown on Table 4. Average irrigation efficiencies (defined as crop consumptive use divided by farm delivery) increased from 50% in 1970 to 65% in 1977. Irrigation efficiencies in areas with field crops were generally greater than 50%, whereas efficiencies in areas with vegetables and citrus were less than 50%. Efficiencies were related to soil types, with lower efficiencies on sandier soils. During the period 1970 to 1977 deep percolation values decreased from a high of about 230,000 acre-feet in 1971 to a low of about 137,000 acre-feet in 1977. Improvements in efficiency and decreases in deep percolation losses are a reflection of several factors including an acreage reduction program, rising costs for irrigation water, and improvements in on-farm water management (The Advisory Committee on Irrigation Efficiency, 1978). Included among the improved management practices is level-basin irrigation, in operation on 40,000 to 50,000 acres of field crops in The Wellton-Mohawk Valley (Erie and Dedrick, 1979).

Evans, Sammis and Warrick (1976) reported the results of a study on deep percolation rates for an irrigated area in the Salt River Valley. Three methods were used to estimate percolation rates: (1) Darcy's equation with appropriate measurements of hydraulic conductivity and hydraulic gradients; (2) temperature gradients in the soil profile;

Table 4. Water Budget Analyses, Wellton-Mohawk Irrigation and Drainage District (From: The Advisory Committee on Irrigation Efficiency, 1978).

Year	Irrigated Area (Ac)	Crop Consumptive Use (C.U.) (AF)	C.U. per Acre (AF/Ac)	Farm Delivery (AF)	Irrigation Efficiency (%)	Deep Percolation (AF)
1970	60,756	228,801	3.77	457,194	50	228,393
1971	61,152	246,510	4.03	476,690	52	230,180
1972	62,351	257,789	4.13	450,357	57	192,568
1973	63,973	269,833	4.22	468,693	58	198,860
1974	64,884	281,846	4.34	499,543	56	217,697
1975	65,529	277,053	4.23	489,531	57	212,478
1976	64,684	267,058	4.13	437,174	61	170,116
1977	60,622	254,902	4.20	391,741	65	136,839

and (3) tritium concentrations of soil water relative to tritium concentration/precipitation records. Estimates of the darcian flux ranged from 9 to 38 cm/yr (4 to 15 in/yr). Corresponding estimates of the average linear velocity ranged from 57 to 130 cm/yr (22 to 51 in/yr).

Summarizing Recharge Values

The data management system which was selected for processing and summarizing deep percolation values in reports collected during the project is designated SELGEM. This system was developed about 10 years ago by the Smithsonian Institution. The basic SELGEM programs include the following capabilities: creation of master files, updating, editing, indexing, retrieving and preparing reports. For the purposes of this project, SELGEM offers numerous advantages for collecting, sorting, and selectively retrieving the different types of recharge-related data. SELGEM is available through the University of Arizona Computer Center.

To facilitate summarizing deep percolation estimates for SWAB/RASA basins, the irrigated acreage in each basin was estimated using the Cropland Atlas of Arizona (Mayes, 1974). Specifically, basin boundaries were superimposed on maps in the atlas and corresponding irrigated areas were detemined by planimetering. Inasmuch as reported values of deep percolation were minimal, alternative approaches for estimating deep percolation in each basin were examined. A simple method consisted of the following steps: (1) estimating crop acreages in each county; (2) estimating water application rates for each crop; (3) estimating consumptive use values for each crop in each area; and (4) calculating deep percolation as the difference between total application rate and total consumptive use. Crop acreages for step (1) were obtained from annual summaries published by the Arizona Crop and Livestock Reporting Service (e.g., Mayes, Britton and Riggs, 1979). Acreages of crops not reported in these annual summaries were obtained from Agricultural Agents of the University of Arizona Cooperative Extension Service. Estimated application rates for field crops (step 2) were obtained from a series of field crop budgets published by the Cooperative Extension Service (see, for example, Hathorn and Grumbles, 1980). Estimates for other crops were provided by Agricultural Agents in the counties. Consumptive use values for each crop (step 3) were available in tables prepared by Enz (No Date) and from the report of Erie, French and Harris (1965). Important (albeit tenuous) assumptions of this approach are: (1) all tailwater generated within the basin does not leave the basin, and (2) the available soil moisture storage remains constant.

An example of a 1976 water budget for the SWAB/RASA basin designated AVRALT, calculated by the above approach is shown on table 5. The estimated total deep percolation for the basin was 50,360 acre feet for a total irrigated area of 49,150 acres. Thus, deep percolation amounted to 1.02 feet per year. The average irrigation efficiency (consumptive use divided by application rate) was 75 percent, with higher efficiencies for alfalfa, cotton, grains, sorghum, and pasture

Table 5. Water Budget for the SWAB/RASA basin AVRALT

Crop	Area (acres)[1]	Estimated Application Rate (AF/A)	Total Applied (AF)	Consumptive Use (AF/A)	Total Consumptive Use (AF)	Irrigation Efficiency %	Deep Percolation (AF)
Alfalfa	3096	6.0	18,580	4.5	13,930	75	4,650
Cotton	17264	4.25	73,370	3.5	60,420	82	12,950
Grain	14285	3.17	45,280	2.5	35,710	79	9,570
Lettuce	4086	4.5	18,390	2.0	8,170	44	10,220
Sorghum	5883	3.17	18,650	2.5	14,710	79	3,940
Misc.	326	3.0	980	3.0	980	100	0
Pasture	1988	5.0	9,940	4.0	7,950	80	1,990
Pecans	2223	6.67	14,820	3.5	7,780	52	7,040
TOTALS	49150		200,010		149,650		50,360
					Average	75	

[1]Crop survey data courtesy of the Department of Soils, Water & Engineering, University of Arizona.

crops. The crop with the lowest efficiency, 44 percent, was lettuce.

Transference of Results

Transference of recharge values from basins with extensive data to basins with insufficient data requires an identification of the components of the recharge process. For recharge of irrigation water the components may be divided into two categories: (1) components relating to percolation of water past the root zone, and (2) components associated with percolation through the lower vadose zone.

As it turns out, the factors relating to percolation beneath the root zone are identical to the factors governing irrigation efficiency. In other words, the amount of deep percolation past the root zone and the amount of tailwater from the field depend directly on irrigation efficiency: the lower the efficiency, the greater will be the losses through deep percolation and tailwater. A detailed review of irrigation efficiency is presented in another paper in this symposium. Excellent reviews of factors involved in irrigation efficiency are also presented by Bos and Nugteren (1974) and by Jensen (1980). For the purposes of this paper the factors associated with irrigation efficiency are grouped as follows: (1) soils related factors (soil types, soil structure), (2) irrigation related factors (soil-water interactions, irrigation methods, application rates, length of sets, leaching requirements, etc.), (3) crop related factors (rooting depths, consumptive use, varieties, cultural practices, etc.), (4) economic factors (market prices of crops, pumping costs), and (5) institutional factors ("duty" of water). A simple approach for evaluating the relative effect of each factor on irrigation efficiency and deep percolation is to use multiple linear regression (MLR) analysis. Unfortunately, this approach is limited by the lack of independent measurements of deep percolation. That is, deep percolation is normally calculated by the water budget approach, the components of which also enter into MLR analysis.

Factors affecting the deep percolation of water through the vadose zone are primarily those relating to the storage and flux of water. Storage properties include such factors as, specific retention (field capacity), specific yield, water content, depth of water table, etc. Properties governing the flux of water through the vadose zone include structural features such as layering, and hydraulic properties such as the hydraulic conductivity. Whether or not water moving below the root zone reaches the water table depends on the relative velocity of deep percolation and the rate of recession of the water table.

Examine Recharge Models

A preliminary listing of deep percolation models is presented in Table 6. The models are categorized according to type. The table also includes information on the input data needed for each model, the output, description and comments of each model, and references.

An examination of this table will show that the models deal primarily with the movement of water through the soil zone. The model of King

TABLE 6

PRELIMINARY LISTING OF IRRIGATION RETURN FLOW MODELS, CLASSIFIED ACCORDING TO MODEL TYPE

MODEL TYPE	INPUT DATA NEEDED	OUTPUT	DESCRIPTION/COMMENTS	REFERENCE/EXAMPLE
1. Water Budget	Irrigation efficiencies (distribution and application), crop consumptive use (ET), rainfall, irrigated acreage, crop type, amount of applied irrigation.	Surface runoff, deep percolation	The hydrological equation is solved for amounts of runoff and deep percolation. Changes in soil water content during the irrigation season are neglected and may be applied on a district-wide basis. Tanji coupled a hydraulic model with a salinity balance model. Generally applied where water tables are shallow. Does not account for spatial variations in application.	Tanji (1977); Advisory Committee on Irrigation Efficiency, Wellton-Mohawk Irrigation and Drainage District (1974); Olmsted, et al, (1973).
	Monthly values of temperatures, ET from Blaney-Criddle, area of land use, inflows, lateral diversions, drainage outflows, water exports and imports, water table fluctuations, precipitation, soil moisture storage capacity, aquifer strata, hydraulic conductivity, and cross-sectional area.	Consumptive use, deep percolation, surface and subsurface flows, water quality.	Hydrosalinity model. Seepage flows from conveyance efficiency, water moving into root zone is subdivided into root zone storage, deep percolation and consumptive use.	Walker (1970)
2. Water Budget with Soil Moisture Accounting	Climatic data (temperature, precipitation, net radiation, albedo, mean solar radiation, etc.), crop conditions, and antecedent soil moisture conditions.	Soil moisture depletion, soil moisture accretion, deep percolation, runoff.	Generally involves a simple book keeping process to account for changes in soil moisture content. A computer program (WATBUG) is available to facilitate computations. An algorithm for programmable calculations is also available.	Thornthwaite, and Mather (1957); Willmott (1977); Heerman and Kincaid (1974).
	Evapotranspiration, depth of applied water, irrigation efficiency, volumetric water content of soil.	Amount of deep percolation, downward velocity of deep percolation.	Method entails dividing amount of deep percolation (flux) by volumetric water content to estimate velocity of deep percolation. Knowing the amount of pumpage, specific yield of aquifer, and fall of water table, the flux across the water table can be estimated.	Bouwer (1979).
3. Analytical	Hydraulic conductivity and water content under steady ponded conditions, root depth, scaling parameters, initial sprinkling rate.	Soil water flux at a given depth (e.g., below root zone).	Requires field measurements, e.g. of hydraulic conductivity and application rates. Method accounts for spatial variability of soil properties, and expresses flux as function of time.	Warrick (1977).
	Saturation moisture content, initial distribution of soil moisture diffusivity, hydraulic conductivity vs. moisture content, discharge of trickle source, duration.	Soil moisture, deep percolation, evaporation.	Employs two-dimensional diffusion type water flow equation to analyze trickle irrigation systems. Analysis is based on application and redistribution of irrigation water. Hysteresis is not included.	Brandt et al (1971).

MODEL TYPE	INPUT DATA NEEDED	OUTPUT	DESCRIPTION/COMMENTS	REFERENCE/EXAMPLE
	Water application efficiency, water storage efficiency, Karmeli distribution curve, intake opportunity at various locations in field, representative infiltration function, level of soil moisture depletion, total applied water, slope, furrow spacing.	Deep percolation, infiltration volumes, runoff volumes.	Model accounts for spatial variability of applied irrigation water, and variations in wetting depth along borders and furrows. To apply in field need data on infiltration rates, initial water content, etc.	Karmeli et al, (1978)
4. Numerical/ Digital	Climatic information (e.g., rainfall, temperature), soil-water characteristics, field capacity-depth relationships, water content-hydraulic conductivity relationships, root zone depth.	Surface runoff, evapotranspiration, soil moisture storage, deep percolation, flux across a water table.	Two computer programs are used. The Root Zone Model uses rainfall and temperature data to determine deep percolation. The Deep Seepage Model simulates movement of deep percolation through the vadose zone. Requires either laboratory determination of soil hydraulic relationships or published curves. Uses Thornthwaite-Mather water budget to calculate flux through segmented soil system.	King and Lambert (1976)
	Saturated hydraulic conductivity, initial moisture distribution, runoff hydraulic parameters, potential evaporation rate, water table elevation, rainfall, relationship between water content and hydraulic conductivity and suction.	Output depicts time and spatial distribution of water in system, and deep percolation.	Two-dimensional soil divided into layers. Model uses iterative process. Macrosystem. Plant uptake and transpiration are not included. Deep percolation is infiltration amount that leaves the least soil segment.	Hillel (1977)
	Initial soil moisture distribution, ground water and surface water and surface water conditions, soil hydraulic properties, irrigation characteristics, geometry, time.	Infiltration, vertical movement, water table fluctuations, flux.	Uses Darcy's equation, exponential relationships between hydraulic conductivity and moisture tension, conservation of mass, and the Houghoudt drainage formula. Soil conditions in depth increments are presented.	Wind and Van Doorne (1975)

MODEL TYPE	INPUT DATA NEEDED	OUTPUT	DESCRIPTION/COMMENTS	REFERENCE/EXAMPLE
5. Empirical	1. Application method, application depth, and flow per unit farm plot area. 2. Irrigation method, soil type, farm size, and delivery period. 3. Irrigation method and area size, size of rotational unit, canal equipment and distribution method.	1. Data from #1 produces estimated application efficiency. 2. Estimated farm ditch efficiency. 3. Estimated conveyance efficiency. 4. Estimated project efficiency.	Relationships between application efficiency, irrigation method, soil type, and farm size were plotted from results of international questionnaire. Similar relations developed for conveyance efficiencies. Relationships are used to develop respective efficiencies for new project area. Knowing efficiencies, crop consumptive use and deliveries, deep percolation and runoff could be calculated. Limited to areas less than 40 acrés.	Bos and Nugteren (1974)

and Lambert (1976) is an exception. Two programs are used. One program called a Root Zone Model determines percolation past the root zone using the Thornthwaite-Mather water budget approach. The second program, called the Deep Seepage Model, simulates movement through the vadose zone. The latter program requires information on hydraulic relationships (e.g., hydraulic conductivity vs. water content) of the vadose zone. Obtaining such relationships for deep, highly-layered vadose zones is a formidable task.

The alternative approach of Bouwer (1979), shown on Table 6, is a simple, yet effective, method for estimating percolation rates through the vadose zone. Basically, this method consists of dividing the estimated flux past the root zone by an average water content (e.g., field capacity) of the vadose zone, to obtain an estimate of the average linear velocity.

Methods for Overcoming Data Gaps

Tentatively, it appears that two approaches could be used when establishing field studies to quantify irrigation return flows: (1) A lumped approach, and (2) site-specific studies. The lumped approach would aim at generating data for an accurate water budget within a large irrigated area, such as an irrigation district. This approach would entail accurate measurement of on-farm conveyance and application losses for a number of "representative" farms. Conveyance and irrigation efficiencies, plus deep percolation and tailwater losses, could thereby be accurately determined. In addition, by appropriate studies the effects of the various factors influencing irrigation efficiency and deep percolation could be quantified. The relative importance of each of these factors could be evaluated using MLR analysis.

The purpose of on-site studies would be to characterize the flux and linear velocity of water through and beneath the root zone. Basically, such studies would show whether or not irrigation water actually recharges underlying ground-water systems. Also, the effect of lithological and hydraulic properties of the vadose zone on recharge could be determined to aid in transferring recharge values. Alternative methods include neutron logging, to characterize changes in water content, and tracers for estimating flow velocities. The cost of field studies to obtain representative values for deep percolation for various hydrogeological conditions will obviously be high; particularly when the spatial variabilities of hydraulic properties in the vadose zone are taken into account. In addition, the cooperation of typical farmers in the conduction of field studies is essential, but may be difficult to obtain.

CONCLUSIONS FROM THE STUDY

Conclusions which have been reached to date for the deep percolation component of the SWAB/RASA recharge study are summarized below:

1. There is a dichotomy of opinion on whether or not deep percolation is fact exists.

2. There is a paucity of substantive data on the amount of deep percolation in thick alluvial basins of the SWAB/RASA project area. Excellent data are available for the Wellton-Mohawk Irrigation and Drainage District. However, water tables in the district are relatively shallow and results cannot be easily extrapolated to basins where the water table may be 100 feet or more in depth. The need to quantify recharge from deep percolation is emphasized by the current focus on ground-water management in Arizona.

3. As a corollary of the above conclusion, data are needed to define representative values of the average linear velocity of irrigation water in the vadose zone. Representative velocity values, coupled with data on water table recession rates, will provide clues on the travel time of water in the vadose zone before recharge occurs.

4. There is a need for a simple, yet accurate routing model to describe deep percolation through the vadose zone.

5. Extensive field studies should be conducted in representative irrigated fields throughout the principal irrigated areas of the state to quantify the relationship of deep percolation to such factors as soil types, irrigation methods, economics, institutional constraints, and crops.

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