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ESTIMATION OF THE ELEMENTS OF THE WATER BALANCE OF AN EPHEMERAL STREAM CHANNEL WITH RIPARIAN VEGETATION

by

Hasan Khalil Qashu

A Dissertation Submitted to the Faculty of the DEPARTMENT OF WATERSHED MANAGEMENT
In Partial Fulfillment of the Requirements For the Degree of DOCTOR OF PHILOSOPHY
In the Graduate College THE UNIVERSITY OF ARIZONA 1966
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SIGNED: Hasen K. Gashu
This dissertation is affectionately dedicated to my baby daughter, Susan Emily Qashu, who tore into the data with enthusiasm equal to her father's.
ACKNOWLEDGEMENT

The author wishes to acknowledge the guidance of the late Professor P. B. Rowe in planning the research. He wishes to express his appreciation to Professor D. D. Evans for his interest in the study and his encouragement and help in the reduction of data. His stimulating and challenging suggestions and ideas in bringing soil physics to field research opened a new avenue in this investigation.

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ABSTRACT

Water is of utmost importance in the southwestern United States where it limits agricultural and industrial development. In southeastern Arizona, where this research was conducted, about two-thirds of the total annual precipitation falls in the summer (from July to September), and it accounts for almost all water yields from watersheds of low efficiencies. These low efficiencies are attributed to convective storm characteristics and patterns, watershed physiography, and high transmission losses in water conveying channels. Knowledge of the paths which water follows and the quantities of water following these paths in time and space is a basic requirement for managing watersheds for improved efficiencies and sustained water yield.

Application of the principle of conservation of mass to an open ecosystem on water in a natural stream channel was attempted through the water balance approach. A ten-acre reach of Walnut Gulch Channel near Tombstone, Arizona, was selected to study water gains and losses in the presence of riparian vegetation.

Delimitation of the area was attained by intensive survey of alluvium depths to confining granite. A seismic refraction procedure
was used in this survey in conjunction with more than twenty wells and soil pits which extended to granite. A topographic map of granite surface and six cross sections of the alluvium at the upper boundary of the research area were drawn from the results of the seismic survey.

Description of water table elevation regime is presented. Four periods were recognized from the annual water table elevations cycle. Elements of the water balance equation which contribute to water flow were different for each period. A model representation of the area and discussion of these periods are presented.

A field method for measuring water flow in saturated channel alluvium is described and was used in estimating subsurface water flow into the research area from the upper reaches of the channel. Average specific yield of the alluvium was calculated from simultaneous measurements of water table elevations and water content above the capillary fringe during plant dormancy when the water distribution approached a dynamic equilibrium. Changes in water storage were calculated from water table measurements and the changes in volumes of saturated alluvium in nine subdivisions of the research area and from water content measurements above the capillary fringe.
Evaporation and transpiration losses were calculated for three periods. They were estimated during flow season when surface water flow was not known. Transpiration losses prior to summer rains were calculated from diurnal fluctuation of water table at one of the observation wells in an area with dense riparian vegetation. More than nine millimeters of water were lost per day by transpiration from riparian vegetation during May and June, a time of water shortage in this region.

Evapotranspiration losses from the research area from July 1964 to June 1965 were equal to 1,898,000 cubic feet. Calculated subsurface inflow amounted to 312,000 cubic feet, and subsurface outflow (seepage) was 807,000 cubic feet.
1. INTRODUCTION

Arid and semiarid regions of the Southwestern United States are characterized by sporadic precipitation, a limited water supply, and high rates of incident solar energy. Although agricultural and industrial developments are generally limited in these areas, they represent regions of high food potential given adequate and sustained water supplies.

Amounts of precipitation which reach the biosphere in these areas cannot generally be predicted and are not subject to man's interference. But the movement, storage, and disposition of these waters can be ameliorated by man. Thus, if water is to be managed, water harvesting schemes and procedures in these areas should be based on understanding the water movement and its disposition. The flux of vapor from the earth to the atmosphere, its movement with air currents, its return to the earth again, and its movement in the soil is called the hydrologic cycle. The hydrologic cycle is studied in terms of water fluxes and the principle of "conservation of matter" and is commonly expressed as a water balance. The components of water balance are simply thought of as quantities of water which follow four paths. (i) Water condenses and falls as precipitation
(rain, snow, ice). (ii) Water evaporates and passes back to the atmosphere either directly by evaporation or indirectly from soil water storage via plants as transpiration. (iii) Some of the precipitation may remain as liquid and either infiltrate into the soil or flow on the ground surface. The infiltrated water is either retained as soil moisture storage or is percolated through the subsoil and the geologic formations into ground water. The surface water flows to streams and rivers and subsequently to the oceans or inland seas and lakes. (iv) A small fraction of water is retained by plants and animals, and is subsequently returned to the soil or the atmosphere upon their death and decomposition. The relative amounts of water which follow these paths vary with time, place, and the existing environmental forces which are subject to amelioration by man and his direct and indirect influences.

The time needed for a unit volume of water to complete a cycle varies with the path it follows, the place or location, and the general or local air circulation of the atmosphere. Evaporation from water surfaces near a seashore may fall as rain or fog drip on the nearest coastal land, evaporate again and return to the ocean within a few hours. Snow which falls at high altitudes may remain for months or for centuries in glaciers before it completes the cycle, while water which percolates deeply into the ground may remain there for months.
or thousands of years before its appearance on the surface.

The study and determination of the amounts of water which follow the paths of the hydrologic cycle for a given location and time interval is defined as the study of water balance. For such a study, a system is defined which is either: (1) simple, where influxes and outfluxes of both energy and mass are accurately determined, or (2) complex and comprises several interdependent components which are subject to both internal interactions and external forces. The ecosystem (soil-plant-water system) and the surrounding environment is a complex open system, and the rates of exchange of water and energy with its surroundings can be evaluated by using both the conservation of mass and the conservation of energy principles. Under controlled conditions, such a system may be thought of as a natural plumbing system with numerous meters and controls for measurements and adjustments of the flows to energy conversion cells with feedback and varying efficiencies. The net useful work produced per unit volume of water through such a cycle varies with the efficiency settings of the controls. In the ecosystem the input and output of mass and energy may be calculated, but the efficiencies are low because the supply of matter and the rates of its transformation are not known. The available energy is not only wasted but contributes to the total inefficiencies of the system.
1.1 THE PROBLEM

In many areas of southeastern Arizona, watershed efficiencies, in terms of water yield (water output to total precipitation), are very low because of the high transmission losses in their conveyance systems. The streams are generally ephemeral and usually flow during summer convective rains. The channel banks support a lush riparian vegetation during the flow season which coincides with maximum evapotranspiration (ET) opportunity. Rates of water movement in the alluvium, and water disposition from such sites are not known.

The Walnut Gulch stream represents such conditions. It drains an experimental watershed area of 58 square miles. In some reaches it traverses undulating granodiorite masses with alluvium filled pockets which vary in depth and extent. These areas are usually recharged with water during the flow season and much of this water is lost as evaporation and transpiration in the spring and summer.

Annual water storage in such areas comprises a large portion of the total water resources in the region. Management planning for water harvesting at these areas would be incomplete without a quantitative scheme for evaluating the rates of water inflow and disposition. To achieve this, quantities of water following the paths of the hydrologic cycle for an area should be known. In this study an attempt will
be made to estimate the rates of water inflow and outflow at a reach of the Walnut Gulch stream channel.

1.2 PURPOSE OF THE STUDY

Shallow water tables along flowing rivers and stream channels are very common in the Southwest. Amounts of water losses as evaporation and transpiration, and the rates of these losses are not known. Field methods for the determination of those losses are either very costly or not applicable to the types of vegetation involved. Management for increasing the water supply and regulating the water harvesting requires determination of soil water movement, patterns of soil moisture regimes, and rates of water disposition.

The purpose of this study is to: (1) develop some field methods for evaluating water disposition in areas with a shallow water table, (2) determine rates of water losses due to evapotranspiration and (3) determine rates of sub-surface flow below the water table.
2. REVIEW OF LITERATURE

Papers and articles reviewed are limited to topics which pertain directly to the problem and no attempt has been made to present a review of all the information covering the related research or all the hydrologic procedures dealing with the different aspects of the problem. The papers reviewed deal with water flow in porous media, some specific methods and techniques in ground water investigation, and similar studies on water disposition.

2.1 WATER MOVEMENT IN SOIL

The basic equation for water flow in soil was presented by Darcy (1856) and one of its forms is

\[ \frac{Q}{t} = KA(H_1 + L - H_2) / L \]  
\[ (2.1) \]

where \( Q \) is the quantity of water passing vertically downward through a sand bed of cross sectional area \( A \) and thickness \( L \) in time \( t \) when the depth of water over the surface is \( H_1 \), and the water is leaving the lower end of the bed at a head \( H_2 \). The constant \( K \) is a coefficient dependent upon the nature of the porous medium.

Equation 2.1 may be written as

\[ q_x = -K \frac{\partial \phi}{\partial x} \]  
\[ (2.2) \]
where \( q_x = \frac{Q}{At} \), which is the water flux, and has the units of quantity per unit area per unit time, and \( \varphi \) is the water potential.

Slichter (1899) noticed that Darcy's law could be combined directly with the continuity equation to give

\[
\frac{\partial}{\partial x} (K_x \frac{\partial \varphi}{\partial x}) + \frac{\partial}{\partial y} (K_y \frac{\partial \varphi}{\partial y}) + \frac{\partial}{\partial z} (K_z \frac{\partial \varphi}{\partial z}) = \frac{\partial \theta}{\partial t} \tag{2.3}
\]

where \( \theta \) is water content.

This equation has been solved by many research workers to obtain analytical solutions to particular ground water flow problems. For the solution of equation 2.3, idealization of the saturated porous media and of the boundary conditions of the flow system are necessary. Although the results only approximate field conditions, the known deviations from the assumptions frequently allow the analytical solutions to be modified to obtain an approximate answer. The most common assumptions regarding the porous media are isotropy and homogeneity.

Forchheimer (1866, 1895) was responsible for many theoretical innovations including the introduction of the concept of equipotential and stream lines and the solution of Laplace's equation using the methods of the theory of functions of a complex variable. He derived Laplace's equation to determine the shape of the free water surface and the rate of flow at any point in a horizontal flow.
system under steady state conditions. He considered a sand column of base \( \Delta x \Delta y \) at height \( h \) to the phreatic surface. On the basis of the principle of conservation of mass he wrote for steady state flow

\[
\left( q_x h + \frac{\partial (q_x h)}{\partial x} \Delta x \right) \Delta y - q_x h \Delta y + \left( q_y h + \frac{\partial (q_y h)}{\partial y} \Delta y \right) \Delta x - q_y h \Delta x = 0
\]

(2.4)

Some of the terms in equation 2.4 are equivalent and it yields

\[
\frac{\partial (q_x h)}{\partial x} + \frac{\partial (q_y h)}{\partial y} = 0
\]

(2.5)

And on the basis of the second Dupuit assumption, he wrote

\[
q_x = -K_x \frac{\partial h}{\partial x} ; \quad q_y = -K_y \frac{\partial h}{\partial y}
\]

When \( K_x = K_y = \text{constant} \), equation 2.5 becomes

\[
\frac{\partial^2 h^2}{\partial x^2} + \frac{\partial^2 h^2}{\partial y^2} = 0
\]

(2.6)

For unsaturated soil Buckingham (1907), reasoning that water conduction in soil is analogous to heat flow, ascribed the driving force to the gradient of "capillary potential" defined as "the work required per gram to pull water away from the soil mass". He predicted the possibility that the permeability function might be a variable, dependent upon water content. On the basis of this reasoning he drew a tentative curve relating water content and permeability,
the general shape of which has proven to be correct.

The capillary potential concept was advanced in a series of papers by Gardner (1920a, 1920b, 1922) in which he agreed with Buckingham on the nature of the driving force and expressed the view that a soil at a given moisture content may be given a distinct "potential" value. A mathematical structure of a conduction theory was completed by Richards (1931) when he wrote an expression equivalent to equation 2.3 for unsaturated horizontal flow. Philip (1955) suggested an improvement in the calculation procedure which agrees with Wang (1963) who used a numerical finite "strip method" and successfully obtained a numerical solution for vertical flow.

Variation of water content and of suction with elevation near the water table has been measured under different conditions and for soils of varying textures. In an experiment by Moore (1939), pressure head and water content were calculated (Figure 2.1). The smooth transition of pressure across the water table shows positive values below the water table to subatmospheric values above the water table. The pressure is not only a continuous function of elevation across the water table, but its derivatives are continuous in all directions (Day, 1961).

The wet zone above the water table is often referred to as the capillary fringe, or simply, the capillary zone. It consists of both
FIGURE 2.1

PRESSURE HEAD AND WATER CONTENT AT VARIOUS ELEVATIONS IN YOLO CLAY SOIL WITH SHALLOW WATER TABLE AND WITH STEADY RATE OF EVAPORATION FROM THE SURFACE. (AFTER MOORE, 1939)
saturated and unsaturated regions. In dynamic or transient situations this zone may be an actively conducting region; it contributes to the lateral flow of water above a sloping water table. From a laboratory experiment using a tank of fine sand, Luthin and Day (1955) found that a considerable amount of water may flow horizontally above the water table. In the example shown by Luthin and Day (Figure 2.2), all of the flow lines in the capillary zone start and end below the water table. They warned that it is not correct in general to attribute a limiting flow surface to a water table since flow lines may intersect isobaric surfaces at any angle depending upon the prevailing conditions. Their data show that the amounts of water flowing in the capillary zone, above the water table, may represent an appreciable portion of the water flow depending on (1) the ratio of the thickness of the capillary zone to the height of the water table above the bottom of the tank, and (2) the texture of the porous medium.

2.1.1 CAPILLARY RISE AND EVAPORATION

The steady state upward flow of water into the soil from a reference water table has received considerable attention because it can be treated directly. Takagi (1954) considered the problem from the thermodynamic standpoint but his conclusions about the upper limit of water rise are not necessarily applicable to soil since they are entirely based upon the capillary theory of retention. Gardner
FIGURE 2.2

EQUIPMENT LINES AND STREAM LINES ACROSS A SAND TANK (AFTER LUTHIN AND DAY, 1955).
(1960) has shown that when the water table is at a point \( Z \) equal zero the distribution of suction \( \tau \) with depth for a given rate of evaporation at a steady state is as shown in Figure 2.3. He expressed unsaturated conductivity \( K \) as a function of \( \tau \) by the equation \( k = a/(\tau^3 + b) \), where \( a \) and \( b \) are constants. His data show that near the water table the suction in centimeters is almost equal to the height above the water table, and the water transmitting gradient is small. The increase in suction with height is very gradual until just below the surface when it increases very rapidly. The evaporation rate as a function of the suction at the soil surface is shown in Figure 2.4.

Evaporation from unsaturated soils is limited by the external evaporative forces or the rates of water movement through the soil, whichever is the lower. Philip (1957) has shown this to be true theoretically and Gardner and Fireman (1958), experimentally. It is also supported by field experiments of Veihmeyer and Brooks (1954).

Philip (1957) and Gardner (1958) have extended their analysis to include water movement in the vapor phase under the steady state conditions, where the soil may be divided into two zones. In the upper zone at and near the soil surface, water movement is almost entirely in the vapor phase, while in the lower zone water movement is in the liquid phase and obeys the unsaturated flow equation. For steady state evaporation and under isothermal conditions the mass
SOIL SUCTION AS A FUNCTION OF HEIGHT ABOVE WATER TABLE FOR YOLO CLAY,
k = 400/(x^2 + 400) CM./DAY, \( q = 0.088 \) CM./DAY. SMOOTH CURVE IS A THEORETICAL SOLUTION, POINTS REPRESENT DATA OF MOORE (1939). (AFTER GARDNER, 1960)
RELATIVE EVAPORATION RATES AS A FUNCTION OF SUCTION AT SOIL SURFACE WHEN WATER TABLE IS 180 CM. BELOW SOIL SURFACE AND $k = \frac{a}{(z^3 + b)}$.

(AFTER GARDNER, 1960)
flux through both regions must be equal. The effect of temperature gradient upon steady state evaporation has also been considered in Philip’s treatment. When the soil surface is warmer than the boundary between the vapor and liquid flow regions where evaporation might be occurring, the rate of evaporation will be reduced; a thermal gradient in the opposite direction will increase evaporation.

2.1.2 WATER USE BY PLANTS

Not all of the soil water in the plant root zone is accessible for plant use. The availability of water is dependent upon soil water potential and soil water flow rates. For water to move from the soil into the roots there must exist a potential gradient. The energy of the water in the plant is generally designated the diffusion pressure deficit (DPD), which, when measured in the same units, can be used interchangeably with soil water stress. The DPD in the plant must be greater than the soil water stress if the plant is to obtain water from the soil. Slatyer (1957) has given a complete review of water use by plants and the wilting phenomena.

Kuiper and Bierhuizen (1958), in experiments under controlled climatic conditions and sufficient water, observed that the influences of suction on evapotranspiration depends on meteorologic conditions. Tension was reported to be of great influence under conditions of high transpiration but was negligible with low transpiration because in the
latter case the water supply was not the limiting factor. Similar results have been reported by Makkink and Van Heemst (1956). Thus, reduced ET rates should not be explained in terms of soil moisture in the root zone alone.

When studies are made of the use of water by plants, it is frequently assumed that, provided plants are never short of water, the transpiration rate is determined by the weather conditions at the site (Penman, 1955). For this assumption to be true it needs further to be assumed that the vegetation is of uniform height, and forms a close stand completely shading the ground. Under such conditions water loss per unit time is said to be the "potential evapotranspiration" (PET) (Thornthwaite, 1948 and Penman, 1948).

Veihmeyer and Hendrickson (1955), and Veihmeyer (1956) reported that ET continues at a potential rate so long as the moisture content in the root zone is above the fifteen-atmosphere suction. Thornthwaite and Mather (1955) maintained that a decrease in soil water necessitates a decrease in water use. Van Hylckama (1963) pointed out that a decrease in growth and development of salt cedar parallels a diminishing use of water even though such water seems to be fully available.
2.2 EVAPORATION AND TRANSPIRATION RATES FROM DIURNAL WATER TABLE FLUCTUATIONS

Smith (1922) demonstrated from data on water table fluctuations under phreatophytic mesquite (Prosopis) and cottonwood (Populus) that the magnitudes of daily fluctuations are proportional to the amounts of water used by vegetation. He recognized that the fluctuations were a function of more than one variable and that the physical properties of the soil in which water table changes take place have much to do with the amounts of daily rise and fall. White (1932), from a thorough and well-planned research project in Escalante Valley, Utah, supported Smith's conclusions that diurnal fluctuations of the water table can be caused by growing vegetation drawing its supply from shallow ground water. White used different types of vegetation, and recorded the water table levels continuously. He analyzed daily graphs from field and tank experiments with the same plant species. He suggested a method for computing the total quantity of water withdrawn by vegetation during a day. Based on his experimental results he assumed that evapotranspiration is negligible from midnight to 4 A.M. and that the water table level during this interval approximates the mean for the day. He also assumed that the hourly recharge from midnight to 4 A.M. may be taken as the average rate for the day. He proposed that the total quantity of ground water
withdrawn by transpiration and evaporation during the 24-hour period can be calculated using the formula

\[ d = S_y (24r + s) \]

in which \( d \) is the depth of water withdrawn in inches, \( S_y \) is the specific yield of the soil in which the daily fluctuation of the water table takes place in cubic feet of water per cubic feet of soil, \( r \) is the hourly rate of rise of the water table from midnight to 4 A.M., in inches, and \( s \) is the net fall or rise of the water table during the 24-hour period, in inches (Figure 2.5).

Troxell (1936) pointed out from a study of stream flows and water table fluctuations in the Santa Ana River Basin that the rate of recharge \( r \) is not a straight line, as assumed by White, but a curve which ranges from zero at the altitude of the static head to a maximum some distance below the point. He indicated that the diurnal cycle as indicated by the ground water table represents an accumulative curve showing the result of rates of inflow to the area minus rates of transpiration. The first hourly derivative of the curve represents the rate of change in the ground water table, or the rate of water inflow minus rate of transpiration (Figure 2.6).
FIGURE 2-5

DIURNAL FLUCTUATION OF A WATER TABLE AS A RESULT OF TRANSPIRATION.
(AFTER WHITE, 1932)
FIGURE 2-6

TRANSPIRATION LOSS AND RATES OF CHANGE IN GROUND WATER ELEVATION
FINITE RATE PROCEDURE. (AFTER TROXELL, 1936)
2.3 HYDRAULIC CONDUCTIVITY BELOW THE WATER TABLE

The theory of hydraulic conductivity measurements with a "piezometer" was proposed by Kirkham (1945). The field method was developed and used by Frevert and Kirkham (1948), Luthin and Kirkham (1949), Johnson et al. (1952), and Reeve and Jensen (1949). The method is based on the measurement of flow into an unlined cavity at the lower end of a pipe inserted in the soil to the desired depth. After the installation of the pipe and before the measurements are taken, the water seeping into the pipe is pumped out several times to remove any clay or silt which might have dispersed in the water during installation. Then the piezometer is left to stand until the water table inside the pipe rises to the same level as that of the soil. After the water has been pumped out two to three times, soil water is then allowed to rise in the tube. The equilibrium water level is determined, and the needed data is obtained (Johnson et al., 1952). The required measurements are shown in Figure 2.7. Reproducibility of results from an individual hole indicates that puddling effects are negligible. To calculate the hydraulic conductivity the following equation is used:

\[
K = \frac{\pi R^2}{A \Delta t} \ln \frac{L_1 - E}{L_2 - E}
\]

where \( R \) = inside radius of the tube (inches)
FIGURE 2.7

DIAGRAM OF PIEZOMETER AND THE REQUIRED MEASUREMENTS FOR THE DETERMINATION OF PERMEABILITY BELOW THE WATER TABLE. (AFTER LUTHIN AND KIRKHAM, 1949)
A = a factor in inches which is a function of the geometry of the flow.

$L_1 = \text{distance (feet) from the top of pipe to water in the pipe at time } t_1 \text{ (seconds)}.$

$L_2 = \text{distance (feet) from the top of pipe to water in the pipe at the } t_2 \text{ (seconds).}$

$\Delta t = t_1 - t_2 \text{ (seconds).}$

$E = \text{distance from the top of pipe to the water table (feet).}$

A is determined directly by electric analogue models. Thus, A is a function of R, the distance d from the water table to the bottom of the sealed pipe, the distance W from the bottom of the tube to the bottom of the hole, and the distance e from the bottom of the hole to a restricting layer. The A-function for different cavity diameters is given in Figure 2.8 (Luthin and Kirkham, 1949).

2.4 WATER CONTENT - NEUTRON THERMALIZATION METHOD

The principle involved in the neutron method for measuring soil moisture, according to van Bavel (1963), is that when a source of fast neutrons is introduced into a material capable of moderating or slowing down (thermalizing) the fast neutrons, it will become surrounded by a cloud of slow neutrons. The density of the slow neutrons in the immediate vicinity of the source is proportional to the concentration and atomic composition of the moderating material.
VARIATION OF A-FUNCTION WITH DIAMETER FOR A CAVITY 4 INCHES LONG.

(AFTER LUTHIN AND KIRKHAM, 1949)
The neutron source is made by mixing an alpha emitter such as radium (Ra), and beryllium (Be). Such source emits about 16,000 neutrons per second per milligram of radium. The energy of the neutrons emitted by such a source is not uniform, but ranges from 0.1 up to 15 Mev. (Million electron volts). The average energy is around 4 Mev., and the speed of such neutrons is about 1,000 miles per second.

Two major factors are involved in the scattering and the thermalization of neutrons. They are (1) the transfer of energy at each neutron collision, and (2) the statistical probability of a collision. The average energy transfer upon collision of a neutron with other nuclei in the soil depends largely upon the mass number of the nuclei encountered. The average number of collisions required to slow a neutron from 2 Mev. to thermal energies (0.03 electron volts) is 18 for hydrogen, 67 for lithium, 86 for beryllium, 114 for carbon, 150 for oxygen, and \((9A + 6)\) for nuclei with large mass numbers, \(A\) (Weinberg and Wigner, 1958).

The statistical probability of collision is dealt with using the concept of the "scattering cross section" which is defined as neutrons interacting with matter in two general ways; by elastic and inelastic collision and by interactions leading to capture with subsequent emission of energy or of other nuclear particles. The probability of
any particular interaction depends upon the neutron energy and the characteristics of the nuclei according to the nuclear cross section which is measured using a unit of area called the "barn" which is $10^{-24} \text{cm}^2$. Cross sectional areas are measured in barns which are proportional to the probability of collision between neutrons and other nuclei in soil.

The scattering cross section for hydrogen varies from 1 barn at 10 Mev. to about 13 barns at 0.1 Mev. Considering both energy transfer and scattering cross section, it is evident that hydrogen, having a nucleus of about the same size and mass as the neutron, has a much greater thermalizing effect on fast neutrons than any other element (Gardner, 1965).

According to Gardner (1965), the nature of the neutrons scattering and the thermalization process imposes an important restriction on the resolution of water content measurements. The volume of soil involved in measurement depends upon the concentration of scattering nuclei, hence, largely upon water content, and upon the energies of the emitted fast neutrons. Experimental work with Ra-Be sources indicate that the practical sphere of influence of such units is about fifteen centimeters, i.e., the soil volume most greatly affecting the slow neutrons count rate is a sphere fifteen centimeters in diameter (van Bavel, 1958). The diameter of this
sphere increases with decreasing water content (van Bavel et al., 1961). Therefore, this lack of high resolution makes it hard to detect accurately any discontinuity or sharp change in water content gradient in a soil profile (McHenry, 1963).

The equipment used in this method includes (1) source of fast neutrons of long half life, (2) shield for storage of the neutron probe between readings, (3) detector of slow neutrons, (4) scaler or a rate meter, and (5) access tubing.

Although the resolution of neutron water content measurements is low, the precision of measurements for a large sample is good. There are three reported sources of error associated with such measurements: (1) random variation in count rate due to random variation in fast-neutron emission from the source, (2) errors associated with the counting equipment including the timer, and (3) errors associated with the calibration curve.

2.5 BULK DENSITY - EXCAVATION METHOD

Soil bulk density is the ratio of the mass to the bulk or macroscopic volume of soil particles plus pore spaces in a sample (Blake, 1965). The mass is determined after drying to constant weight at 105°C, and the volume is that of the sample as taken in the field. In the excavation method, bulk density is determined by collecting a soil volume, determining the volume by packing the cavity with a known
volume of sand, and weighing the soil after drying. This method is recommended for gravelly soils.

A detailed procedure of the excavation method was outlined by Zaidelman (1957). He proposed an excavation method for the determination of bulk density and moisture of stony soils and suggested formulae for the calculation of porosity, aeration, water contents, etc. He succeeded in characterizing soil profiles with stones and pebble deposits underlying sand, loam, and silt. In his method he recognizes the importance of the excavated volume and relates that to the soil heterogeneity, and the required number of replicates.

2.6 EVAPORATION AND TRANSPIRATION - CLIMATOLOGICAL METHODS

Blaney (1933) and Penman (1956) proposed that evaporation from an open water surface may be used to estimate potential transpiration from areas covered with vegetation. As a convenience, Penman (1956) used the empirical equation

\[ \text{PET} = f E_o \]

where PET is potential evapotranspiration, and \( E_o \) is evaporation from an open water surface, and \( f \) is a factor having the values which vary with latitude and time of the year.

Several empirical methods have been developed for correlating PET and temperature. They require temperature data from a
standard meteorological station. Thornthwaite (1948) worked primarily with data from 21 irrigation projects in the western United States and obtained the following empirical relationship between PET, and the mean monthly temperature, $T$, in °C:

$$\text{PET} = 16(10 \frac{T}{I})^a, \text{ millimeter per thirty-day month where}$$

$$a = (0.675 I^3 - 77.1 I^2 + 17920 I + 492390) \cdot 10^{-6},$$

$$I = \sum_{i=1}^{12} \left( \frac{T}{5} \right) \cdot 1.514$$

where $I$ is the heat index, which is the sum of 12 monthly indices $i$. These relations are valid only where

$$0 \leq T \leq 26.5 \text{ °C}.$$

Thornthwaite assumes that $\text{PET} = 0$ when $T = 0°C$. When $T = 26.5°C$, $\text{PET}$ is considered to be a function only of temperature without the heat index. According to Sellers (1964), the biggest objections to the Thornthwaite method are that (1) it gives values which are too low in warm arid regions at all temperatures and in all climates at low temperatures, and (2) it does not take into account humidity variations.

Budyko (1956) has noted that the annual radiation balance ($R_o$), in langley's per year, for a surface with an assumed albedo of 0.18 is closely related to the sum of all daily mean temperatures ($T$) greater than $10°C$ (50 F). He found from data in all geographic regions except Antarctica that
\[ R_0 = 10 \sum_{i=1}^{N} T_i \]

where \( N \) is the number of days with mean temperatures greater than \( 10^\circ \text{C} \). The temperature summation according to Sellers (1963) takes on physical meaning because of its relationship to radiation \((R_o)\). Since it is a relatively stable parameter, being about the same over an irrigated field as over a nearby dry desert, it is quite useful as an index of PET. For a very crude estimation of PET on a daily or monthly basis the approximation is

\[ \text{PET} = 0.2 \, T \, \text{mm/day} \]

where \( T = \text{mean temperature in degrees centigrade} \).
3. THE RESEARCH AREA

3.1 LOCATION

The Walnut Gulch experimental watershed near Tombstone, Arizona, is drained by an ephemeral stream channel into the San Pedro River (Figure 3.1). The watershed area is fifty-eight square miles. Across the main channel and its tributaries, a series of critical depth flumes have been constructed to measure water flow.

The study area is ten acres of the main channel. It is bounded at its lower end by one of the flumes and extends 2,000 feet upstream. It ranges in width from 200 to about 500 feet (Figure 3.2). It is located in the southwest quarter of section 34, R.22 E, T.19 S, Cochise County Arizona, at 110° 04' W, 31° 43' N.

3.2 GEOLOGIC FORMATION AND STRUCTURE

Schieffelin Granodiorite forms the northern and southern boundary and bedrock of the study area forming a pocket which is filled with stream alluvium. The area represents an old flood plain in places with older meander loops and channels now covered by layers of sand and gravel. Many layers and lenses are evident but are believed not to be continuous. Particle size in the lenses range from silt and very fine well-sorted sand near the surface to gravel and cobble beds with particle size ranging up to eight inches
FIGURE 3.1

ARIZONA, LOCATION OF THE WALNUT GULCH EXPERIMENTAL WATERSHED
FIGURE 3.2

AERIAL PHOTOGRAPH OF THE RESEARCH AREA SHOWING THE WELLS (TRIANGLES), SOIL MOISTURE MEASURING SITES (SQUARES), PIEZOMETERS(♦) AND SOIL SAMPLING SITES(◊)
in diameter at lower depths. Large granite and quartzite boulders were also encountered during drilling at three to forty-foot depths. The surface geology of the area is as shown in Figure 3.3. A topographic map of the granite surface was drawn from seismic depths and drill holes and is shown in Figure 3.4.

3.3 SURFACE TOPOGRAPHY

The altitude of the watershed above mean sea level ranges from 4,200 feet at the lowest gaging station (Flume 1) to 6,000 feet at the upper end. The altitudes for the research area are from 4,230 feet at the lower end to 4,246 feet at the upper end. The channel bed is dynamic and its surface topography changes after each flow. The magnitude of variability in the channel is up to plus or minus two feet. The area was surveyed in October 1964 and a topographic map at six-inch contour intervals was prepared (Figure 3.5). A stereogram of the area is shown in Figure 3.6.

3.4 DESCRIPTION OF SOILS

Depths of alluvium deposits in this area vary from 5 to 40 feet. Bulk densities and particle size distribution for the various layers in five profiles were determined, and are presented in Appendix A. The top two to three feet are usually sandy underlain by sand and gravel to bedrock. The soil in the vegetated areas adjacent to the stream bed
FIGURE 3.3

TOPOGRAPHY AND SURFACE GEOLoGY ABOVE FLUME 2
FIGURE 3.4

TOPOGRAPHIC MAP OF THE GRANITE SURFACE, AT THE RESEARCH AREA ABOVE FLUME 2, WALNUT GULCH EXPERIMENTAL WATERSHED.
FIGURE 3.5

TOPOGRAPHIC MAP OF THE RESEARCH AREA ABOVE FLUME 2, WALNUT GULCH EXPERIMENTAL WATERSHED.
FIGURE 3.6

STERE OGRAM SHOWING THE RESEARCH AREA (MAY 1964)
was classified by Buol (1965) in the Comoro series (Cumulic Haplustoll).

3.5 VEGETATION

The dominant vegetation cover in the area is mesquite (Prosopis juliflora var. velutina). Growing along the channel are also scattered trees of cottonwood (Populus fremontii), Arizona walnut (Juglans major), and seep willow (Salix taxifolia). The dominant vegetation on the upland surrounding the area is Whitethorn (Acacia constricta), creosote bush (Larrea tridentata), and tarbush (Flourensia catnua). During and following the flow season of 1964 (August, September, and October), the area along the channel was covered by a lush herbaceous vegetation attaining heights up to three feet under the mesquite (Figures 3.7, 3.8, and 3.9).

All the shrubs and trees in the area are deciduous species. They lose their leaves after the first frost in late fall and commence their growth in April or May. The sharp contrast between such areas and the surrounding slopes is a characteristic scene in southeastern Arizona. Such contrast provides a useful quality for estimating the extent of these areas from aerial photos.

3.6 CLIMATE

The research area is located in a semiarid climatic region (Thornthwaite, 1948). The annual precipitation is seven to fifteen
PHOTOGRAPH SHOWING THE VEGETATION ALONG CHANNEL BANKS (AUGUST 1964)
FIGURE 3.8

PHOTOGRAPH SHOWING VEGETATION IN A CLEARING
(AUGUST 1964)
PHOTOGRAPH SHOWING ONE OF THE OBSERVATION WELLS, A MICROMETEOROLOGICAL STATION, AND HERBACEOUS VEGETATION UNDER MESQUITE (AUGUST 1964)
inches and falls during the winter and summer months (Figure 3.10). Winter precipitation is from extensive frontal storms and is generally of low intensities with no runoff. The summer rains occur when moist air masses from the Gulf of Mexico move over this region at times of high ground surface temperatures and insolation, which results in convective thunderstorms of small areal extent, short duration, and very high intensities. Summer rains account for almost all the water yield. The hottest months are usually June, July, and August. November, December, January, and February are the coldest months (Figure 3.11).
FIGURE 3.10

HISTOGRAM SHOWING THE AMOUNTS OF PRECIPITATION IN 1964 FROM A RAIN GAUGE LOCATED IN THE RESEARCH AREA.
FIGURE 3.11

MAXIMUM AND MINIMUM TEMPERATURES, AND WIND SPEDS
4. THE EXPERIMENTAL MODEL

Water flow into and out of the research area is presented diagramatically in Figure 4.1. Volumes of water following each of the indicated paths change with time. The available data from the research area for the period January 1964 to July 1965 indicate definite periods during which water flow in some paths is negligible or nonexistent.

A generalized water balance equation for the area was developed using the principle of conservation of mass. This equation was further simplified by applying it to study the water disposition in the research area by periods. It was derived as follows:

Water inflow \( F_i \) equals water outflow \( F_o \) minus change in storage \( \Delta s \). When each of these terms is substituted for by its components as shown in Figure 4.1, this expression becomes:

\[
\Delta s = Q_i + q_i + P - Q_o - q_o - E - T
\]  

(4.1)

where \( \Delta \theta + \Delta s_w = \Delta s \),

\[ P + q_i + Q_i = F_i \]

\[ q_o + E + T + Q_o = F_o \], and
CONCRETE

LEGEND

1 PRECIPITATION
2 TRANSPIRATION
3 SUBSURFACE FLOW
4 SURFACE FLOW
5 INFILTRATION
6 SEEPAGE
7 EVAPORATION
8 TRICKLE FLOW

SS TEMPERATURE AND HUMIDITY
W WELL
SP SOIL PIT
NP ACCESS TUBE

FIGURE 4.1
A MODEL REPRESENTATION OF THE RESEARCH AREA
where

\[ P = \text{precipitation, in volume (} L^3) \]
\[ q_i = \text{subsurface inflow (} L^3) \]
\[ Q_i = \text{surface inflow (} L^3) \]
\[ Q_o = \text{surface outflow above the flume (} L^3) \]
\[ q_o = \text{seepage (} L^3) \]
\[ E = \text{evaporation (} L^3) \]
\[ T = \text{transpiration (} L^3) \]
\[ \Delta \theta = \text{change of soil moisture storage above the capillary fringe (} L^3) \]
\[ \Delta s_w = \text{change in water storage due to change in the water table (} L^3) \]
\[ \Delta \theta \text{ and } \Delta s_w \text{ take a minus sign for water losses and a plus sign for water gains.} \]

The following observations and assumptions are made from the flow patterns and the characteristics of the deciduous vegetative cover:

(a) Surface inflow and outflow of water occur only for a few days in the year during the summer rains.

(b) Surface outflow at the flume often continues for some time after a storm at a rate less than 1000 cubic feet per day, and is referred to as trickle flow.
(c) Transpiration losses of water are negligible and may be assumed to be equal to zero during the period of plant dormancy.

(d) Evaporation losses of water are equal to both precipitation and change in soil moisture content in the upper three feet of the soil profile \(E = P - \Delta \theta\) during the period from January to April or May when the water table is four to fifteen feet below the soil surface.

According to the foregoing presentation, a year is divided into four periods in order to simplify the evaluation of the amounts of water represented by the terms in equation 4.1 and Figure 4.1:

(a) The first period from January first to April (1964) or May (1965) is characterized by: (1) lack of surface flow, i.e., \(Q_j = 0\), \(Q_o = 0\), (2) evaporation is equal to precipitation minus the change in soil water content in the top three feet of alluvium or above capillary fringe whichever is less, or \(E = P - \Delta \theta\), and (3) transpiration may be assumed to be equal to zero, since this period corresponds to the dormancy period of the deciduous riparian species. Therefore, equation 4.1 becomes

\[
\Delta s_w = q_i - q_o
\]

(4.2)
(b) The second period is from the start of foliage appearance on the trees and shrubs to the first channel flow (usually in July). It is marked by active plant growth and substantial rates of transpiration losses. And since $Q_i$, $Q_o$ are zero, and $E = P$, the water balance equation for this period is:

$$\Delta s = q_i - q_o - T$$  \hspace{1cm} (4.3)

During this period water use by vegetation is reflected in the diurnal water table fluctuation which is apparent only when plants commence their growth. This characteristic provides another procedure for evaluating the validity of the given assumptions.

(c) The third period (from July to October) is the flow season and is characterized by (1) high rainfall intensities and frequent channel flows; (2) ground water recharge; (3) high rates of evaporation and transpiration; and (4) trickle flow which is not distinguishable from surface outflow above the flume. Therefore, the applicable equation is 4.1.

(d) The fourth period is from the time of last channel flow to December 31. During this period:
(1) Transpiration is at a diminishing rate because this is the period when most of the shrubs and trees start losing their foliage.

(2) Trickle flow ($Q_o$) above the flume continues at a decreasing rate.

The water balance equation for this period:

$$\Delta s = q_i + P - Q_o - q_o - E - T \quad (4.4)$$
5. METHODS OF MEASUREMENTS AND CALCULATIONS

5.1 DELIMITATION OF THE RESEARCH AREA

A seismic refraction method was used to determine alluvium depths to granite. The procedure of determining the depths is essentially that of Phelps (1962, and 1964). It is based on measuring the time required for a sound wave to reach a detector (geophone) placed at a known distance from an impact. In soil and alluvium, the waves travel at a slow velocity, $V_1$. In granite, or other dense material, they travel at higher velocity, $V_2$. When the impact point is close to the geophone, the surface waves reach the geophone first. As the impact point is moved farther from the geophone a point will be reached at which the refracted waves from the dense material and the surface waves will arrive at the same time. This point is called the "critical point", and its distance from the geophone the "critical distance". Figure 5.1 shows the critical point and the method of calculating the depth of the alluvium. The seismic equipment consisted of a timer, a series of detectors (geophones), and a sledge hammer.

Thirteen transects across the channel were selected and depth to granite was determined at five- and ten-foot intervals. Depth measurements were also taken near twenty observation wells where
SAMPLE CALCULATION OF DEPTH, \( d \), FROM SEISMIC WAVE TRAVEL TIMES AND DISTANCES OF IMPACT FROM A GEOPHONE

\[
d = \frac{1}{4} \frac{\sqrt{V_2^2 - V_1^2}}{V_2 - V_1}
\]

\( d = 13.8 \) when \( L = 36 \) FT.
the actual depths were known. There was no significant difference between the actual and calculated depths at the five per cent level. Actual and calculated seismic depths are plotted in Figure 5.2.

A surface topographic map of the area was prepared at the time of the seismic survey. It was used in conjunction with the measured alluvium depths to draw the topographic map of granite surface shown in Figure 3.4.

5.2 TRICKLE OUTFLOW

Following the summer convective rain storm season, a small flow continues through the large critical depth flume which is used to measure the large flows at the research area. The flume extends into the bedrock and serves to eliminate subsurface outflow from the area at that site. The water level recorder used to record water depths in the flume does not give the desired accuracy on trickle flows of less than 2000 cubic feet per day since it was designed to measure storm runoff with peak discharges up to 18,500 cubic feet per second. A water meter was used to measure this trickle flow. It was adapted to make use of the available water level recorder with minimum amount of both modification and maintenance.

A recording system was developed to measure the trickle flow from the area. It consisted of three components: a collecting funnel in the critical depth flume, a standard one-inch gravity flow water
FIGURE 5.2
ACTUAL AND CALCULATED ALLUVIUM DEPTHS
meter, and a recorder.

A thin sheet metal funnel was fabricated with a flexible hose dropping downstream to the water meter. This collecting funnel was then attached to the flume with synthetic rubber which made a watertight seal between the concrete and the funnel. Prior to a surface runoff event, the funnel could be easily dislodged and thereby allow the flume to operate in the normal manner.

A one-inch water meter was used to measure the volume of the trickle flow. This water meter was modified to indicate volumetric readings on a separate recorder by inserting a metal contact point on one of the totalizing gears. The contact point was attached to the gear in such a position that each gear revolution made a contact which activated a relay and a pen on the recorder.

The recording portion of the measuring system consisted of a pen positioned to record on the strip chart of the water level recorder. The pen was attached to a relay which was wired to the contact points of the meter across a 6-volt battery. Each gear revolution, therefore, made one mark on the chart which represents five cubic feet of water.

Water flowing over the flume entered the funnel through a sieve to remove any litter. Periodic cleaning of the sieve was necessary in the autumn when the leaves were falling from Aspen and Mesquite. Next, the water was passed through a strainer which collected the
fine sediments. An aeration pipe was attached to the strainer in order to free the water of any air bubbles prior to entering the water meter. Water passing through the meter would turn the impeller to which the gear with the contact point was attached.

The unit was calibrated volumetrically during operation using barrels of six cubic-foot capacity and a stop watch. The calibration chart (Figure 5.3) shows a direct linear relationship through a wide range of discharge. In other words, the water meter was of such design that it had neither an acceleration bias at high flows nor a lack of sensitivity at low flows.

5.3 BULK DENSITY

Soil pits from seven to fifteen feet in depth were excavated in the research area. One pit in the channel extended to granite. Bulk densities of the different texture layers were determined by using three methods. The core method (Blake, 1965) was used to sample silt and sandy loam horizons. Two excavation methods were used in horizons where sand, gravel and rocks are mixed.

In the first excavation method, bulk densities were determined by removing a quantity of soil, whose original volume was measured by packing the cavity with sand of known volume. Samples were collected separately for the different strata and their positions in the profile were indicated.
FIGURE 5.3

CALIBRATION CHART FOR THE TRICKLE FLOW RECORDING SYSTEM
The second method, the area excavation, is slow and laborious, but very accurate and precise. It encompasses the marking of an area on the surface of the soil by one of the exposed pit walls and removing all the soil of each horizon. The area varied from sixteen square inches to a few square feet depending on the homogeneity of the material.

Each of the collected samples was subjected to the following analysis:

(a) The sample was air dried, weighed, mixed thoroughly, and subsampled for oven drying and texture analysis.

(b) The subsamples were oven dried at 105°C until the weight was constant.

(c) The oven dry weight of the bulk sample was calculated.

(d) Soil bulk density was determined by dividing the oven dry weight of the sample by the volume of the cavity.

5.4 COLLECTION OF SOIL SAMPLES FOR LABORATORY ANALYSIS

Bulk density samples were collected from each of the horizons of soil sampling pits and were subsampled for particle size analysis. In addition to these, samples from six other locations were collected by a vacuum procedure during the drilling of water table observation wells. Location of the sampling sites are shown
5.5 MEASUREMENTS OF WATER TABLE ELEVATIONS

An arbitrary bench mark was installed in the research area and was given 100-foot elevation. All measurements which involve a vertical scale were taken with reference to this mark.

Water table elevations in twenty wells were measured periodically, and in six others the measurements were continuous. The periodic measurements were done by a steel tape which is graduated in feet, 1/10 foot, and 1/100 foot. The distance from the top of the well casing to the water table was measured. The measurement procedure comprised the coating of two to three feet of the end of the tape with colored chalk and reeling the tape into and out of the well. The depth of water from a point of known elevation on the well top was recorded. The accuracy of this procedure is to ± 0.005 foot provided the same tape is used at all times. The continuous measurements were taken by two types of recorders:

(a) FD-4 Friez horizontal drum type recorder with a weight driven clock. Five recorders of this type were used with a time scale of 24 hours for one foot chart length (along the drum), and a drum circumference of one foot. Accuracy of this type recorder is to ± 0.005 foot change in water table elevation.
(b) FW-1 Friez recorders: Three of these were used; these are simple, have a spring driven clock supported on a vertical spindle and are equipped with a variety of gears to make one revolution every 6, 12, 24, 48, or 192 hours. The clocks will run eight days on one winding regardless of the time scale used. The instruments have a reversing mechanism and can record an unlimited range in changes of the water table on a scale of five inches of water table elevation change. Accuracy of this type recorder is to ± 0.01 foot change in water table elevation.

Both kinds of recorders are equipped with a steel tape that passes over a float wheel and has the ends attached by ring connectors to the float and to a counter weight.

The clocks on all the recorders were kept synchronized by checking them once a week. Calibrations of all the recorders were done prior to installation.

5.6 WATER FLOW IN SATURATED CHANNEL ALLUVIUM

A field method was developed for measuring subsurface water flow into the research area from the upper reaches of the channel. Volumes of flow in the channel alluvium were calculated using Darcy's equation
\[ Q = K \alpha i \]

where \( Q \) is the rate of water inflow to the area in cubic feet per day, \( K \) is the hydraulic conductivity in feet per day, \( A \) is the cross-sectional area of the saturated alluvium in square feet, and \( i \) is the hydraulic gradient.

5.6.1 Cross Sectional Areas of the Alluvium

Six transects were selected at the upper end of the research area. They were taken perpendicular to the stream channel and were spaced 85 to 100 feet apart. Figure 5.4 shows the location and orientations of the six transects. Depths to granite were determined by the seismic refraction method at five- to ten-foot intervals along each of the transects. Cross-sectional area of the alluvium along each transect was delineated from the measurements of surface elevations and the calculated seismic depths. As an example, Figure 5.5 shows the cross-sectional area at transect 1.

Minimum elevations at the ground and granite surfaces were determined at each of the cross-sectional areas of the channel to mark the lower limit and upper extent of the cross-sectional areas of alluvium where subsurface flow may occur. Accumulated areas at one-foot increment in elevation, upward from the minimum elevation point at the granite surface, were measured by a planimeter.

Measured cross-sectional areas at several elevations for the six
AERIAL PHOTOGRAPH SHOWING THE LOCATIONS OF THE SIX SECTIONS AT THE UPPER BOUNDARY OF THE RESEARCH AREA
FIGURE 5.5: CROSS SECTION OF THE CHANNEL AT TRANSECT 1
sections are presented in Table 5.1. Square roots of areas were plotted against the corresponding elevations in order to determine any discontinuities in the slope of the lines. As an example, Figure 5.6 shows the data for section 1. Regression equations of areas as function of elevations in Appendix B were calculated using Thornton's (1965) Multiple-Regression Program for the 1401-7072 computer system. The derived regression equations were used in the special FORTRAN program in Appendix C to compute the cross-sectional areas corresponding to measured water table elevations.

Since subsurface flow of water is not restricted to the zone below the free water surface, a correction for the capillary fringe was calculated from field observations of color change of alluvium above water table. The observed heights of capillary fringe above the free water surface are presented in Table 5.2 for several locations. The average value of 0.85 feet was added to the measured water table elevations in the computations of the cross-sectional areas of alluvium below capillary fringe.

5.6.2 Hydraulic Gradients

Water table elevations were measured at the observation wells shown in Figure 5.4. The hydraulic gradients were calculated from water table measurements and the distances between the locations of
Table 5.1

Elevations (E) and the Corresponding Channel Cross Sections at the Upper Boundary of the Research Area

<table>
<thead>
<tr>
<th>E (ft.)</th>
<th>Transects</th>
<th>Transects</th>
<th>Transects</th>
<th>Transects</th>
<th>Transects</th>
<th>Transects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>89.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>90.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>91.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>106</td>
</tr>
<tr>
<td>92.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>230</td>
<td>234</td>
</tr>
<tr>
<td>93.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>110</td>
<td>380</td>
<td>375</td>
</tr>
<tr>
<td>94.0</td>
<td>0</td>
<td>94</td>
<td>46</td>
<td>234</td>
<td>570</td>
<td>530</td>
</tr>
<tr>
<td>95.0</td>
<td>54</td>
<td>226</td>
<td>188</td>
<td>400</td>
<td>800</td>
<td>750</td>
</tr>
<tr>
<td>96.0</td>
<td>100</td>
<td>400</td>
<td>315</td>
<td>630</td>
<td>1036</td>
<td>952</td>
</tr>
<tr>
<td>97.0</td>
<td>244</td>
<td>575</td>
<td>480</td>
<td>825</td>
<td>1280</td>
<td>1168</td>
</tr>
<tr>
<td>98.0</td>
<td>426</td>
<td>750</td>
<td>670</td>
<td>1052</td>
<td>1545</td>
<td>1370</td>
</tr>
<tr>
<td>99.0</td>
<td>635</td>
<td>951</td>
<td>888</td>
<td>1306</td>
<td>1806</td>
<td>1594</td>
</tr>
<tr>
<td>100.0</td>
<td>864</td>
<td>1175</td>
<td>1150</td>
<td>1559</td>
<td>2060</td>
<td>1802</td>
</tr>
<tr>
<td>101.0</td>
<td>1188</td>
<td>1432</td>
<td>1410</td>
<td>1866</td>
<td>2350</td>
<td>--</td>
</tr>
<tr>
<td>102.0</td>
<td>1410</td>
<td>1695</td>
<td>1690</td>
<td>2120</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>103.0</td>
<td>1670</td>
<td>2000</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>104.0</td>
<td>1940</td>
<td>2252</td>
<td>2362</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
Figure 5.6
Cross-sectional Areas of Alluvium Below Given Elevations
### Table 5.2

**Measured Heights of Capillary Fringe (CF) Above Free Water Table**

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>CF (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.95</td>
</tr>
<tr>
<td>2</td>
<td>0.80</td>
</tr>
<tr>
<td>3</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>0.90</td>
</tr>
<tr>
<td>5</td>
<td>0.88</td>
</tr>
<tr>
<td>6</td>
<td>0.80</td>
</tr>
<tr>
<td>7</td>
<td>0.85</td>
</tr>
<tr>
<td>8</td>
<td>0.83</td>
</tr>
<tr>
<td>9</td>
<td>0.77</td>
</tr>
<tr>
<td>10</td>
<td>0.92</td>
</tr>
<tr>
<td>11</td>
<td>0.86</td>
</tr>
<tr>
<td>12</td>
<td>0.87</td>
</tr>
</tbody>
</table>

**Average**

0.85

**Standard error of the mean** = 0.016

**Coefficient of variation** = 0.066
observation wells. As an example, the hydraulic gradient at a given time across section five was determined as the difference between water table elevations at sections six and four divided by the average distance between them (Figure 5.7).

5.6.3 Hydraulic Conductivity Below the Water Table

Hydraulic conductivities below the water table were measured at the nine locations shown in Figure 5.4, by using the piezometer method (See Review of Literature). Elevations at piezometer cavities and the calculated hydraulic conductivities are presented in Table 5.3. The average hydraulic conductivity of 75.84 feet per day was taken as an estimate of hydraulic conductivity of the saturated alluvium at the upper end of the research area where the cross-sectional areas of alluvium and hydraulic gradients were determined.

5.7 WATER STORAGE

Changes in water storage within the research area for a given period were calculated from measurements of soil water content, specific yield, and water table elevations at various locations.

5.7.1 Water Content in Unsaturated Alluvium

Soil water contents above the water table were determined by the neutron thermalization method (Gardner, 1965). The unit used is manufactured by Nuclear Chicago Corporation. The probe is a P-19 Depth Moisture Gauge, 15 inches long and 1.5 inches in
FIGURE 5-7: SECTION PARALLEL TO CHANNEL BED
Table 5.3

Elevations at the Centers of Piezometer Cavities (E) and Calculated Hydraulic Conductivities (K) at the Sites Shown in Figure 5.4

<table>
<thead>
<tr>
<th>Site Number</th>
<th>E (feet)</th>
<th>K (inches/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>98.4</td>
<td>36.36</td>
</tr>
<tr>
<td>2</td>
<td>99.5</td>
<td>35.28</td>
</tr>
<tr>
<td>3</td>
<td>97.5</td>
<td>45.36</td>
</tr>
<tr>
<td>4</td>
<td>98.6</td>
<td>34.20</td>
</tr>
<tr>
<td>5</td>
<td>100.1</td>
<td>41.76</td>
</tr>
<tr>
<td>6</td>
<td>98.5</td>
<td>36.36</td>
</tr>
<tr>
<td>7</td>
<td>96.0</td>
<td>36.00</td>
</tr>
<tr>
<td>8</td>
<td>100.3</td>
<td>39.60</td>
</tr>
<tr>
<td>9</td>
<td>100.2</td>
<td>36.36</td>
</tr>
</tbody>
</table>

Average Hydraulic Conductivity 37.92 or 75.84 ft/day

Standard Error of the Mean = 1.2
Coefficient of variation = 0.095
diameter, with a 5-mc. Ra-Be source at the center of the probe.

Shelby seamless, 1.55" i. d., 1.75" o. d., steel tubes were used. They were installed by drilling inside the tube a few inches at the time using a vacuum drill specially designed for this purpose to avoid large cavities around the tube. Six inches of the tube were left protruding above the soil surface in the channel banks area, and all were covered by a rubber stopper and an empty can. Special precautions were observed to minimize soil or natural vegetation disturbance during the installation.

The neutron probe and scaler used in soil water content determinations were calibrated in the field. Water contents were determined gravimetrically and scaler readings were recorded simultaneously at the same soil depths at moisture site 1 which is shown in Figure 3.5. Actual water contents as determined by the gravimetric method were plotted against the scaler readings as shown in Figure 5.8. The scaler readings in counts per minute (C) as a function of water content (Figure 5.8) can be expressed by the regression equation

\[ C = 588.48 + 30.35 \theta + 6.31 \theta^2 - 0.106 \theta^3, \]

with \( r = 0.99 \), and \( \theta \) is soil water content by volume.

To facilitate the reduction of data by digital computers, the graph in Figure 5.8 was represented by the three regression equations
FIGURE 5-8

FIELD CALIBRATION CHART FOR THE NEUTRON PROBE
which are given in the figure. These equations were used in calculating the volumetric soil water content from field data by using IBM 1401-7072 Computer System of the Numerical Analysis Laboratory at the University of Arizona.

5.7.2 Water Storage in Saturated Alluvium

Soil water distribution above the water table at equilibrium is a unique property of the soil profile. When the water table is dropping at a constant rate in an isotropic and homogeneous soil mass, the soil water distribution curve above the water table shows a repetitive pattern with a displacement as shown in Figure 5.9. Curve 2 in Figure 5.9 shows the same water distribution as curve 1, the displacement is due to the drop in water table from a to b. The change in water storage due to the drop in water table is represented by the shaded area. This change in water storage can be computed and was used for calculating specific yield of the alluvium from soil water content data as presented in Table 5.4 from the equation

\[ S_y = \frac{W}{d} \]

where \( S_y \) is the specific yield of alluvium, \( W \) is the change in water storage in volume per unit area as a result of a drop in water level equal to distance \( d \). Specific yield data in Table 5.4 were calculated during the period of plant dormancy when there were no changes in the
FIGURE 5.9

CHANGE OF MOISTURE DISTRIBUTION IN A SAND COLUMN DUE TO THE LOWERING OF WATER TABLE LEVEL FROM a TO b.
Table 5.4

Specific Yield ($S_y$) as Calculated from Changes in Water Content Due to Drop in Water Table

<table>
<thead>
<tr>
<th>Location</th>
<th>$d^*$</th>
<th>$W^{**}$</th>
<th>$S_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clyne Well</td>
<td>0.5</td>
<td>0.940</td>
<td>0.188</td>
</tr>
<tr>
<td>Clyne Well</td>
<td>1.0</td>
<td>0.201</td>
<td>0.201</td>
</tr>
<tr>
<td>Clyne Well</td>
<td>1.3</td>
<td>0.256</td>
<td>0.197</td>
</tr>
<tr>
<td>Channel</td>
<td>1.2</td>
<td>0.240</td>
<td>0.200</td>
</tr>
<tr>
<td>Channel</td>
<td>2.0</td>
<td>0.380</td>
<td>0.190</td>
</tr>
<tr>
<td>Channel</td>
<td>2.5</td>
<td>0.485</td>
<td>0.194</td>
</tr>
<tr>
<td><strong>Average Specific Yield</strong></td>
<td></td>
<td></td>
<td><strong>0.195</strong></td>
</tr>
</tbody>
</table>

*The drop in water table (feet)

**Change in water storage (cubic feet of water/square feet of area)

Standard error of the mean = 0.0022
Coefficient of variation = 0.0272
shape of water contents distribution above the water table.

The research area was divided into nine subdivisions representing areas where at least one water table observation well is located. Each of the subdivisions was marked so that each point within the area bounded by a polygon, as shown in Figure 5.10, was nearer to the observation well contained therein than to any other. Volumes of alluvium from the granite surface to planes of equal elevation bounded by contour lines on the granite were used to calculate the changes in water storage.

Areas of planes at each contour line within each of the polygons in Figure 5.10 were measured by a planimeter. Measured areas were made at one foot contour intervals starting from the curve with the lowest elevation in each of the subdivisions.

Volumes of alluvium at each contour interval were computed for each of the subdivisions by multiplying the measured areas in square feet by the contour interval in feet. Volumes corresponding to each elevation were calculated by accumulating the volumes of the contour intervals at all elevations lower than that interval. Accumulated volumes and the corresponding elevations were plotted in order to detect any discontinuity in a curve connecting the points. A regression equation or regression equations of volumes as function of elevations were derived using a Multiple Regression Program
LEGEND
Δ OBSERVATION WELLS
○ NEUTRON PROBE HOLES

FIGURE 5-10
MAP OF GRANITE SURFACE SHOWING SUBDIVISIONS
OF
STUDY AREA
(Thornton, 1965) and are presented in Appendix D. These equations were used to calculate the total volume of alluvium below a measured water table in each of the subdivisions at times of observation.

Changes in water storage as a result of changes in water table elevations were calculated for each of the subdivisions and the total research areas by using the FORTRAN program as listed in Appendix C. The change in storage during a given period was calculated as the difference between volumes of water storage at the beginning and at the end of that period multiplied by average specific yield.

5.8 PARTICLE SIZE ANALYSIS

The hydrometer method as described by Day (1965) was used for the determination of the sand, silt, and clay fractions. Fractions of particles larger than two millimeters were determined by sieving.
6. RESULTS AND DISCUSSIONS

Data were collected at the research area from July, 1964 to June 15, 1965. Water disposition through evaporation and transpiration was calculated from measurements and/or computations of subsurface water inflow to the research area, changes in soil water storage, seepage, trickle outflow above the flume at the lower end of the area, and precipitation.

Two independent procedures were used to calculate evaporation and transpiration losses. One procedure is based on the principle of conservation of mass using the water balance approach. The other procedure is based on the diurnal fluctuation of the water table.

6.1 WATER BALANCE

Application of the conservation of mass principle to water in field hydrological investigations requires complex instrumentation installations for the measurements of the quantities of water influxes and outfluxes in the system under study. The obtained results from such a study are generally of limited application to other areas unless they are correlated with some fixed meteorological and biotic elements.

Basically, the use of the conservation of mass principle in field research would allow the numeration of water flow paths.
The research area is unique in that it resembles a large natural lysimeter; and is an open ecosystem. A change in the water content of this system would be equal to the mass of water exchange with the exterior. This exchange is through one or more of the water paths as shown diagramatically in Figure 4.1. Relative quantities of water following each of the paths vary with time. Figure 6.1 shows the annual water table regime from daily observations at one site.

Four periods were apparent with respect to the number of elements in the water balance equations (See Chapter 4). Water disposition for the four periods was simplified by the use of four equations which differ in the number of the elements of water balance present in each.

The first period from January to April, 1965 was characterized by lack of surface flow into and out of the research area, evaporation losses were equal to precipitation, and transpiration loss was negligible.

The beginning of the second period was marked by active plant growth and was similar to the first period except for an added water loss due to transpiration. Change in rate of water table elevations was evident after the first week in April, 1964 and the third week of April, 1965. Water table elevation, during this period, was
FIGURE 6.1 WATER TABLE REGIME AT CLYNE WELL (1964-65)
characterized by a diurnal cycle. This diurnal water table fluctuation characteristic was utilized in a method for calculating transpiration losses.

The third period from the last week in July to the last week in September, 1964 was characterized by several channel flows as shown by the insert in Figure 6.1. Dates of channel flows and estimated water transmission losses were calculated by Renard (1964) and are presented in Table 6.1. During this period water was frequently flowing in all the paths indicated in Figure 4.1. Quantitative evaluation of the elements of water balance during this period was not possible because of lack of information on quantities of water flow into the research area. The insert in Figure 6.1 shows the transmission losses and corresponding high rates of recharge in the channel reach which includes the research area. When surface flow of water into the area ceased in the last week of September it marked the start of the fourth period which was characterized by a steady drop in water table elevations as shown in Figure 6.1.

6.1.1 Subsurface Inflow

Water flow into the research area ($q_i$) for 43 times of measurement, from July, 1964 to June 15, 1965, were calculated using Darcy's equation, and are given in Table 6.2. A decrease in water flow volumes with time was evident in all the cross sections after the
Table 6.1

Estimated Transmission Losses (H) for the Flow in a Channel Reach Which Includes the Research Area

(After Renard, 1964)

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L* = Length of channel reach
af** = Acre feet
Table 6.2

Volumes of Subsurface Water Flow Across Six Sections (S) of the Channel

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last surface flow in the channel. Average rates of water flow into the
study area from the six sections are shown in Table 6.3. No signifi-
cant change in the differences of volumes of subsurface flow (between
volumes of flow at transect 6 and each of the other five transects in
Figure 5.5) was found (t = .05) with distance from transect 6. There­
fore, it was assumed that the average rates of flow as shown in Table
6.3 are estimates of subsurface inflow to the study area.

6.1.2 Water Losses Through the Confining Granite (Leakage or
Seepage)

From July 22 to the last week of September, 1964, there were
several flow producing storms (See insert in Figure 6.1). Calcula-
tions of water gains and losses from the field data for this period were
not possible because of lack of data on surface water inflow to the
study area.

From the last week of September, 1964 to December 31, 1964,
trickle flow above flume 2 continued. This indicated that the study
area was above its maximum equilibrium storage capacity, when
there is no surface flow, and that seepage losses were at rates higher
than those for periods of no trickle flow.

From January to the third week in April, 1965, there were no
rain producing storms and the plants were dormant. Water from
precipitation was observed to percolate into the soil to a maximum
Table 6.3

Average Volumes of Water Inflow ($q_i$) and the Calculated Standard Deviation ($S$), Standard Error of the Mean ($S_q$), and Coefficient of Variation (CV)

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<td>39.78</td>
<td>16.45</td>
</tr>
<tr>
<td>19</td>
<td>576.67</td>
<td>97.65</td>
<td>39.87</td>
<td>16.93</td>
</tr>
<tr>
<td>26</td>
<td>570.07</td>
<td>95.10</td>
<td>38.83</td>
<td>16.68</td>
</tr>
<tr>
<td>May 3</td>
<td>557.01</td>
<td>95.97</td>
<td>39.18</td>
<td>17.23</td>
</tr>
<tr>
<td>10</td>
<td>544.53</td>
<td>95.15</td>
<td>38.85</td>
<td>17.47</td>
</tr>
<tr>
<td>17</td>
<td>531.07</td>
<td>92.83</td>
<td>37.90</td>
<td>17.48</td>
</tr>
<tr>
<td>24</td>
<td>517.71</td>
<td>98.01</td>
<td>40.01</td>
<td>18.93</td>
</tr>
<tr>
<td>Jun 14</td>
<td>413.66</td>
<td>89.75</td>
<td>36.64</td>
<td>21.70</td>
</tr>
</tbody>
</table>
depth of two feet. This water was generally lost as evaporation during the periods between storms. The water balance equation which is applicable for this period is:

\[ \Delta s_w = q_i - q_o \]  

To solve this equation for seepage losses \( q_o \) it becomes:

\[ q_o = q_i + \Delta s_w \]  

where \( q_i \) is water inflow through the saturated alluvium from the upper reaches of the channel (Table 6.3), and \( \Delta s_w \) is the change in water storage within the research area and during a given time interval due to changes in water table elevation.

Seepage losses \( q_o \) using equation 6.2 were calculated and are presented in Table 6.4. Rate of change in \( q_o \) from January 1 to April 11 was equal to 10.74 cubic feet per day as shown by the regression equation:

\[ q_o = 2698.00 - 10.74 t \]  

with \( r = 0.97 \) and where \( t \) is the time in days from January 1 to April 11, 1965, \( r \) is the correlation coefficient. Equation 6.3 can be used to estimate \( q_o \) at any time during the period when surface water flow is equal to zero.

Computation of water losses as seepage from equation 6.2 were based on the assumption that changes in water storage were independent of precipitation, evaporation, and transpiration. This was a valid assumption for the period when equation 6.2 was applied. During this period there was no change in the shape of the soil water
Table 6.4
Subsurface Inflow ($q_i$), Changes in Water Storage ($\Delta s_w$) and Seepage Losses ($q_o$) from January 1 to April 11, 1965

<table>
<thead>
<tr>
<th>Time (days)</th>
<th>$q_i$ (cubic feet/day)</th>
<th>$\Delta s_w$ (cubic feet/day)</th>
<th>$q_o$ (cubic feet/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>745</td>
<td>-1966</td>
<td>2711</td>
</tr>
<tr>
<td>13.0</td>
<td>721</td>
<td>-1931</td>
<td>2652</td>
</tr>
<tr>
<td>23.5</td>
<td>706</td>
<td>-1609</td>
<td>2315</td>
</tr>
<tr>
<td>34.0</td>
<td>685</td>
<td>-1636</td>
<td>2321</td>
</tr>
<tr>
<td>44.5</td>
<td>672</td>
<td>-1546</td>
<td>2218</td>
</tr>
<tr>
<td>51.5</td>
<td>663</td>
<td>-1452</td>
<td>2115</td>
</tr>
<tr>
<td>58.5</td>
<td>654</td>
<td>-1356</td>
<td>2010</td>
</tr>
<tr>
<td>65.5</td>
<td>642</td>
<td>-1461</td>
<td>2103</td>
</tr>
<tr>
<td>72.5</td>
<td>628</td>
<td>-1185</td>
<td>1813</td>
</tr>
<tr>
<td>79.5</td>
<td>618</td>
<td>-1246</td>
<td>1864</td>
</tr>
<tr>
<td>86.5</td>
<td>612</td>
<td>-1205</td>
<td>1817</td>
</tr>
<tr>
<td>93.5</td>
<td>601</td>
<td>-1256</td>
<td>1857</td>
</tr>
<tr>
<td>100.5</td>
<td>597</td>
<td>-864</td>
<td>1461</td>
</tr>
</tbody>
</table>
profile above the water table and there were no changes in soil water content in the top three feet of soil at the five soil water measuring sites (Table 6.5). Therefore it was concluded that seepage losses from January 1 to April 5, 1965 can be estimated by using equation 6.3.

It was observed from water contents of the profile at each of five sites that the amounts of water remaining in the profile at a given time was different, as shown in Table 6.5. The rates of change in water content were also different at each of the sites after plants commenced their growth in April.

Variabilities in the amounts of water storage between sites for a given time of measurement in Table 6.5 were due to the differences in the soil profile depths. The differences in the rates of water depletion between the five sites may be related to vegetation types and densities at each of the five neutron probe sites. The first site is located in a mesquite stand which is composed of trees of numerous dead or dying branches, and had a very sparse foliage in April and May. The second and fourth moisture sites are located in areas with a few scattered mesquite trees and dense annual and perennial grasses which do not commence growth prior to the first summer rain. The third site is located in a thicket of vigorous mesquite trees. And the fifth site is located in the channel bed where water losses are due to subsurface flow and evaporation.
<table>
<thead>
<tr>
<th>Time Date</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
<th>Site 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/30</td>
<td>.872</td>
<td>.666</td>
<td>.444</td>
<td>.689</td>
<td>---</td>
</tr>
<tr>
<td>7/8</td>
<td>.797</td>
<td>.682</td>
<td>.378</td>
<td>.690</td>
<td>---</td>
</tr>
<tr>
<td>7/13</td>
<td>.799</td>
<td>.659</td>
<td>.397</td>
<td>.680</td>
<td>1.090</td>
</tr>
<tr>
<td>7/21</td>
<td>1.099</td>
<td>.668</td>
<td>.401</td>
<td>.668</td>
<td>1.240</td>
</tr>
<tr>
<td>7/23</td>
<td>.998</td>
<td>.688</td>
<td>.452</td>
<td>.679</td>
<td>2.065</td>
</tr>
<tr>
<td>7/29</td>
<td>.975</td>
<td>.675</td>
<td>.434</td>
<td>.661</td>
<td>1.735</td>
</tr>
<tr>
<td>8/4</td>
<td>.869</td>
<td>.726</td>
<td>---</td>
<td>.710</td>
<td>---</td>
</tr>
<tr>
<td>8/7</td>
<td>.969</td>
<td>.744</td>
<td>.512</td>
<td>.701</td>
<td>---</td>
</tr>
<tr>
<td>8/15</td>
<td>.855</td>
<td>.935</td>
<td>.520</td>
<td>.661</td>
<td>---</td>
</tr>
<tr>
<td>8/21</td>
<td>.852</td>
<td>.997</td>
<td>.513</td>
<td>.681</td>
<td>---</td>
</tr>
<tr>
<td>8/27</td>
<td>.850</td>
<td>1.046</td>
<td>.547</td>
<td>.725</td>
<td>---</td>
</tr>
<tr>
<td>9/10</td>
<td>.879</td>
<td>1.309</td>
<td>.894</td>
<td>.878</td>
<td>---</td>
</tr>
<tr>
<td>9/18</td>
<td>.891</td>
<td>1.779</td>
<td>1.145</td>
<td>.946</td>
<td>---</td>
</tr>
<tr>
<td>10/9</td>
<td>.873</td>
<td>1.863</td>
<td>1.166</td>
<td>.955</td>
<td>---</td>
</tr>
<tr>
<td>10/23</td>
<td>.913</td>
<td>1.875</td>
<td>1.667</td>
<td>.954</td>
<td>---</td>
</tr>
<tr>
<td>11/18</td>
<td>.946</td>
<td>1.731</td>
<td>---</td>
<td>.968</td>
<td>2.080</td>
</tr>
<tr>
<td>12/4</td>
<td>.995</td>
<td>1.721</td>
<td>.892</td>
<td>.964</td>
<td>1.945</td>
</tr>
</tbody>
</table>

(1964)

<table>
<thead>
<tr>
<th>Time Date</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
<th>Site 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/2</td>
<td>.996</td>
<td>1.193</td>
<td>.826</td>
<td>.942</td>
<td>1.615</td>
</tr>
<tr>
<td>2/9</td>
<td>.952</td>
<td>1.112</td>
<td>.820</td>
<td>.959</td>
<td>1.570</td>
</tr>
<tr>
<td>2/16</td>
<td>.969</td>
<td>1.134</td>
<td>.809</td>
<td>.978</td>
<td>1.600</td>
</tr>
<tr>
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<td>.986</td>
<td>1.093</td>
<td>.800</td>
<td>.945</td>
<td>1.600</td>
</tr>
<tr>
<td>3/2</td>
<td>1.005</td>
<td>1.142</td>
<td>.817</td>
<td>.941</td>
<td>1.550</td>
</tr>
<tr>
<td>3/9</td>
<td>.968</td>
<td>1.101</td>
<td>.792</td>
<td>.931</td>
<td>1.530</td>
</tr>
<tr>
<td>3/16</td>
<td>1.018</td>
<td>1.155</td>
<td>.830</td>
<td>.944</td>
<td>1.560</td>
</tr>
<tr>
<td>3/23</td>
<td>.971</td>
<td>1.129</td>
<td>.811</td>
<td>.939</td>
<td>1.540</td>
</tr>
<tr>
<td>3/30</td>
<td>.987</td>
<td>1.115</td>
<td>.828</td>
<td>.952</td>
<td>1.525</td>
</tr>
<tr>
<td>4/6</td>
<td>.996</td>
<td>1.147</td>
<td>.811</td>
<td>.925</td>
<td>1.480</td>
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<tr>
<td>4/13</td>
<td>.970</td>
<td>1.129</td>
<td>.816</td>
<td>.930</td>
<td>1.490</td>
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<tr>
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<td>.988</td>
<td>1.082</td>
<td>.785</td>
<td>.888</td>
<td>1.400</td>
</tr>
<tr>
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<td>.960</td>
<td>1.059</td>
<td>.753</td>
<td>.841</td>
<td>1.455</td>
</tr>
<tr>
<td>5/11</td>
<td>.967</td>
<td>1.014</td>
<td>.709</td>
<td>.893</td>
<td>1.445</td>
</tr>
<tr>
<td>5/18</td>
<td>.968</td>
<td>.981</td>
<td>.663</td>
<td>.871</td>
<td>1.440</td>
</tr>
</tbody>
</table>

(1965)
Table 6.5--Continued

<table>
<thead>
<tr>
<th>Time Date</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
<th>Site 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/25</td>
<td>.953</td>
<td>.948</td>
<td>.594</td>
<td>.845</td>
<td>1.400</td>
</tr>
<tr>
<td>6/2</td>
<td>.940</td>
<td>.875</td>
<td>.538</td>
<td>.769</td>
<td>1.330</td>
</tr>
<tr>
<td>6/15</td>
<td>.915</td>
<td>.780</td>
<td>.451</td>
<td>.711</td>
<td>1.385</td>
</tr>
</tbody>
</table>

cu. ft/sq. ft

*Profile depths are 106 inches at Site 1, 112 inches at Site 2, 76 inches at Site 3, 64 inches at Site 4, and 84 inches at Site 5.
Average water loss of 2.54 millimeters per day was calculated from changes in soil water contents at site three for the month of May. Such value does not represent the actual total loss since during May, the water table was about three feet below the deepest level of water measurement at that particular site, and mesquite roots extend to at least four more feet into the saturated alluvium as was observed in a pit 50 feet away from the measuring site. Therefore, calculated volumes of water losses from unsaturated soil water measurements do not represent total losses but they represent a fraction of the total water losses in the area. As an example of net changes in soil water distribution at the five neturon probe sites, from July 1964 to June 15, 1965, soil water content profiles for conditions of maximum and minimum water contents are plotted in Figure 6.2.

6.1.3 Evaporation and Transpiration Losses

Rates of evaporation from a wet surface depend on vapor pressure gradient from the soil to the air layer near the ground, incident solar radiation, physical properties of the material, and air movement. When the water table is deeper than three feet from the surface, evaporation losses become negligible (Gardner, 1960).

Transpiration losses from the area are dependent on plant and environmental variables. Plant variables include foliage characteristics, physiological factors, and amounts of ground cover.
FIGURE 6.2 MAXIMUM AND MINIMUM SOIL WATER DISTRIBUTION WITH DEPTH FOR FIVE SITES
The environmental variables include air and soil temperatures, solar radiation, vapor pressure in the air, roughness of ground surface and wind flow patterns, and the soil moisture potential.

6.1.3.1 Transpiration Losses from April 12 to June 15, 1965

Rates of transpiration losses from April 12 to June 15 were calculated using the equation:

\[ \Delta S = q_i - q_o + P - E - T \]  

(6.4)

and since \( S = \Delta S_w + \Delta \theta \) , and \( E = P \) (See the Experimental Model), equation 6.4 becomes

\[ T = q_i - q_o - \Delta \theta - \Delta S_w \]  

(6.5)

Subsurface water flow into the research area \( (q_i) \), seepage \( (q_o) \), and change in water storage due to changes in water table elevation \( (\Delta S_w) \) were calculated from the field data and are presented in Table 6.6.

The changes in soil moisture content \( (\Delta \theta) \) were calculated from soil water measurements above the capillary fringe.

6.1.3.2 Evapotranspiration Losses from July to October 1964

Water disposition from the research area during this period could be computed by using the equation:

\[ \Delta S = Q_i + q_i + P - q_o - ET \]  

(6.6)

The collected data was not sufficient for the calculations of evapotranspiration \( (ET) \) losses by equation 6.6. Surface water flow into the research area \( (Q_i) \) was not known. Because of this lack of
Table 6.6

Calculated Transpiration Losses from April 12 to June 15

<table>
<thead>
<tr>
<th>Date</th>
<th>Loss $q_i - \Delta S$ (cu. ft/day)</th>
<th>Seepage $q_o$ (cu. ft/day)</th>
<th>$T^*$ (mm/day)</th>
<th>$T^{**}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/12 to 4/19</td>
<td>1730</td>
<td>1548</td>
<td>182</td>
<td>0.5</td>
</tr>
<tr>
<td>4/20 to 4/26</td>
<td>1840</td>
<td>1468</td>
<td>372</td>
<td>1.0</td>
</tr>
<tr>
<td>4/27 to 5/3</td>
<td>2050</td>
<td>1393</td>
<td>657</td>
<td>1.7</td>
</tr>
<tr>
<td>5/4 to 5/10</td>
<td>2292</td>
<td>1318</td>
<td>974</td>
<td>2.6</td>
</tr>
<tr>
<td>5/11 to 5/17</td>
<td>3148</td>
<td>1243</td>
<td>1905</td>
<td>5.1</td>
</tr>
<tr>
<td>5/18 to 5/24</td>
<td>4170</td>
<td>1168</td>
<td>3002</td>
<td>8.0</td>
</tr>
<tr>
<td>5/25 to 6/14</td>
<td>4620</td>
<td>1092</td>
<td>3528</td>
<td>9.4</td>
</tr>
</tbody>
</table>

$T^*$ = Transpiration Loss Cu. Ft./Day

$T^{**}$ = Transpiration Loss (cu. ft./day) divided by the area with 100 per cent vegetation cover (114,800 sq. ft.) multiplied by 304.8 mm/ft.
information an attempt was made to estimate ET by empirical methods and by extrapolating the calculated maximum rate of water loss for this period as shown in Table 6.7.

Table 6.7 gives estimates of ET losses as calculated by three methods for 100 per cent vegetation cover.

6.1.3.3 Evapotranspiration Losses from October through December 1964

The last surface water inflow to the area was observed on October 6, 1964. From that day on to December 31, 1964 evapotranspiration losses were calculated by using the equation:

$$\Delta S = q_i + P - Q_o - q_o - ET$$  \hspace{1cm} (6.7)

The calculated ET losses are presented in Table 6.8.

6.2 Transpiration Losses as Shown by Diurnal Changes in Water Table Elevations

Hourly measurements of water table elevations at one site in the research area (Clyne Well) were used to calculate transpiration losses for periods when the changes in water table elevations exhibited a diurnal pattern as shown in Figure 6.3. Graph A in Figure 6.3 does not show a diurnal cycle. As plants progressed in their growth and foliage development, a diurnal change in water table elevations became increasingly more apparent (in May and June) as shown in Graphs B and C. This characteristic was utilized in a
Table 6.7

Potential Evapotranspiration Losses from June to October 1964

<table>
<thead>
<tr>
<th>Month</th>
<th>$R_0$</th>
<th>PET(^1)</th>
<th>PET(^2)</th>
<th>PET(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964</td>
<td></td>
<td>mm/day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>16.5</td>
<td>4.9</td>
<td>9.4</td>
<td>9.4</td>
</tr>
<tr>
<td>July</td>
<td>16.2</td>
<td>5.4</td>
<td>9.2</td>
<td>10.3</td>
</tr>
<tr>
<td>August</td>
<td>15.3</td>
<td>4.7</td>
<td>8.7</td>
<td>8.9</td>
</tr>
<tr>
<td>September</td>
<td>13.5</td>
<td>3.5</td>
<td>7.7</td>
<td>6.7</td>
</tr>
</tbody>
</table>

$R_0$ = Midmonthly solar radiation intensity in millimeter of water evaporated per day (Veihmeyer, 1964)

PET\(^1\) = Potential evapotranspiration. It was calculated by Thornthwaite's (1956) method.

PET\(^2\) = Evapotranspiration loss (From multiplication of the ratios of $R_0$ for each month to $R_0$ in June by the calculated transpiration loss from May 25 to June 14, 1965)

PET\(^3\) = Corrected evapotranspiration loss relative to PET\(^1\)

(The ratios of PET\(^1\) by Thornthwaite's method to that for June multiplied by calculated transpiration loss from May 25 to June 14, 1965)
Table 6.8

Evaporation and Transpiration Losses for the Period

After the Flow Season, 1964

<table>
<thead>
<tr>
<th>Time Date</th>
<th>AS (\Delta S_w)</th>
<th>(q_i)</th>
<th>(P - Q_o)</th>
<th>(\Delta \theta)</th>
<th>(q_o)</th>
<th>ET</th>
<th>mm/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/1 to 10/31</td>
<td>-5390</td>
<td>1136</td>
<td>-1680</td>
<td>-3368</td>
<td>2698</td>
<td>5516</td>
<td>3.8</td>
</tr>
<tr>
<td>11/1 to 11/5</td>
<td>-6623</td>
<td>1073</td>
<td>-1300</td>
<td>-2952</td>
<td>2698</td>
<td>5500</td>
<td>3.8</td>
</tr>
<tr>
<td>11/6 to 11/10</td>
<td>-4946</td>
<td>984</td>
<td>-1000</td>
<td>-3248</td>
<td>2698</td>
<td>5480</td>
<td>3.8</td>
</tr>
<tr>
<td>11/11 to 11/28</td>
<td>-5007</td>
<td>907</td>
<td>- 853</td>
<td>-3068</td>
<td>2698</td>
<td>5431</td>
<td>3.8</td>
</tr>
<tr>
<td>11/29 to 12/2</td>
<td>-2451</td>
<td>796</td>
<td>+2213</td>
<td>-2618</td>
<td>2698</td>
<td>5380</td>
<td>3.7</td>
</tr>
<tr>
<td>12/3 to 12/15</td>
<td>-4111</td>
<td>760</td>
<td>- 187</td>
<td>-3314</td>
<td>2698</td>
<td>5300</td>
<td>3.7</td>
</tr>
<tr>
<td>12/16 to 12/22</td>
<td>-5444</td>
<td>759</td>
<td>- 187</td>
<td>-1202</td>
<td>2698</td>
<td>4520</td>
<td>3.1</td>
</tr>
</tbody>
</table>

\(\Delta \theta\) = Average change in water storage above capillary fringe

\(\Delta S_w\) = Change in water storage due to change in water table elevation

\(q_i\) = Subsurface inflow

\(P\) = Precipitation

\(Q_o\) = Surface outflow

\(q_o\) = Seepage

ET = Evapotranspiration
FIGURE 6.3

WATER TABLE ELEVATIONS AT ONE OF THE WELLS IN THE RESEARCH AREA
comparative study of three methods which were used to estimate transpiration losses during the period when the diurnal cycle was apparent (April to July 1965).

One method is based on the daily changes in average water table elevations. Water losses were calculated using this method by multiplying the daily drop in water table elevations by the specific yield of the material. One of the other two methods is that of White (1932). In this method, the changes in water storage were calculated by using the equation:

\[ d = S_y (24 r + s) \]  \hspace{1cm} (6.8)

where \( d \) is the depth of water loss in feet, \( S_y \) is the specific yield of the soil, \( r \) is the hourly rate or rise in water table elevation from midnight to 4 A.M. in feet, and \( s \) is the change in water table elevation (rise or fall) during a 24-hour period, in feet.

The third method is essentially that of Troxell (1936), where ET losses from 4 to 6 A.M. were assumed to be negligible. Therefore, the diurnal cycle as reflected in water table elevations represent an accumulation curve of water flow rates into the site minus the transpiration rates. The hourly change in water table elevation curves a, b, c, and d shown in Figure 6.4 represent rates of change in saturated storage. In this method, water losses were calculated by multiplying the change in saturated storage by specific yield. The
FIGURE 6.4 CHANGE IN VOLUME OF SATURATED ALLUVIUM COMPUTED FROM DIURNAL WATER TABLE FLUCTUATIONS USING TROXELL METHOD
shaded areas in Figure 6.4 represent the total change in saturated storage due to transpiration. It can be observed from Figure 6.4 that in July water use exceeded recharge which resulted in an increasing rate of drop in water table during a 24-hour period as shown in Graph D.

Calculated transpiration losses from April 10 to June 15, 1964 by using the three methods are presented in Figure 6.5. The daily rate method gives the calculated water losses from the average daily water table elevations when the diurnal cycle was not taken into consideration. White's method gives the losses when the diurnal variations in water table elevations were taken into consideration using equation 6.8. Calculated water losses from the hourly changes in water table elevations were comparable to those obtained by the water balance method as shown in Table 6.9.

The four graphs in Figure 6.4 show a change in the amplitudes of the diurnal fluctuations in water table for the designated dates. These diurnal amplitudes at a given area and for given climatic conditions may be related to the stage of plant foliage development, available water in the root zone, permeability of the soil, and the area of a horizontal plane corresponding to average daily water table elevation. These variables may be expressed by the function:
Figure 6.5 Scatter Diagram of Transpiration Losses—1965
Table 6.9

Calculated Transpiration Losses Using the Diurnal Fluctuation of Water Table (Troxell, 1936) and the Water Balance Methods

<table>
<thead>
<tr>
<th>Date</th>
<th>1965</th>
<th>1965</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T\textsubscript{1}\textsuperscript{*}</td>
<td>T\textsubscript{2}\textsuperscript{**}</td>
</tr>
<tr>
<td>4/13 to 4/19</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>4/20 to 4/26</td>
<td>1.5</td>
<td>1.0</td>
</tr>
<tr>
<td>4/27 to 5/3</td>
<td>2.1</td>
<td>1.7</td>
</tr>
<tr>
<td>5/4 to 5/10</td>
<td>2.4</td>
<td>2.6</td>
</tr>
<tr>
<td>5/11 to 5/17</td>
<td>4.9</td>
<td>5.1</td>
</tr>
<tr>
<td>5/18 to 5/24</td>
<td>6.3</td>
<td>8.0</td>
</tr>
<tr>
<td>5/25 to 6/14</td>
<td>8.8</td>
<td>9.4</td>
</tr>
</tbody>
</table>

\textbf{T}\textsubscript{1}\textsuperscript{*} = Transpiration losses by the diurnal cycle change in hourly rates method

\textbf{T}\textsubscript{2}\textsuperscript{**} = Transpiration losses by the water balance method
\[ \alpha = f \left( \frac{1}{A}, \frac{1}{K}, G \right) \]

where \( \alpha \) is the amplitude of the diurnal change in water table in feet, \( A \) is the surface area of the saturated alluvium at the average daily water table elevation in square feet, \( K \) is the hydraulic conductivity of the alluvium in feet per unit time, and \( G \) is a vegetation variable directly related to the plant characteristics and ground cover density.

The process which causes such a diurnal water table elevation cycle may be visualized by referring to Figure 6.6 A which gives a vertical section of a segment of the research area at Clyne Well. Below the level \( e_o \) the soil is saturated and water movement follows the saturated flow equations.

The shape of the graph in Figure 6.6 B is due to varying rates of water use and water movement in the soil in areas with varying vegetation cover. At about six in the evening water recharge was equal to discharge from the saturated soil, and the rates of change in water table elevation were equal to zero. Between the hours of midnight and sunrise, transpiration losses were assumed to be at a minimum. This assumption is true only when the soil moisture distribution above the water table is at steady state at all times. In Figure 6.6 B, at point \( a \) the rate of water flow into the site will be at a minimum. At point \( b \) the rate will be at a maximum in areas
FIGURE 6.6
DIAGRAM SHOWING A—CROSS SECTION OF A SEGMENT OF THE STUDY AREA, AND B—DIURNAL FLUCTUATION OF WATER TABLE ($e_o$)
which are partly covered with vegetation.

6.3 WATER FLOW AND DISPOSITION

Calculated daily rates of water influxes and outfluxes and the changes in storage are presented in Table 6.10. These volumes are converted to depths of water equivalents when divided by the total area for all the periods except from April to June 15, 1965 when transpiration loss is restricted to the area with riparian vegetative cover as shown in Table 6.11.
Table 6.10

Water Balance for the Study Area

<table>
<thead>
<tr>
<th>Year and Month</th>
<th>1965*</th>
<th>1964**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jan</td>
<td>Feb</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cu. ft./day</td>
</tr>
<tr>
<td>Q_i</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>q_i</td>
<td>710</td>
<td>660</td>
</tr>
<tr>
<td>P</td>
<td>570</td>
<td>120</td>
</tr>
<tr>
<td>Q_o</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>q_o</td>
<td>2500</td>
<td>2110</td>
</tr>
<tr>
<td>Δθ</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ΔS_w</td>
<td>-1790</td>
<td>-1450</td>
</tr>
<tr>
<td>ΔS</td>
<td>-1790</td>
<td>-1450</td>
</tr>
<tr>
<td>T</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>570</td>
<td>120</td>
</tr>
<tr>
<td>ET</td>
<td>570</td>
<td>120</td>
</tr>
</tbody>
</table>

*Transpiration is from an area of 114,800 square feet.

**Evapotranspiration is from an area of 440,400 square feet.
### Table 6.11

**Areas of the Different Vegetation Types and the Channel Bed**

<table>
<thead>
<tr>
<th>Area</th>
<th>Square Feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Channel</td>
<td>142 800</td>
</tr>
<tr>
<td>Grass</td>
<td>124 000</td>
</tr>
<tr>
<td>Mixed Shrubs*</td>
<td>117 600</td>
</tr>
<tr>
<td>Mesquite**</td>
<td>56 000</td>
</tr>
<tr>
<td>Total Area</td>
<td>440 400</td>
</tr>
</tbody>
</table>

*Ground cover density is 50 per cent*

**Ground cover density is 100 per cent**
7. SUMMARY AND CONCLUSIONS

To assess water resources and make efficient use of water for livestock or agriculture in the southwest, knowledge of water disposition under natural conditions is required. Presence of plants in areas of shallow water table and along rivers and stream channels causes an increase in evapotranspiration losses. The economic value of these plants relative to the amounts of water they use is often taken as the only criterion in planning systems of management for these areas.

7.1 SUMMARY

The water balance methods for the estimation of transpiration are very promising. However, field methods of estimating the rates of water flow need to be refined and should be verified by other methods of calculation.

To accomplish this, a channel reach at Walnut Gulch Experimental Watershed was chosen and some standard and modified methods of measuring water flow and the changes in water storage were used.

The vegetation along the channel banks was dormant for a period of about five months which ended in April during the study period. From April to August mesquite and other deep-rooted species
were dominant in the area, from August to November other herbaceous species and annual and perennial grasses were growing as understory with mesquite and in openings bringing the cover density along the channel banks to 100 per cent in most of the area.

Water table changes were characterized by a rapid rise during the flow season with intermittent slow drop between flow events. After the last flow in September the water table dropped at a decreasing rate until plants commenced their growth in April when the rate of drop in the water table elevation increased. Thus, annual changes in vegetation, water table elevations, and the regional climate resulted in a sequential annual cycle characterized by four distinct periods of varying complexities in terms of the elements of water budget for the research area. This characteristic simplified the calculations of water disposition on seasonal basis.

Research completed to the middle of June 1965 combining the water balance approach and the diurnal water table fluctuations in certain periods was limited to evaluating water disposition from the research area as shown in Figure 7.1.

7.2 CONCLUSIONS

From the research results and computations the following conclusions can be drawn:
\[ \Delta S_W + \Delta \theta = \text{Change in Storage} \]

\[ P = \text{Precipitation} \]

\[ Q_o = \text{Surface Outflow} \]

\[ Q_i = \text{Sub-surface Inflow} \]

**Summary of Water Inflow and Disposition at the Study Area**
1. The standard field methods which were used in the measurements and/or computations of the elements of the water balance proved to be satisfactory for estimating water gains and losses at the study area. These methods included (1) a calibrated recording system for accurate measurements of trickle surface water flow out of the research area, (2) a seismic refraction method for the estimation of alluvium depths to granite, and (3) a piezometric method for estimating hydraulic conductivity of alluvium below water table.

2. Water use by riparian vegetation was negligible during plant dormancy. It increased to 9.4 millimeters per day in June for areas with 100 per cent vegetation cover. Direct estimates of transpiration losses were obtained during the growing season prior to summer rains using the water balance and the diurnal change in water table elevation methods of calculation. Estimated evapotranspiration losses at the study area from July 1964 to July 1965 were 1,898,000 cubic feet (51.7 inches).

3. Estimated subsurface inflow amounted to 312,000 cubic feet, and subsurface outflow was 807,000 cubic feet for the period of study.

7.3 RECOMMENDATIONS

Research in the area should continue at a more refined scale with an attempt to correlate soil properties, vegetation characteristics
and some climatic parameters so that the obtained results may be projected to other areas.

The use of water balance equations for calculating the rates of water disposition can be improved by:

1. Determination of soil water contents at fifteen to twenty sites and to granite surface at each of the sites. A continuous record should be kept with no interruptions.

2. Calculation of hydraulic conductivity at several sites and by using different methods to permit the estimation of the accuracy of the piezometer method.

It was apparent from the research that the riparian species use substantial amounts of water during the growing season which may exceed one foot per month under 100 per cent ground cover. The results of the research, however, should in no way be used for large scale management planning for the purpose of water conservation. In the research area and in many similar areas in the southwest a complete understanding of the hydrologic cycle, channel morphology, recreation and aesthetic values, socio-economic forces, wildlife habitat should be prerequisite to any management planning.
APPENDIX A

SOILS BULK DENSITIES AND TEXTURES IN THE
STUDY AREA AT LOCATIONS SHOWN IN FIGURE 3.5
Table A.1

Bulk Densities and Particle-Size Analysis for Soil Samples Collected from Two Sites

<table>
<thead>
<tr>
<th>Location</th>
<th>Depth</th>
<th>Bulk Density cm</th>
<th>Density g/cm³</th>
<th>&gt;2</th>
<th>2-1</th>
<th>1-.5</th>
<th>.5-.25</th>
<th>.25-.1</th>
<th>.1-.05</th>
<th>.05-.02</th>
<th>.02-.002</th>
<th>&lt; .002</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 feet East</td>
<td>0-7</td>
<td>1.31</td>
<td>24.30</td>
<td>6.18</td>
<td>9.58</td>
<td>21.92</td>
<td>25.08</td>
<td>5.79</td>
<td>0.80</td>
<td>1.20</td>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td>of Clyne</td>
<td>7-12</td>
<td>1.16</td>
<td>3.66</td>
<td>3.09</td>
<td>6.40</td>
<td>24.22</td>
<td>43.04</td>
<td>10.87</td>
<td>1.20</td>
<td>1.80</td>
<td>6.00</td>
<td></td>
</tr>
<tr>
<td>Well</td>
<td>12-24</td>
<td>0.64</td>
<td>5.27</td>
<td>9.22</td>
<td>19.62</td>
<td>35.02</td>
<td>6.15</td>
<td>3.00</td>
<td>3.00</td>
<td>2.00</td>
<td>10.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24-34</td>
<td>1.38</td>
<td>23.55</td>
<td>7.03</td>
<td>8.72</td>
<td>19.77</td>
<td>26.58</td>
<td>4.20</td>
<td>2.00</td>
<td>0.80</td>
<td>7.20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>34-43</td>
<td>1.66</td>
<td>30.10</td>
<td>9.52</td>
<td>8.92</td>
<td>18.14</td>
<td>21.70</td>
<td>4.00</td>
<td>0.70</td>
<td>0.08</td>
<td>6.70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>43-53</td>
<td>1.72</td>
<td>32.47</td>
<td>9.97</td>
<td>9.61</td>
<td>17.85</td>
<td>18.88</td>
<td>3.65</td>
<td>1.00</td>
<td>.00</td>
<td>6.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>53-63</td>
<td>2.07</td>
<td>27.02</td>
<td>9.57</td>
<td>10.01</td>
<td>19.28</td>
<td>21.34</td>
<td>4.00</td>
<td>2.00</td>
<td>0.11</td>
<td>6.30</td>
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<td></td>
<td>63-73</td>
<td>1.64</td>
<td>13.22</td>
<td>9.29</td>
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<td>25.26</td>
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<tr>
<td></td>
<td>73-83</td>
<td>1.53</td>
<td>7.05</td>
<td>8.61</td>
<td>12.94</td>
<td>27.35</td>
<td>28.04</td>
<td>4.90</td>
<td>2.70</td>
<td>1.30</td>
<td>7.10</td>
<td></td>
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<tr>
<td></td>
<td>83-93</td>
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<td>5.18</td>
<td>7.00</td>
<td>13.04</td>
<td>28.10</td>
<td>29.73</td>
<td>5.30</td>
<td>3.00</td>
<td>1.00</td>
<td>7.50</td>
<td></td>
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<tr>
<td></td>
<td>93-103</td>
<td>1.61</td>
<td>6.20</td>
<td>6.79</td>
<td>12.78</td>
<td>29.50</td>
<td>27.87</td>
<td>4.28</td>
<td>2.00</td>
<td>3.00</td>
<td>7.50</td>
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<td></td>
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<td>1.50</td>
<td>6.62</td>
<td>7.02</td>
<td>12.12</td>
<td>31.50</td>
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<td>4.00</td>
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<td>Channel bed</td>
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<td>1.75</td>
<td>40.62</td>
<td>18.14</td>
<td>18.65</td>
<td>15.72</td>
<td>5.17</td>
<td>1.00</td>
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<tr>
<td></td>
<td>10-16</td>
<td>2.04</td>
<td>54.51</td>
<td>15.60</td>
<td>13.75</td>
<td>11.00</td>
<td>4.00</td>
<td>0.80</td>
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<td>.00</td>
<td>0.51</td>
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<tr>
<td>Well A I</td>
<td>16-23</td>
<td>1.90</td>
<td>38.22</td>
<td>24.44</td>
<td>16.38</td>
<td>13.91</td>
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<td>12.18</td>
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<td></td>
<td>34-53</td>
<td>----</td>
<td>51.25</td>
<td>22.56</td>
<td>14.70</td>
<td>8.93</td>
<td>2.38</td>
<td>1.20</td>
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<td>61.56</td>
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<td>.00</td>
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<td>74.33</td>
<td>6.68</td>
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<td>.70</td>
<td>.00</td>
<td>.00</td>
<td>0.21</td>
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</tr>
</tbody>
</table>
### Table A.2

Texture for Soil Samples from Four Sites in the Study Area

<table>
<thead>
<tr>
<th>Location*</th>
<th>Depth</th>
<th>Sand 2-0.02 mm</th>
<th>Silt 0.02-0.002 mm</th>
<th>Clay &lt;0.002 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well 44</td>
<td>0-30</td>
<td>69.5</td>
<td>20.0</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>30-60</td>
<td>61.5</td>
<td>22.5</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>60-120</td>
<td>61.5</td>
<td>24.0</td>
<td>14.5</td>
</tr>
<tr>
<td></td>
<td>120-150</td>
<td>62.5</td>
<td>26.5</td>
<td>11.0</td>
</tr>
<tr>
<td>Well 41</td>
<td>0-90</td>
<td>77.0</td>
<td>13.1</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>90-150</td>
<td>59.0</td>
<td>21.0</td>
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<td></td>
<td>150-210</td>
<td>69.0</td>
<td>19.0</td>
<td>12.0</td>
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<td></td>
<td>210-240</td>
<td>76.5</td>
<td>17.5</td>
<td>6.0</td>
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<td></td>
<td>240-270</td>
<td>72.0</td>
<td>21.5</td>
<td>6.5</td>
</tr>
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<td></td>
<td>270-360</td>
<td>53.5</td>
<td>34.5</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>360-390</td>
<td>69.0</td>
<td>21.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Well 45</td>
<td>0-60</td>
<td>82.5</td>
<td>12.5</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>60-120</td>
<td>79.0</td>
<td>15.0</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>120-150</td>
<td>79.0</td>
<td>15.0</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>150-210</td>
<td>67.5</td>
<td>22.0</td>
<td>10.5</td>
</tr>
<tr>
<td>30 Feet</td>
<td>0-25</td>
<td>94.0</td>
<td>4.0</td>
<td>2.0</td>
</tr>
<tr>
<td>South of</td>
<td>25-60</td>
<td>90.5</td>
<td>5.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Well 9</td>
<td>60-180</td>
<td>94.5</td>
<td>3.5</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>180-270</td>
<td>91.0</td>
<td>3.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

*See Figure 3.5 for the location
APPENDIX B

REGRESSION EQUATIONS FOR THE ALLUVIUM CROSS-SECTIONAL AREAS (A) AS A FUNCTION OF ELEVATIONS (E) AT THE TRANSECTS SHOWN IN FIGURE 3.2
THE FIRST TRANSECT

If $E$ is less than or equal to ($\leq$) 101.00 feet:

$$A_1 = 179\,653.24 - 3842.85\,E + 20.55\,E^2,$$

and the correlation coefficient ($r$) = 0.99.

If $E$ is larger than ($>$) 101.00

$$A_1 = 87045.98 - 1923.67\,E + 10.63\,E^2,$$

$r = 0.99.$

THE SECOND TRANSECT

If $E \leq 96.50$

$$A_2 = 209492.46 - 45541.84\,E + 24.75\,E^2,$$

$r = 0.99.$

If $E > 96.50$

$$A_2 = 95215.50 - 2115.90\,E + 11.75\,E^2,$$

$r = 0.99.$

THE THIRD TRANSECT

If $E \leq 96.50$

$$A_3 = 225481.89 - 4870.02\,E + 26.30\,E^2,$$

$r = 0.99$

If $E > 96.50$

$$A_3 = 127915.84 - 2799.03\,E + 15.31\,E^2,$$

$r = 0.99.$
THE FOURTH TRANSECT

If \( E \leq 96.00 \)
\[
A_4 = 193508.77 - 4259.96E + 23.44E^2 ,
\]
\( r = 0.99 \).

If \( E > 96.00 \)
\[
A_4 = 100705.25 - 2264.31E + 12.73E^2 ,
\]
\( r = 0.98 \).

THE FIFTH TRANSECT

If \( E \leq 95.00 \)
\[
A_5 = 162706.16 - 3666.62E + 20.66E^2 ,
\]
\( r = 0.99 \).

If \( E > 95.00 \)
\[
A_5 = -23415.80 + 254.66E ,
\]
\( r = 0.97 \).

THE SIXTH TRANSECT

If \( E \leq 95.00 \)
\[
A_6 = 113604.48 - 2581.92E + 14.67E^2 ,
\]
\( r = 0.99 \).

If \( E > 95.00 \)
\[
A_6 = -19376.04 + 211.76E ,
\]
\( r = 0.99 \).
APPENDIX C

LISTING OF THE FORTRAN PROGRAM USED IN
THE COMPUTATIONS OF WATER INFLOW AND CHANGES
IN WATER STORAGE, WRITTEN FOR IBM 1401-7072
COMPUTER SYSTEM OF THE NUMERICAL ANALYSIS
LABORATORY AT THE UNIVERSITY OF ARIZONA
HASAN QASHU
* COMPIL FORTRAN, EXECUTE FORTRAN, DUMP IF ERROR

C CV COEFFICIENT OF VARIATION
C STD STANDARD DEVIATION(S)
C ASQ (SUM OF VALUES SQUARED)/6
C SSQ SUM OF SQUARES FOR THE SIX VALUES
C SVIN SUM OF OBSERVATIONS(VALUES)
C VBAR MEAN OF VALUES
C DVLM CHANGE IN WATER STORAGE CU FT/DAY
C TCSM CHANGE IN WATER STORAGE MM/DAY
C ERROR STANDARD ERROR OF THE MEAN
C TCSD CHANGE IN WATER STORAGE FT/DAY
C VOLX AVERAGE VOLUME OF INFLOW OF WATER
C EXS(1:10)=WATER ELEVATION AT THE FIRST CROSS
C SECTIONAL AREA ON 10TH. TIME OF MEASUREMENT
C GRAD(2:20)= HYDRAULIC GRADIENT AT THE SECOND
C SECTION AND ON 20TH. TIME OF MEASUREMENT
C AXS(1:2)= CROSS SECTIONAL AREA OF THE SATURATED
C SOIL AT THE 1ST. CROSS SECTION AND ON THE
C SECOND TIME OF MEASUREMENT FT SQ.
C VOL(2:2)= VOLUME OF WATER FLOWING ACROSS THE
C 2ND. SECTION ON THE 2ND. TIME OF MEASUREMENT
C WE(9:9)= WATER TABLE ELEVATION AT THE NINTH
C SITE AND ON THE NINTH TIME OF MEASUREMENT.
C VLS(3:1)= THE BULK VOLUME OF ALLUVIUM ABOVE
C GRANITE SURFACE AND WITHIN THE AREA OF INFLUENCE
C OF THE THIRD SITE ON THE FIRST TIME OF MEASURE
C MENT
C DVL= FIRST DIFFERENCE OF WATER VOLUME CU FT.
C WTE WATER TABLE ELEVATION FEET
C VLOSS WATER LOSSES FROM THE AREA
C SUMDV TOTAL CHANGE IN WATER STORAGE
C P DAYS BETWEEN TIMES OF MEASUREMENTS
C DVD= SUMDV/P (CU FT/DAY)
FORTRAN PROGRAM—CONTINUE

DIMENSION CV(50),STD(50),ASQ(50),SSQ(50),
1SVIN(50),VBAR(50)

DIMENSION EXS(6*43),GRAD(6*43),AXS(6*43),VOL
1(6*43),WE(9*50),DVLS(9*50),VLS(9*50),DVLM(9*50)

DIMENSION WTE(13*50),TCSM(50),SUMDV(50),ERROR(50)
1,DVD(50),TCSD(50),P(43),VOLX(43),VLOSS(43)

DO 1 1=1,13
1 READ 3,ID*(WTE(I,J),J=1,43)
3 FORMAT(I5.15F5.2/5X.15F5.2/5X.13F5.2)

READ 8,P(N,N=1,43)
8 FORMAT(40F2.0/3F2.0)

JJ=1

DO 102 I=1,43
102 EXS(1,I)=WTE(2,I)
EXS(2,I)=(WTE(3,I)+WTE(4,I)+WTE(5,I))/3.0
EXS(3,I)=(EXS(1,I)+EXS(3,I))/2.0
EXS(5,I)=WTE(6,I)
EXS(4,I)=(EXS(3,I)+EXS(5,I))/2.0
EXS(6,I)=(EXS(5,I)+WTE(7,I))/2.

C SLOPES OF WATER TABLE AND VOLUMES OF FLOW FOR
C THE CROSS SEC.

GRAD(1,I)=(EXS(1,I)-EXS(5,I))/408.0
IF(EXS(1,I)-101.0)10,10,11
10 AXS(1,I)=(20.551)*(EXS(1,I)-93.50)**2
GO TO 12
11 AXS(1,I)=(10.628)*(EXS(1,I)-90.5)**2
12 VOL(1,I)=AXS(1,I)*GRAD(1,I)*(75.84)

C SLOPES OF THE WATER TABLE AND VOLUMES OF FLOW
C FOR THE SECOND SEC

GRAD(2,I)=(EXS(1,I)-EXS(5,I))/408.0
IF(EXS(2,I)-96.50)20,20,21
20 AXS(2,I)=(24.751)*(EXS(2,I)-92.0)**2
GO TO 22
21 AXS(2,I)=(11.755)*(EXS(2,I)-90.0)**2
22 VOL(2,I)=AXS(2,I)*GRAD(2,I)*(75.84)

C VOLUMES OF FLOW FOR THE THIRD SECTION

GRAD(3,I)=GRAD(2,I)
IF(EXS(3,I)-96.50)30,30,31
30 AXS(3,I)=(26.296)*(EXS(3,I)-92.6)**2
GO TO 32
31 AXS(3,I)=(15.312)*(EXS(3,I)-91.4)**2
32 VOL(3,I)=AXS(3,I)*GRAD(3,I)*(75.84)
FORTRAN PROGRAM-CONTINUE

C VOLUMES OF FLOW FOR THE FOURTH SECTION

GRAD(4,I) = GRAD(2,I)
IF(EXS(4,I)-96.0) 40,40,41
40 AXS(4,I) = (23.445)*(EXS(4,I)-90.85)**2
GO TO 42
41 AXS(4,I) = (12.728)*(EXS(4,I)-88.95)**2
42 VOL(4,I) = (AXS(4,I))*(GRAD(4,I))*75.84

C VOLUMES OF FLOW FOR THE FIFTH SECTION

GRAD(5,I) = (EXS(3,I)-WTE(8,I))/600.0
IF(EXS(5,I)-95.0) 50,50,51
50 AXS(5,I) = (20.657)*(EXS(5,I)-88.75)**2
GO TO 52
51 AXS(5,I) = (254.658)*(EXS(5,I)-91.95)
52 VOL(5,I) = (AXS(5,I))*(GRAD(5,I))*75.84

C VOLUMES OF FLOW FOR THE SIXTH SECTION

GRAD(6,I) = (EXS(5,I)-WTE(7,I))/237.0
IF(EXS(6,I)-95.0) 60,60,61
60 AXS(6,I) = (14.670)*(EXS(6,I)-88.00)**2
GO TO 62
61 AXS(6,I) = (211.76)*(EXS(6,I)-91.50)
62 VOL(6,I) = (AXS(6,I))*(GRAD(6,I))*75.84

71 CONTINUE
DO 205 J = 1,6
DO 205 I = 1,43
205 PUNCH 201,J,EXS(J,I),GRAD(J,I),AXS(J,I),VOL(J,I)
201 FORMAT(15X,2F10.2,F10.4,F10.1,F10.1)
601 PUNCH 600,I,VOL(1,I),VOL(2,I),VOL(3,I),VOL(4,I),VOL(5,I),VOL(6,I)
600 FORMAT(15X,12,F10.2,2X,6F8.1)

SSQ(I) = 0.
SUMDV(I) = 0.
SVIN(I) = 0.
DO 93 I = 1,43
DO 93 J = 1,6
93 SVIN(I) = SVIN(I) + VOL(J,I)
DO 63 I = 1,43
63 VBAR(I) = SVIN(I)/6.0
DO 64 I = 1,43
DO 64 J = 1,6
64 SSQ(I) = SSQ(I) + VOL(J,I)**2
FORTRAN PROGRAM—CONTINUE

DO 65 I = 1, 43
ASQ(I) = SVIN(I)**2 / 6.0
STD(I) = SQRTF((SSQ(I) - ASQ(I)) / 5.0)
ERROR(I) = STD(I) / SQRTF(6.0)
65 CV(I) = (STD(I) * 100.0) / VBAR(I)
DO 69 I = 1, 43
69 PUNCH 70, I, VBAR(I), STD(I), ERROR(I), CV(I)
70 FORMAT (15X, I2, 3X, 4F9.2)

DO 72 I = 1, 43
WE(1, I) = EXS(3, I)
WE(2, I) = WTE(6, I)
WE(3, I) = WTE(7, I)
WE(4, I) = WTE(8, I)
WE(5, I) = WTE(9, I)
WE(6, I) = WTE(10, I)
WE(7, I) = WTE(11, I)
WE(8, I) = WTE(12, I)
WE(9, I) = WTE(13, I)
C FIRST SITE
VLS(1, I) = (60.60)**2 * (WE(1, I) - 91.30)**2
C SECOND SITE
IF(WE(2, I) - 95.00) 80, 81
80 VLS(2, I) = (74.50)**2 * (WE(2, I) - 89.55)**2
GO TO 82
81 VLS(2, I) = (47.80)**2 * (WE(2, I) - 86.50)**2
C THIRD SITE
82 IF(WE(3, I) - 91.00) 90, 90, 91
90 VLS(3, I) = (43.80)**2 * (WE(3, I) - 86.60)**2
GO TO 92
91 VLS(3, I) = (60.0)**2 * (WE(3, I) - 87.80)**2
C FOURTH SITE
92 IF(WE(4, I) - 91.70) 15, 15, 16
15 VLS(4, I) = (50.80)**2 * (WE(4, I) - 86.75)**2
GO TO 17
16 VLS(4, I) = (37.60)**2 * (WE(4, I) - 85.0)**2
C FIFTH SITE
17 IF(WE(5, I) - 91.45) 25, 25, 26
25 VLS(5, I) = (43.0)**2 * (WE(5, I) - 85.40)**2
GO TO 27
26 VLS(5, I) = (31.8)**2 * (WE(5, I) - 83.30)**2
FORTRAN PROGRAM-CONTINUE

C SIXTH SITE
27 VLS(6*I) = (20.40)**2 * (WE(6*I) - 86.7)**2

C SEVENTH SITE
35 VLS(7*I) = (18.0)**2 * (WE(7*I) - 78.7)**2
GO TO 37
36 VLS(7*I) = (34.0)**2 * (WE(7*I) - 83.0)**2

C EIGHT
37 IF(WE(8*I) > 94.50) 45 45 46
45 VLS(8*I) = (56.0)**2 * (WE(8*I) - 85.5)**2
GO TO 47
46 VLS(8*I) = (42.5)**2 * (WE(8*I) - 84.00)**2

C NINTH SECTION
47 IF(WE(9*I) > 84.00) 55 55 56
55 VLS(9*I) = (53.6)**2 * (WE(9*I) - 76.3)**2
56 VLS(9*I) = (70.0)**2 * (WE(9*I) - 78.10)**2

72 CONTINUE
DO 57 J = 1, 9
DO 57 I = 1, 43
DVLS(J*I) = VLS(J*I) - VLS(J*I + 1)

57 DVLS(J*I) = DVLS(J*I) * 0.195
DO 28 J = 1, 9
DO 28 I = 1, 43
28 DVLM(J*I) = DVLS(J*I) / P(I)

C TOTAL WATER LOSSES
DO 2 I = 1, 43
DO 2 J = 1, 9
2 SUMDV(I) = SUMDV(I) + DVLS(J*I)

DO 4 I = 1, 43
TCSD(I) = SUMDV(I) / (390000.0 * P(I))
TCSM(I) = TCSD(I) * 304.80
N = I

4 DVD(I) = SUMDV(I) / P(N)

C WATER STORAGE
141 FORMAT(15X, I2, 4F12.1) / (17X, 4F12.1))
PUNCH 161
161 FORMAT(30H1CHANGE IN WATER STORAGE CU FT///)
DO 165 J = 1, 9
165 PUNCH 141, J*(DVLS(J*K), K = 1, 43)
DO 166 J = 1, 9
FORTRAN PROGRAM—CONTINUE

166 PUNCH 141,J*(DVLM(J)*I=1,43)
   DO 167 I=1,43
167 PUNCH 162*P(I)*TCSD(I)*TCSM(I)
162 FORMAT(15X,I2,F5.0,F8.3,F6.1)
   PUNCH 163
163 FORMAT(27H1CHANGE IN WATER STORAGE MM///)
   DO 701 I=1,43
      VOLX(I)=VBAR(I)
      VLOSS(I)=VOLX(I)+DVD(I)
701 PUNCH 702*I*P(I)*SUMDV(I)*VOLX(I)*DVD(I)*VLOSS(I)
702 FORMAT(15X,I2,F5.0,F11.1)
    JJ=JJ+1
   DO 33 I=1,43
      SVIN(I)=0.
      SSQ(I)=0.
33 SUMDV(I)=0.
   DO 800 J=1,13
   DO 800 I=1,43
800 WTE(I,J)=WTE(I,J)+0.85
    IF(JJ-2)102,102,802
802 STOP
    END
APPENDIX D

REGRESSION EQUATIONS USED IN CALCULATING
VOLUMES OF ALLUVIUM (E) BELOW GIVEN ELEVATIONS
(E) FOR THE NINE SUBDIVISIONS OF THE STUDY AREA
SHOWN IN FIGURE 5.10
REGRESSION EQUATIONS FOR THE NINE SUBDIVISIONS

SUBDIVISION 1

\[ V_1 = 30,611,650 - 670,570 E + 3,670 E^2 \]
\[ r = 0.96 \]

SUBDIVISION 2

If \( E \) is less than or equal to (\( \leq \)) 95.00

\[ V_2 = 43,912,044 - 980,204 E + 5476 E^2, \]
\[ r = 0.98 \]

for \( E \) larger than (> 95.00)

\[ V_2 = 17,096,370 - 395,305 E + 2,285 E^2, \]
\[ r = 0.99 \]

SUBDIVISION 3

If \( E \leq 91.00 \)

\[ V_3 = 14,385,000 - 331,814 E + 1,918 E^2, \]
\[ r = 0.99 \]

for \( E > 91.00 \)

\[ V_3 = 27,752,400 - 633,600 E + 3,600 E^2, \]
\[ r = 0.99 \]

SUBDIVISION 4

If \( E \leq 91.70 \)
\[ V_4 = 19,424,606 - 449,094 \, E + 2,581 \, E^2, \]
\[ r = 0.99 \]
for \( E > 91.70 \)

\[ V_4 = 10,216,150 - 240,380 \, E + 1,414 \, E^2, \]
\[ r = 0.96. \]

**SUBDIVISION 5**

If \( E \leq 91.45 \)

\[ V_5 = 14,779,057 - 314,330 \, E + 1,849 \, E^2, \]
\[ r = 0.99. \]

for \( E > 91.45 \)

\[ V_5 = 7,015,329 - 168,837 \, E + 1,011 \, E^2, \]
\[ r = 0.97. \]

**SUBDIVISION 6**

\[ V_6 = 3,127,488 - 71,968 \, E + 416 \, E^2, \]
\[ r = 0.98. \]

**SUBDIVISION 7**

If \( E \leq 87.80 \)

\[ V_7 = 2,006,856 - 50,868 \, E + 424 \, E^2, \]
\[ r = 0.99. \]

for \( E > 87.80 \)
\[ V_7 = 7,963,684 - 191,896 E + 1,156 E^2, \]
\[ r = 0.99 \]

**SUBDIVISION 8**

If \( E \leq 90.50 \)

\[ V_8 = 22,924,160 - 536,256 E + 3,136 E^2, \]
\[ r = 0.99 \]

for \( E > 90.50 \)

\[ V_8 = 12,743,136 - 303,408 E + 1,806 E^2, \]
\[ r = 0.98 \]

**SUBDIVISION 9**

If \( E \leq 84.00 \)

\[ V_9 = 16,726,606 - 439,569 E - 2,873 E^2, \]
\[ r = 0.99 \]

for \( E > 84.00 \)

\[ V_9 = 29,890,000 - 764,400 E + 4,900 E^2, \]
\[ r = 0.99 \]
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