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9. ABSTRACT

Waterlogging and excess salinity in irrigated soils is a major impediment to increased productivity of agricultural systems in many developing countries. Removing this impediment requires a methodology for the systematic study of the nature, seriousness, and sources of the problem. This thesis attempts to develop such a methodology by drawing on existing knowledge and incorporating it into a logical investigative framework. First presented is background information in the form of a model of how agricultural water is used, followed by a description of the problems caused by waterlogging and excess salinity. An agricultural system is defined and described in terms of water delivery, water use, and removal and drainage subsystems. The general concept of water and salt budgeting is used to define data needs and to identify linkages among system components. Appropriate techniques for measuring the quantity and quality of relevant surface and ground water flows are then presented, with special attention paid to the farm water-use subsystem that is the heart of the irrigated agricultural enterprise. Finally, water and salt budgets for each subsystem and for the system as a whole are developed and presented.

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THESIS

INVESTIGATING AGRICULTURAL WATERLOGGING AND SALINITY PROBLEMS

Submitted by

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ABSTRACT OF THESIS

INVESTIGATING AGRICULTURAL WATERLOGGING AND SALINITY PROBLEMS

The world's agricultural systems will be called upon to double their production of food and fiber during the next thirty years. A primary impediment to achieving this goal is the twin problem of waterlogging and salinization of agricultural land. Removing this impediment requires a methodology for the systematic study of the nature, seriousness, extent, and sources of the problem. This paper attempts to develop such a methodology by drawing on existing knowledge and incorporating it into a logical investigative framework.

Background information on the agricultural water use model is presented and the nature of the problems caused by waterlogging and salinity is described. An investigative approach is described whereby an agricultural system is delimited and then broken down into water delivery, water use, and removal and drainage subsystems. The general concept of water and salt budgeting is used to define data needs and to identify linkages among system components.

Appropriate techniques for measuring the quantity and quality of relevant surface and ground water flows are then presented, with special attention being paid to the farm water-use subsystem which is the heart of the irrigated agricultural enterprise. Finally, water and salt budgets for each subsystem and for the system as a whole are developed and presented as a means of integrating the data collected.

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LIST OF SYMBOLS

A	A constant
A'	Cross-sectional area of flow
A_s	Bulk specific gravity of a soil
AW	Available water
b	An exponent
C	A constant
C_a	Experimental coefficient
C_b	Experimental coefficient
C_c	Experimental coefficient
C_{DP}	Deep percolation TDS concentration
C_{GW}	Equilibrium ground water concentration of TDS
C_I	Inflow TDS concentration
C_O	Outflow TDS concentration
C_{RO}	Runoff TDS concentration
C_S	Seepage TDS concentration
C_{SP}	Spillage TDS concentration
C_T	Air temperature coefficient
CEC	Cation exchange capacity
D	Inside diameter of a pipe
E	Energy available for evaporating water
E_a	Vapor transported per unit time
E_t	Evapotranspiration
E_{tp}	Potential evapotranspiration
E_{tr}	Soil surface evaporation
e	A coefficient
e_d	Vapor pressure in the atmosphere

e_s Vapor pressure at an evaporating surface

EC Electrical conductivity

EC_d Electrical conductivity of drainage water

EC_e Electrical conductivity of a saturation extract

EC_i Electrical conductivity of applied irrigation water

ESP Exchangeable sodium percentage

ET Evapotranspiration

EV Quantity of evaporation

f(u) A function of horizontal wind velocity

FC Field capacity

G Stage height

g Acceleration due to gravity

H Head

H' Net of short and long wave radiation

H_a Head measured above a flume throat

H_b Head measured at or below a flume throat

h Velocity head

h_c Cavity height below the end of a piezometer

K Hydraulic conductivity

K_c Overall crop coefficient

K_{co} Crop/stage of growth coefficient

K_s Water stress coefficient

L Crest length of a weir

L_f An end correction factor

LR Leaching requirement

n Number of items

OP Osmotic potential

p A coefficient

PET Potential evapotranspiration

PPT Effective precipitation

PWP Permanent wilting point

Q A flow quantity

Q_d Quantity of drainage water

Q_{et} Quantity of water used in evapotranspiration

Q_i Quantity of applied irrigation water

QDP Quantity of deep percolation

QI Quantity of inflow

QIA Quantity of subsurface flow intercepted by surface drainage channels

QIT Quantity of subsurface flow intercepted by surface drainage channels and natural water courses

QO Quantity of outflow

QRO Quantity of surface runoff

QS Quantity of seepage

QSP Quantity of spillage

R_s Incoming short wave radiation

r Piezometer radius

RAW Readily available water

SAR Sodium adsorption ratio

SMC Soil moisture content

SSC Salt storage change

T Mean daily air temperature

T_{FC} Transpiration at field capacity

T_x A temperature-related constant

t_i Time

TAW Total available water

TDS Total dissolved solids

TR Quantity of transpiration

UCC Christiansen uniformity coefficient

v Stream velocity

W Gravimetric water content

W_t Throat width of a flume

W_A/W_T Fraction of total available water present in the root zone

WSC Water storage change

X A horizontal distance

x_i An unknown

Y A vertical distance

y_i Water table depth below ground surface

Z Root zone depth

γ Psychrometric constant

γ_s Specific gravity of solid soil grains

Δ Slope of the saturation vapor pressure curve at mean air temperature

θ Volumetric water content

θ_{FC} Volumetric water content at field capacity

λ An empirical parameter which is a function of PET

ϕ Porosity

Chapter I

INTRODUCTION

Background

The luster of the Green Revolution has dulled and the world once again is concerned for its food supply. The 175-year-old Malthusian model of a geometrically increasing human population based on an arithmetically growing food supply has not been rendered obsolete. In fact, equipped with slightly more sophisticated mathematics and projections, it is being put forth with increasing frequency.

Malthus is no doubt correct in saying that the potential for human reproduction is greater than the potential for increasing world food production. It is equally correct to say that these two technologies will never reach a serious imbalance. At this late hour, the important question is whether this balance will be achieved through conscious, collective and individual action, or whether the age-old mechanicsms of famine and starvation will work a "death-rate solution" to the problem.

In the short run, efforts must be directed toward increasing the rate of growth of the world food supply, buying time for what, hopefully, will be a more stable balance through lowered birth rates. The fervor with which many embraced Green Revolution technology as The Solution to this problem is a revealing indicator of the intractability of the population side of the equation.

Fortunately, population growth rates and income level are not unrelated as a comparison of figures for low and high income nations will show. The exact causal relationship between these two variables is hotly debated, but it does seem likely that a rising standard of living tends to create an incentive climate in which population control measures can operate more effectively. Thus efforts to increase agricultural production, particularly in low-income, agriculturally-based nations, should help to lay the groundwork for a longer term solution while fending off the more immediate prospect of suffering and starvation.

Problem

Why did the Green Revolution fail to meet the expectations which many held for it? As recently as 1970, Lester Brown, then a Senior Fellow of the Overseas Development Council, predicted a glut of food-grains on the world market in the seventies (Brown, 1970). Reversing his field in 1974, he wrote that we are entering a period of more or less chronic food scarcity and higher prices and that the reason for this is that demand is beginning to outstrip productive capacity (Brown, 1974).

One answer to this question is that expectations were unreasonably high. Many of the constraints which have held production below projections should have been obvious in the sixties. Among these are the inadequacy of credit and extension services and the indivisibility of many of the additional inputs, such as irrigation systems, necessary to achieve high yields with the new seeds. Others, such as the seven-fold increase in fertilizer prices between 1971 and 1974, were largely unforeseeable but were nonetheless real (USDA, 1974).

Another answer, perhaps a more heuristic one, is that the introduction of any significant technological innovation changes the whole context of production. It shifts physical and social balances which, in the case of subsistance agriculture, have existed for centuries and may have social and political repercussions which far exceed, in magnitude, the primary effect.

This may well be the case with the improved seeds which sparked the Green Revolution. The skewed distribution of the resulting production increases has induced significant changes in land tenure patterns; caused civil unrest, for example, in India; and may, in the long run, result in increased unemployment and migration to already overcrowded cities because of agricultural mechanization.

The seeds, however, did what they were supposed to do, at least in a limited sense, and increased grain production for those who were in a position to employ them effectively. Eventually, however, even these producers encountered, or will encounter, some new set of constraining factors which must then be dealt with before output can rise again. This dialectic is represented schematically in Figure 1.

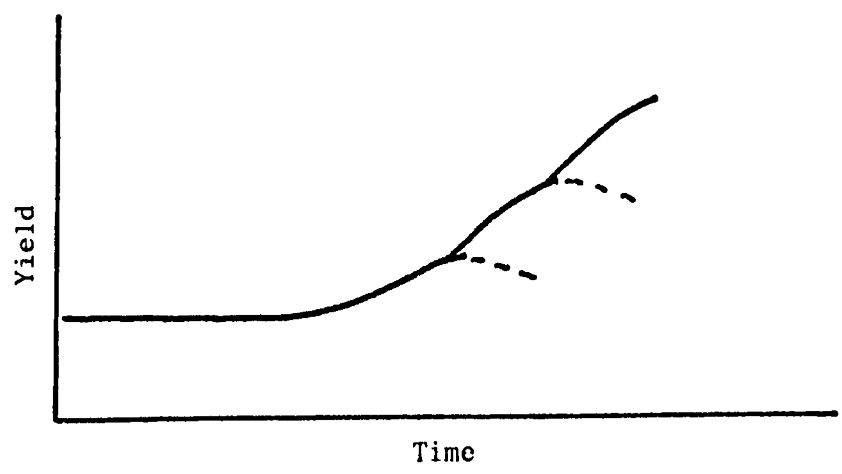

Figure 1. Qualitative Representation of Yield Versus Time.

The discontinuities on the curve may represent limitations imposed by, for example, soil fertility, cultural practices, salinity problems, or by combinations of these or other factors. This is not to say that these constraining factors must be dealt with one at a time, but simply that change causes more change and that this process continues seemingly without limit. An important implication of this is that the skills, attitudes, and institutions necessary to deal with the ever-changing context of agricultural production must be developed locally throughout the developing world.

If world-wide agricultural production is to increase to meet the growing demand placed on it, limitations must be identified and available technology brought to bear on their removal. Many of these limitations are obvious, even now, and among them are inferior seed, a shortage of chemical fertilizer, inadequate credit and extension services, a lack of appropriately-simple machinery, and unequal access to agricultural inputs in general. Others will certainly emerge in the future. Indeed, one of the most important tasks facing workers in agricultural development is the early identification of incipient limiting conditions, since, in the words of W. A. Hall (1975), the effectiveness of general goal achievement is almost directly proportional to the lead time provided.

Awareness is now growing, however, that one of the most significant limitations is not one of those mentioned above. This limitation is the non-optimal utilization of existing and potential irrigation water supplies. This is a topic included under the general heading of water management, defined by Bishop (1975) as the space-time-quantity-quality allocation of the water resource in and between various water uses to meet societal goals. In developing countries, it is the most significant aspect of the water management problem and one that must receive a substantial amount of attention if the progress initiated by the improved seeds of the Green Revolution is to continue. On one hand it is manifested by reduced yields and productive land left fallow due to a lack of water. On the other hand are the problems of waterlogging and soil salination, often caused by excessive application of water and "inadequate" drainage.

This thesis focuses on the twin problems of waterlogging and salinization of agricultural lands. These problems are not new. They have existed since the dawn of irrigated agriculture and, unchecked, have resulted in the decline of great civilizations. Today it is estimated that more than 100 million acres of irrigated land are affected by salinity problems (Reeve and Fireman, 1967).

Purpose

The purpose of this thesis is to detail a procedure for investigating waterlogging and salinity problems. Background information on the nature of the water cycle centering on irrigated agriculture and the nature of waterlogging and salinity problems is presented. The concept of water and salt budgeting is employed to identify data needs and to connect the various techniques described. The heart of the paper comprises the measuring and sampling methodology used in gathering the requisite data.

Scope

The investigation process described herein is limited to technical consideration of the nature, source, seriousness, and extent of salinity and waterlogging problems. The study draws on existing knowledge which is compiled and organized to comprise a guide of state-of-the-art techniques for carrying out these investigations. While the techniques presented have general applicability, they are keyed most specifically to arid and semiarid regions. The level of sophistication is generally limited to that appropriate for developing countries.

The technical information collected through this process is a necessary, but by itself an insufficient, base for building solutions to the problems identified. It must be taken together with inputs of complementary social, political, and economic data before solutions can be developed.

Chapter II

THE NATURE AND EFFECTS OF WATERLOGGING AND SALINITY PROBLEMS

Trends

Irrigated agriculture was first practiced five to six thousand years ago in the fertile but arid valleys of central Asia and the Middle East. Waterlogging and salinity problems probably arose at about the same time as man applied water, in trial and error fashion, to soils that were well-drained and those that were not. Eventually, great civilizations developed in this area based on irrigated agriculture. Some years later these civilizations would decline, partially at least, as a result of rising water tables and accompanying salinization of irrigated croplands.

The basic elements of this same scenario have been repeated more recently in the Punjab. In the latter half of the nineteenth century, British military engineers began building one of the largest integrated irrigation systems in the world in the fertile Indus Valley. At the turn of the century, the water table there was still 80 feet or more below the surface. Sixty years later, it had risen to within a few feet of the surface over much of the area and five million acres, or about 18 percent of the area sown, were severely affected by salinity problems (Revelle et al., 1964).

During the remainder of this century, irrigated agriculture will be asked to provide the bulk of the additional foodgrains needed to feed a burgeoning world population. Most of this additional production must come from arid and semiarid developing countries. It is here that the need will grow most rapidly. It is also here that the potential for relative increases in production with existing technology is the greatest. In absolute terms as well, this region, because of the intense solar radiation it receives and its long growing season, has the potential to achieve much higher levels of production than the grain-producing regions of the United States and Canada.

In attempting to realize these potentials, it will be necessary for farmers to turn to such practices as multiple cropping, intercropping, higher planting densities, increased fertilizer usage and expanded use of improved seed. In addition to increasing production, all of these practices will tend to increase the use, reuse, and misuse of irrigation water increasing the need for improved on-farm water management practices. In the following section, we will explore, in general terms, the implications of agricultural water use and reuse for waterlogging and salinity problems.

The Agricultural Water Use Model

The hydraulic regime of a river flowing through a section of an irrigated agricultural valley is shown schematically in Figure 2. This model is a general one and is as applicable to the ancient systems on the Tigris-Euphrates as it is to present-day Colorado River irrigation. Such special situations as conjunctive use of ground and surface waters and interbasin transfers may alter the model somewhat, but do not change qualitatively, the components of the flow diverted for agriculture.

It is important to realize that the upstream river flow shown in the model may itself be composed of agricultural and municipal/industrial return flows. The sequence shown may be repeated many times from the headwaters of the river to its mouth. On the Sevier River in Utah, for example, there are numerous diversions, seven of which take

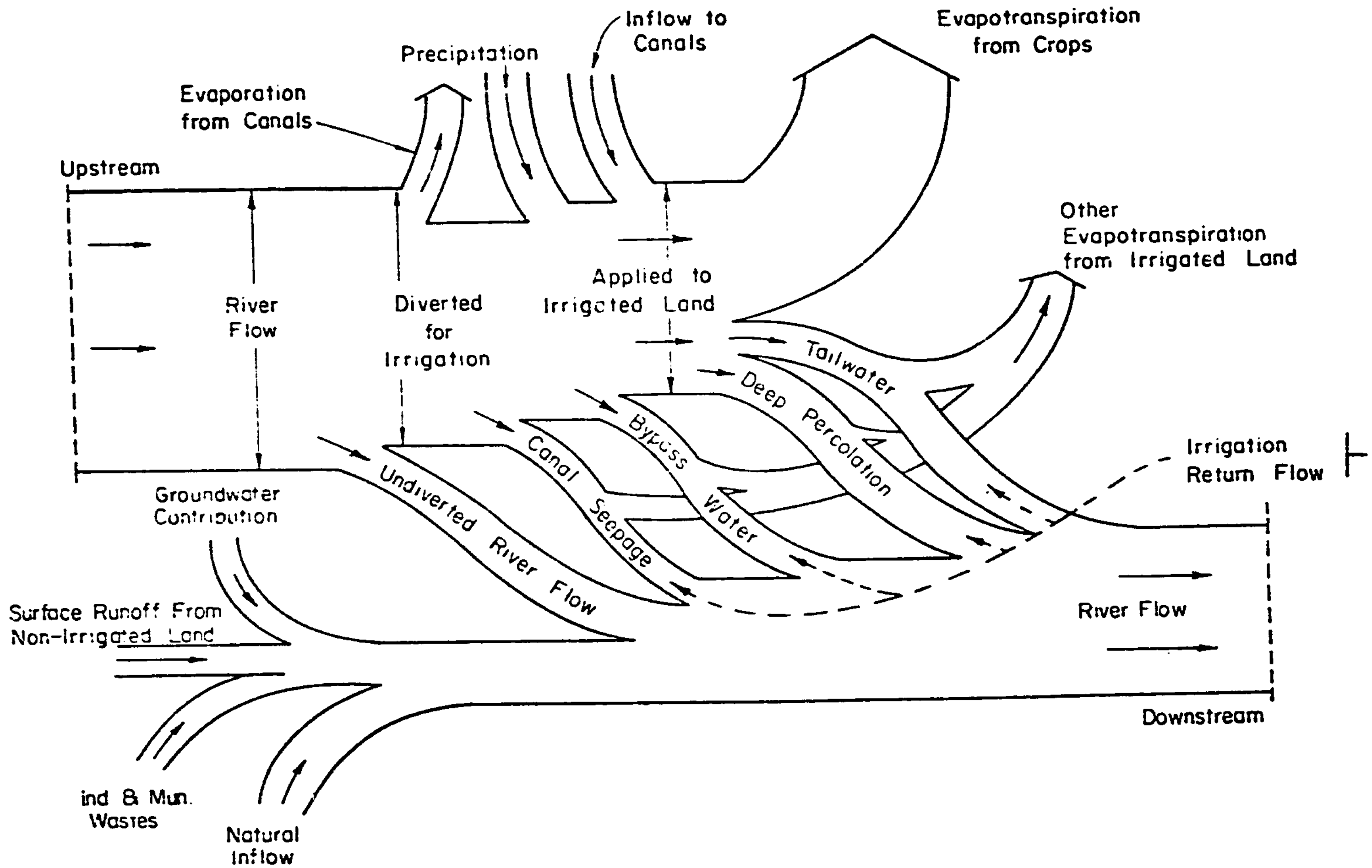

Figure 2. The Agricultural Water Use Model (from Skogerboe and Law, 1971).

the entire flow of the river at the point of diversion (AAAS quoted in USUF, 1969).

Surface Flows

Of particular interest is the irrigation return flow system comprising canal seepage, bypass water, deep percolation, and tailwater. Of these four components two-tailwater and bypass water-constitute surface flows.

Tailwater is water which is applied to a field and flows over its surface but does not enter the soil profile. It is returned, via natural or artificial drainage channels, to the river. In the process it may acquire increased amounts of pesticides, fertilizer elements, sediments and organic debris, but its concentration of dissolved solids, or salts, will usually increase only slightly (USUF, 1969).

Bypass water is water which flows through the canal system but is not applied to the fields. Its purpose is to maintain adequate head and flow volume through the canal system and is usually returned directly to the river. As a result, it is little changed in composition and, while unavailable for irrigation use in the system under consideration, its quality is unimpaired for use downstream.

To the extent that bypass flows move in unlined channels after entering the drainage system, they may also contribute to deep seepage. The amount of this seepage, however, is a small fraction of a small fraction and is usually inconsequential.

Sub-surface Flows

The two remaining components do enter the soil profile and, as a result, their behavior is much more complex. Canal seepage is water that infiltrates through the canal perimeter and enters the groundwater flow regime. Deep percolation is water applied to fields which is in excess of the amount that is capable of being stored in the upper levels of the soil profile comprising the plant root zone. It moves downward below the root zone and enters the groundwater region.

As will be described in Chapter IV, some of this deep percolation is beneficial and indeed necessary if agriculture is to be practiced on a permanent basis. Nevertheless, both canal seepage and deep percolation flows are additions to ground water and cause the water table to rise. If this rise approaches the vicinity of the plant root zone, waterlogging may result. In addition, high water tables encourage the growth of phreatophytes and may displace saline water from the groundwater aquifer into streams and rivers creating problems for downstream users.

Irrigation drainage water which has moved through the soil undergoes a more significant change in composition than do the surface return flows. Most important is the increase in concentration of dissolved solids as discussed in the following section. Proportions of the various ions will also change, with a likely increase in the proportion of sodium and chloride ions. Colloidal or sediment material will be filtered out and the amount of degradable pesticides, detergents, chlorinated hydrocarbons, organic material, and bacteria will be reduced (USUF, 1969).

Evapotranspiration

All of the flows discussed thus far, however changed in composition, are available for further use, either locally through pumping, or by gravity flow to downstream users. A large share of the water diverted for irrigation, however, is lost to all users through evapotranspiration.

Evapotranspiration, or ET, is the process whereby water is changed from a liquid to a gaseous state through the addition of energy. The term itself is a combination of "evaporation" which denotes the vaporization of water at water and soil surfaces, and "transpiration" which refers to water taken up through the roots of living plants and released as vapor from plant surfaces.

The largest portion of the evapotranspiration component comes from irrigated fields of agricultural crops. This is a combination of water transpired by the crop, water transpired by natural vegetation and phreatophytes, and water which evaporates directly from soil or water surfaces within the perimeter of the field. Additional amounts of water are lost as evaporation from water surfaces in canals and drainage channels outside the boundaries of the field and through consumptive use by phreatophytes along conveyance and drainage channels.

Water which has infiltrated into the soil can also undergo evapotranspiration through the mechanism of capillary rise. This effect, which is caused by the interaction between water and the surfaces of soil particles, can cause limited soil water movement in any direction within the soil profile. When this movement is upward, soil water may come within the reach of plant roots and be transpired or it may reach the ground surface and evaporate.

The overriding significance of this is that when water is lost to the gas phase of the system, any dissolved solids present in the water are left behind. This increases the concentration of the dissolved solids in the remaining liquid. Thus, water applied to fields inevitably becomes "saltier" as portions of it are used consumptively.

The important connection between high water tables and salinization should be noted here. The two are linked by the phenomena of capillary action mentioned earlier. Because of it, water may rise above the water table from a few inches in coarse gravel to several feet in silty clay. If the water table is closer than this distance to the surface, evaporation and deposition of salts will result. Since groundwater is often more saline than the applied irrigation water, the problem becomes doubly serious. Whether or not water table depth and soil salinity are problems is a function of the tolerance limits of the crops being grown. The nature of these limits will be discussed in the remainder of the chapter.

The Effects of Waterlogging on Agriculture

Taken literally, waterlogging refers to soil that is permanently saturated with water. As commonly used, however, it also applies to instances of temporary saturation and to situations where the permanent water table is high enough to reduce significantly the amount of air-filled pore space in the root zone. Because we are concerned with the effects of waterlogging on agriculture, we can reference the problem to crop yield and define it as the presence of excess water in the root zone in amounts and over times that are sufficient to reduce crop yields perceptably.

In arid regions, waterlogging is normally accompanied by soil salinization as water evaporates from the ground surface leaving behind its cargo of salts. The effects of these two problems are difficult to separate out, and practically this is often unnecessary as the solution to one problem is the solution to both.

There are, however, exceptions. Where there are high groundwater tables but good leaching, salinity may not be a problem. A number of irrigated oases in North Africa fall into this category (FAO/UNESCO, 1973, p. 263). Such high water tables may, in fact, supply a portion of the crop water need through capillary rise. On the other hand, in situations where there is a continuous flow of fresh groundwater through a permeable sub-soil, waterlogging problems may exist alone.

Waterlogging effects are felt through the plant root system. The root system occupies a volume of soil roughly equivalent to the volume of the above-ground plant parts. It serves to physically support the plant, and as an entry point for water, nutrients, and oxygen. The roots also release carbon dioxide, an end product of plant metabolism, into the soil. The presence of excess water in the root zone affects the plant in three basic ways; through its influence on gas diffusion, soil microflora, and soil temperature.

Effects on Gas Diffusion

While non-aquatic plants may take in some O_2 through above-ground plant parts, the bulk of the oxygen requirement must be met by uptake through the roots. Oxygen must thus move by diffusion from the atmosphere through the soil profile to the vicinity of the roots. Exceptions to this are aquatic plants, such as paddy rice, which have the ability to take in oxygen through above-ground plant parts and transport it throughout the plant.

Diffusion may take place either in air or in water and both processes are governed by the same equation. The rate of diffusion in water, however, is slower by about four orders of magnitude. Therefore the existence of continuous channels of air-filled pore space connecting the soil surface with the various regions of the root zone is necessary for adequate aeration.

The roots themselves are surrounded by a thin film of water and oxygen passing through the semi-permeable membrance of the root does so in aqueous solution. If the thickness of this water film around the root is larger than some small value, however, an oxygen deficiency will result. Clark and Kemper (1967) give a value of from 0.1 to 0.5 mm for this critical thickness.

One of the first effects of waterlogging to be felt by the plant, therefore, is a reduction in respiration. As a result, root growth is arrested, water and ion uptake are decreased, and fluid transport within the plant is inhibited. An excess of CO_2 in the vicinity of the roots exacerbates these effects but because of its high solubility in water, this is seldom a problem in practice (Wesseling, 1974).

Effects on Microflora

All soil supports populations of microflora which may exert both harmful and beneficial influences on plants. In well-drained soils this population is composed largely of aerobic organisms which fix atmospheric nitrogen and mineralize organic material in the soil into forms of N useable by plants. Under conditions of prolonged water-logging, these aerobic organisms are replaced by anaerobic forms with the result that nitrogen fixation and mineralization are greatly reduced. Additionally, nitrate and ammonium ions already present in the soil may be decomposed into forms which are unavailable for plant use. Anaerobic organisms also may produce compounds, such as sulfides and butyric acid, which are extremely toxic to plant growth. The effect of these changes will not be felt as quickly as a reduction in root respiration, but over longer periods of time they will contribute to the reduction in growth and even the death of agricultural plants.

Effects on Soil Temperature

The heat capacity of a soil is the sum of the capacities of its components; soil, air, and water. Since the heat capacity of air is negligible and that of water quite large, replacement of air in the soil by water will increase the capacity of the soil mass considerably. The result is that more solar energy is required to raise the temperature of wet soil than of dry soil. Additionally, since evaporation is greater from wet soil, more energy is required for this process. These factors can keep wet soils colder than dry ones during cold to warm seasonal changes.

Indirectly, cooler soil temperatures influence the availability of nutrient elements in soil, soil moisture relations, and water uptake. As might be expected, physiological processes are more strongly temperature-dependent than physical ones. Germination, emergence, and early growth stages are affected significantly. Walker (1969) indicates that in early growth stages, growth rates may be decreased by as much as 39 percent as a result of a one degree Celsius temperature drop. At the other end of the growing season, this may lengthen the time of crop ripening by several weeks.

In climates where evaporation exceeds precipitation, and where temperatures are reasonably uniform year around, the effect of water-logging on soil temperature is greatly reduced. It may become a significant factor, however, if a second or a third crop is added during a cooler season.

The Effects of Salinity on Agriculture

The mechanism by which saline soil water solutions affect plant growth is not well understood. While there is convincing evidence that the soil solution is the best expression of the soil chemical environment that immediately governs plant response (Pearson, 1971), there is disagreement over the relative importance of toxicity and osmotic effects. American authorities, led by Bernstein, generally hold that osmotic effects are the more important. Others argue that, in the usual case, toxic effects of the various specific ions such as chloride are more significant. Experimental evidence shows the existence of both. In the following discussion, the osmotic effects will be given prominence reflecting the viewpoint of available literature and the spirit of Occam's theorem on simplicity.

Toxicity

Almost any salt present in excess quantities may be termed toxic. It is better to use this term only in reference to those ions that cause characteristic and acute plant injury (Bernstein, 1964). The most common occurrence of this effect is the sensitivity of many woody plants, including fruit crops, to sodium and chloride ions. While rootstocks show wide variability in their willingness to take up these ions, those that do so most readily may be adversely affected by concentrations as low as 5 milliequivalents/liter in the soil water saturation extract (Bernstein, 1974).

Field, forage, and truck crops do not exhibit this extreme sensitivity to sodium and chloride, but are affected by other ions. Boron is an often-mentioned example. This is probably because of the extremely narrow range of acceptable concentrations of this important trace element. While a concentration of about 0.2 to 0.5 mg/liter is required for optimum plant growth, increasing this by several fold may damage the plant (Wilcox, 1960). A number of other ions such as lithium and selenium can prove toxic to plants at low concentrations but the reaction of different plant species to all of these ions is highly variable. In addition, many of the ions are held very strongly by the soil and it may be a matter of decades or even centuries before appreciable harm occurs to plants. This problem, while important in specific situations, is not one that is generally and necessarily associated with salinity problems.

Nutritional Imbalance

Plants require a balanced diet of nutrients to maintain optimal growth. That balance may be disturbed by the influx and root zone storage of salts carried by irrigation water. Thus, for example, a high concentration of calcium ions in the soil solution may prevent the plant from absorbing enough potassium to meet plant requirements even though sufficient potassium may be present in the soil solution. Frequently, however, an ion present in excess may have 10, 100, or even 1000 times the concentration of other ions essential for growth. Under these circumstances, it is remarkable that nutritional effects occur as infrequently as they do (Bernstein, 1961).

Because plants vary widely in their nutrient requirements and in their ability to absorb specific nutrients, the effects of salinity on nutrition vary markedly from species to species. At a given level of salinity, however, growth and yield are depressed more when nutrition is disturbed than when it is normal (Bernstein, 1965). These effects are easy to demonstrate under experimentally controlled conditions.

Under field conditions, however, where a mixture of salts is usually present, nutritional imbalance is usually a minor consideration (Bernstein, 1974).

Osmotic Effects

The most serious and common problem associated with agricultural salinity is the result not of an individual ion or combination of ions, but of the total amount of dissolved solids occurring in soil water. The quantity of such dissolved solids determines the osmotic potential of the soil water which is the key determinant of plant response to salinity (Bernstein, 1974).

Since a growing plant must expend energy in removing water from the soil water reservoir, it is useful to look at the energy with which that water is held in the soil. This energy is termed soil water potential and is defined by the soil physics committee on terminology for the International Society of Soil Science as follows (Aslyng, 1963).

> "The amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water (at the point under consideration)."

Since energy must be added to soil water to restore it to its reference state, its potential energy is said to be negative.

This total water potential can be divided into four parts to distinguish the four different force fields acting on the water. They are: (1) the matric or capillary potential which results from the interaction of soil particle surfaces with water, (2) the osmotic potential which results from the solutes dissolved in the soil water, (3) the gravitational potential which results from elevation with respect to the reference level, and (4) the pressure potential which results from external pressure on the soil water. The algebraic sum of these component potentials must always equal the total water potential (FAO/UNESCO, 1973).

Potential can be measured in terms either of energy per unit mass or energy per unit volume. The latter is most commonly used, in which case potential has the units of ergs/cm^3. Since dimensionally, this is equivalent to pressure and since 10^6ergs/cm^3 is numerically equal to a bar pressure, water potential can be expressed in bars if desired. Since one bar pressure equals 0.987 atmospheres, these two units are approximately equal.

To avoid the use of negative quantities for the expression of soil water potential, the term soil sunction is often used in reference to a plant-soil-water system. The reference state used here is a pool of pure water at the same elevation as the soil water and separated from it by a semipermeable membrane. Suction is defined as the negative gauge pressure which must be exerted on the pure water to achieve equilibrium with the soil water. It is the sum of the osmotic and matric potentials and, if volume units are used, the components are identical with those in the previous definition except for algebraic sign. This is an exceedingly useful definition of the concept since the pressure potential in unsaturated soils is usually considered zero, and the gravitational potential involved in moving across the semi-permeable membrane of the plant root is negligible.

These two components then, the osmotic and matric potentials are the critical ones in governing plant uptake of water. Their effects are additive and are shown for a typical case in Figure 3.

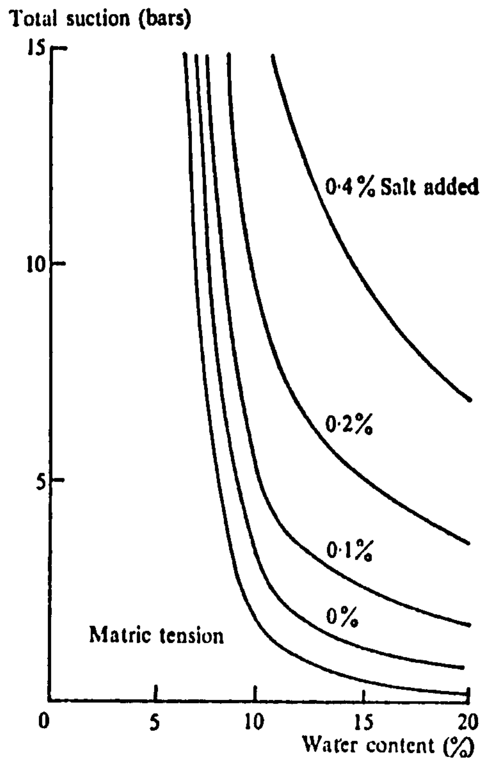

Figure 3. Matric Suction and Total Suction for a Soil to Which Various Quantities of NaCl have been Added (after FAO/UNESCO, 1973).

In this example sodium chloride was added to the soil water, although different salts or combinations of salts would show the same effect. The result is that the energy required to withdraw water from the soil reservoir increases with increasing salt concentration, and eventually exceeds the plant's ability to do so.

The resultant water stress on the plant is evidenced by retarded growth, smaller plants, and fewer and smaller leaves (which may have a darker green or bluish-green color than usual). Crop plants generally show a progressive decrease in growth rate and size with increasing salinity although fruit and seed yields may or may not parallel vegetative growth. Crop yield reductions shown wide variability both among crops and growing conditions and this area is the subject of continuing research efforts.

Sensitivity to soil water salinity at different plant growth stages has also received much attention from plant scientists. Formerly it was thought that the germination stage was much more salt sensitive than later growth stages. However, salt accumulation at seeding depth is often much greater than at lower levels in the soil profile, especially in arid regions where ET rates are high. It is now felt that, considering actual ambient salinity, the germination stage is, in general, no more salt sensitive than later growth stages (Bernstein and Hayward, 1958).

Seedling stages, up to the four-leaf stage, of grains such as wheat, barley, and rice are, on the other hand, more salt sensitive than either germination or later growth stages (Bernstein, 1974). For this reason and the one given above, particular attention should be given to the salinity of the upper levels of the soil profile early in the growing season for these important food grains.

For other plants, a number of different stage sensitivities have been noted. These include tillering and, particularly, the flowering stage. These sensitivities must be examined for particular crops and growing conditions.

Effects on Soils

Soils containing significant clay fractions can be affected severely by particular mixtures and concentrations of salts. The result is a loss of soil structure and impairment of water movement through the soil as measured by both infiltration rate and hydraulic conductivity. This restricts the movement of irrigation water into and through the root zone and also makes leaching of the affected soil difficult.

The reason for this behavior can be traced primarily to the crystalline structure of the clay minerals in the soil. Chemically hydrous aluminum silicates, they are characterized by a plate-like crystalline structure with the individual plates stacked together in parallel fashion. Because of their enormous specific surface area, they have a significant ion exchange capacity or ability to hold charged particles on their surfaces. Since the clay platelets themselves acquire a negative charge in the presence of water, they attract and hold positively charged ions or cations. The composition of the set of cations held or adsorbed on the ion exchange complex varies according to the chemical and physical properties of the solution surrounding it.

This process in itself is not harmful. It is, in fact, essential to plant growth in that it is the mechanism by which nutrient minerals are held in available form. However, when a significant portion of the exchange capacity becomes occupied by sodium ions, say 10 to 20 percent, the clay platelets tend to swell and, eventually, to disperse. Pore space is diminished and permeability is greatly reduced.

Fortunately, even with a high exchangeable sodium percentage, swelling is inhibited by the presence of cations other than sodium in the soil water solution. This is particularly true for divalent cations such as calcium and magnesium which are more strongly bound to the exchange complex than is sodium. Thus the effects of a saline soil water solution on a particular clay soil depend principally on two factors. The first is the ionic composition of the soil water. The second is the total concentration of dissolved solids in the solution. In general, half or more of the soluable cations must be sodium before significant amounts are adsorbed by the exchange complex (Richardson et al., 1954).

Clays vary widely in ion exchange capacity and in the degree to which they exhibit swelling and dispersion. Of the three main types of clays, the montmorillonite group has the largest ion exchange capacity, on the order of 80 to 100 milliequivalents (me.) of cation per 100 grams of dry clay, and swells most seriously. In the kaolinite group, ion exchange capacity is on the order of 5 to 10 me. per 100 grams of clay and swelling is least serious. The illite clays are intermediate (Childs, 1957). Montmorillonite and illite are most commonly found in arid regions (Richardson et al., 1954).

Organic materials in the soil profile also possess ion exchange capability. Their dispersion under high sodium, low salinity conditions results in the "black alkali" or "slick spots" common to sodic soils. To date, however, no definitive evidence links the dispersion of organic materials to decreases in water penetration or increases in dispersion of mineral particles in sodic soils (McNeal, 1974). Arid region soils are typically low in organic material anyway, and in these regions, clays are by far the most important component of the ion exchange complex.

In practice, it is not sufficient merely to look at the concentration and composition of the applied irrigation water and the ion exchange capacity of the soil in question. Weathering of soil minerals and solution of fossil salt can release additional ions into the soil water solution. Evaporation from the soil surface and transpiration by plants remove almost pure water from the solution and increase its concentration. When this occurs, slightly soluble compounds such as the alkaline-earth carbonates and evaporites may precipitate out of solution increasing the relative concentrations of the remaining ions.

This precipitation can be used beneficially to reduce the salinity of return flows if sodium is not a problem. Bower suggests leaching with the smallest volume of water consistant with no significant salinity damage to crops. This maximizes the concentration of salts in the drainage water and hence the precipitation of harmless salts such as calcium carbonate and gypsum while minimizing sub-surface salt pick-up (Bower, 1974).

Attempts have been made to build theoretical models of the precipitation of minerals within the soil profile (Dutt and Tanji, 1962; Oster and McNeal, 1971; Tanji et al., 1967). However, the reactions involved are extremely complex, depending not only on the concentration and cation composition of the soil water solution, but also on its pH, dissolved CO_2 content, temperature, and anion composition. Consequently such models have not yet found wide use in the field.

Associated with the problem of swelling and dispersion in clay soils is that of surface crusting. In arid regions, substantial quantities of salts are transported upward by water evaporating from the surface, resulting in high salinity concentrations and exchangeable sodium levels there. When water is subsequently applied to the surface as irrigation water or rainfall, these surface salts leach readily. The exchangeable sodium percentage, however, decreases less rapidly than does the total salt concentration. The resulting high sodium, low salt condition tends to cause dispersion at the surface and, aided by mechanical disturbance of the surface by wind and water, a rather dense crust may form. Some seedlings may be unable to penetrate this crust and a poor crop stand will result.

Chapter III

AN OVERVIEW OF THE TECHNICAL INVESTIGATIONS

Goals and Scope

Having described, in general terms, the nature and effects of agricultural waterlogging and salinity problems, we must consider a methodology for investigating suspected specific occurrences of these problems. Since the purpose of this paper is to lay out such a methodology rather than to detail solutions, this methodology will provide a matrix for the investigative techniques comprising the remainder of the paper.

The exact form a technical investigation of waterlogging and salinity problems will take depends on the goals set out by the sponsors of the research. It is assumed that the usual goal generating such studies will be framed in terms of increasing national or regional agricultural productivity. This goal may, in turn, be subsumed under a broader goal of national economic development. It is assumed also that the causes of the waterlogging and salinity problems are found in the same geographical location as are the problems. If this is not the case, the problem becomes one of spillover effects and the investigations will take a related but somewhat modified form.

The scope of the study effort depends on the severity and areal extent of the problems, the degree to which the causes of the problem are known, the extent of previously collected data, and the resources available for conducting the research. Investigations of any size will usually proceed in several stages. The first will be a reconnaissance survey, collecting existing information and seeking to define the goals and scope of the investigation. Based on an understanding of the goals and the findings of the reconnaissance investigation, a tentative model would be developed to specify data collection needs and to pinpoint linkages within the system which need to be examined. This would be followed by an input-output analysis and more detailed water budget studies. Following data collection and analysis, the model can then be used to extrapolate the findings of the study to larger regions.

Because problems of waterlogging and salinity are usually collective rather than individual in nature, a study restricted entirely to individual fields or farms is of limited value. Where these problems exist, they have occurred because of the actions of a number of cultivators over a broad area. A study of the problems must include a similarly broad area to reach valid conclusions. This is not to say that investigations of sample areas cannot be extrapolated to a large region. However, the dynamics of water and salt movements through the entire region must be considered in the final budgeting process. It follows that corrective action must be taken by this same group of cultivators whose collective actions resulted in the problems.

Solutions to waterlogging and salinity problems will seldom be functions of a single variable and may have unintended or undesirable side effects. Investigations should be sufficiently detailed to provide an understanding of intra-system interactions. They should produce sufficient information to allow evaluation of the effects of change in a single system element on the problem objective and to predict unintended consequences. In this point, the methodology differs from that of a simple design investigation where the purpose is to develop design parameters for a particular solution technology.

The System

Delimitation

In defining the extent of the system to be studied, care must be taken to minimize input and output flows across the system boundary. This is most important in the case of difficult-to-measure flows such as groundwater movement into and out of the system. The size of the system considered depends on the nature, extent and homogeniety of the problem area and on the resources which can be devoted to the investigations.

The word "system" is used in two different contexts throughout this paper. Most formally, a system is a set of elements, distinguished from the surrounding environment by a system boundary, which interact in a regular and independent manner (after Hall and Dracup, 1970). When used with a modifier, e.g., an "irrigation system," it denotes elements commonly thought of as working together to execute a particular function.

It must be recognized that objects or elements may comprise parts of a number of different systems, depending on how each system is defined. System outputs in the context of this paper will commonly comprise inputs to other systems in the region. The quality of irrigation return flows, for example, can be ignored once the flows have left the system under consideration. Water quality may be of great concern, however, to downstream users of that water. Since it is often impossible to draw system boundaries in such a way as to contain these effects entirely within the system, it will usually be necessary to impose somewhat arbitrary constraints on the quality or quantity of flows leaving the system. This problem of external or spillover effects is a thorny one and can be expected to become increasingly intractable as more intensive resource use occurs.

One problem of special concern in setting system boundaries is that of the closed or semi-closed groundwater basin. Just as surface drainage systems must be adequate to carry away natural runoff and field tailwater, sub-surface drainage systems must be capable of removing deep percolation flows to some external sink.

If the groundwater basin containing the agricultural system is closed, or nearly so, problems will inevitably result. More precisely, if the natural groundwater outflow is small compared to the minimum deep percolation flows necessary for adequate leaching, water tables will rise inexorably and the practice of agriculture on a long-term basis will be impossible. If groundwater is pumped to lower the water table and meet a portion of the crop ET requirement, the salinity of the groundwater will increase and eventually the water will become too saline for use.

A problem arises if the system to be studied is chosen to include only a part of such a closed groundwater basin. If the closed nature of the entire basin is not obvious and a steady-state drainage flow regime is then assumed, attractive but false results will be obtained.

Subdivision

In order to make detailed water budget studies of the system, it is helpful to divide the system into smaller units or subsystems. Again, the principal of minimizing interconnections applies. For conceptual purposes at least, it is usually most convenient to divide the system into a water delivery subsystem, a water-use subsystem, and a drainage and removal subsystem. During the actual modeling and computational stages, it may be advantageous to modify this scheme somewhat. Calculating ET from crops and phreatophytes together, even though water use is from different subsystems, might be an example.

The Model

The model employed is based on mass balance principals and accounts for flows into and out of a system or subsystem and the changes which occur within the system. The principal budget employed in the model is the water budget, since salt flows occur as dissolved constituents in the water flow regime. Salt flows are accounted for by multiplying the appropriate water flow by the concentration of dissolved solids which it contains.

Inputs to and outputs from the three major system components are shown in the following outline. These are the water flow quantities which must be measured, either directly or indirectly, to meet the data requirements of the model. The salt flow model is analogous and requires the measurement of the concentrations of dissolved solids in the respective water flows. Storage changes are discussed in the more detailed explanation of the water and salt budgets in Chapter VII.

1. WATER DELIVERY SUBSYSTEM
   - 1.1 Inputs
     - 1.11 Inflows to canal system
     - 1.12 Precipitation
   - 1.2 Outputs
     - 1.21 Seepage
     - 1.22 Evaporation
     - 1.23 Spillage
     - 1.24 Delivery to farm water-use subsystem

2. FARM WATER-USE SUBSYSTEM

2.1 Inputs

2.11 Irrigation water deliveries

2.12 Precipitation

2.2 Outputs

2.21 Evapotranspiration

2.22 Field tailwater

2.23 Deep percolation flows

2.3 Storage Changes

3. DRAINAGE AND REMOVAL SUBSYSTEM

3.1 Inputs

3.11 Spillage from canal system

3.12 Surface runoff

3.13 Deep percolation flows

3.2 Outputs

3.21 Outflows to sink

3.22 Phreatophyte evapotranspiration

3.23 Outflows across system boundary

3.3 Storage Changes

The Investigations

Before actual field studies are begun, it is advisable to collect and analyze relevant existing data. This may help to define the scope of related field investigations and to avoid duplication. Examples of data which should be sought are maps and recent aerial photography, drillers' logs, reports on surface and subsurface geology, climatological data, streamflow records, land use data, and agricultural and agronomic information.

The time frame and scale to be used should also be determined in advance. Data acquisition should cover at least one cropping season with several seasons being desirable. A commonly used time step for water budgets is one month.

The following three chapters discuss individually the three subsystems mentioned above. The farm water-use subsystem is treated first as its importance is paramount. In each chapter the subsystem is defined and described. The flows which must be measured, both quantitatively and qualitatively, are noted and measurement procedures described. Since a detailed description of laboratory analytic procedures for water quality determination is beyond the scope of this paper, only sampling for analysis is indicated.

Chapter VII discusses the integration of the data collected into meaningful results. Measures of the nature, seriousness, and areal extent are discussed first. The system as a whole is then considered in an input-output analysis. Finally water budgets for the three individual subsystems are developed. Chapter VIII is a summary of the problems, procedures, and techniques discussed in the paper.

Chapter IV

THE FARM WATER-USE SUBSYSTEM

Description and Boundary Definition

The farm water-use subsystem is the core of the entire irrigation enterprise. Other system elements exist solely to permit the practice of long-term irrigated agriculture here. This subsystem comprises all land within the overall system on which irrigated agricultural crops are grown and extends downward from the ground surface to the bottom of the root zone.

In examining waterlogging and salinity problems, it is crucial to gain an accurate understanding of the fate of all water entering this subsystem. Water enters as irrigation applications and precipitation and may then exit via ET, deep percolation, or surface runoff; or it may be stored in the soil profile.

Because of the complexity of this undertaking, it is impossible to study these interactions over the entire study region. Instead, intensive studies are made on a small number of fields and the results extrapolated to the system as a whole. This implies the need for an accurate and comprehensive knowledge of the land use pattern for the entire system. It means also that the fields intensively studied must be sufficiently representative to allow extrapolation.

Since accurate meteorological data are necessary for the ET and water input portions of the farm water budget, a weather station should be established on the site of the farm-use subsystem prototype. The station should include a rain gage, maximum and minimum thermometers, an hygrometer, a solar radiation gage, and an anerometer. Additional equipment might include a water table lysimeter and a class A evaporation pan.

Measurement of Inputs to the Farm-Use Subsystem

For a number of reasons, it is necessary to make a more precise accounting of water and salt flows for the farm-use subsystem than was made for the delivery subsystem. First, the quantities are smaller per unit of land, but small errors on the intensive study croplands, when extrapolated, have greater significance. The physical phenomena occurring in the root zone with time are fairly complex, even on a single field, thereby complicating the development of accurate water and salt budgets. Finally, ET and deep percolation, which are significant components of the farm water-use subsystem water budget, are determined indirectly and may have substantial uncertainties associated with them.

Irrigation

The most important component of water and salt inputs to the subsystem comprises inflows of irrigation water. For the purposes of analysis, water enters the farm-use subsystem when it leaves a lateral or canal serving a number of fields and is applied to cropland. Such applications will be intermittent and will depend on such factors as rate of crop ET, the storage capacity of the root zone, water turns, and the availability of labor.

Water applied must be measured accurately. However, because of the large number of possible combinations of irrigation, head, and available equipment, it is difficult to prescribe specific methods of measurement. For the most common case in arid developing regions, that of basin irrigation from an unlined open channel, flumes placed at the points of release from the canal should work well. In other situations, v-notch weirs or closed conduit measuring devices may be more appropriate.

It can often be assumed that water quality is little changed from that of the river at the point of diversion, but this assumption should be validated. If there are significant return flows entering the distribution canal above the farm turnout, water quality may be substantially changed and continuous monitoring of inflows at the turnout may be necessary.

Precipitation

Precipitation falling during the period of the water budget study may also constitute a significant input of water to the farm-use subsystem. Because it contains an extremely low concentration of dissolved solids, however, its salt contribution can be ignored. The farm study area must be equipped with a rain gage to determine the amount of precipitation entering the farm subsystem.

It may not be correct, however, to consider the contribution of precipitation to the water budget in full. If the precipitation event is of low intensity, producing no runoff, and does not wet more than the top inch or two of soil, two possible conditions may result. If the precipitation has occurred during mid-summer weeks when the crop has achieved full cover and is amply supplied with water, the rate of ET may be limited by the amount of solar energy available for vaporization. In this case it would be correct to include the entire amount of the event as a water input, since ET from soil and leaf surfaces will be reduced by an amount equivalent to the amount of precipitation. Early in the growing season however, when ample energy for vaporization is available and the rate of ET is limited by the available leaf area, a low intensity rainfall event will increase the actual rate of ET by some amount not accounted for by the predictive ET equation. The result is that the precipitation received need not be included in the water budget calculations and may be regarded as an essentially separate account.

If the intensity and duration of the precipitation is sufficient to cause runoff from the field and to wet a significant fraction of the root zone profile, most, if not all, of the water received must be accounted for. The same comments made above, however, do apply to the upper few inches of the profile and to wetted leaf surfaces.

The decision as to what portion of a particular rainfall event to consider in budget calculations can be made judgementally on a case by case basis. Alternatively, an arbitrary fraction of all precipitation received during the budget period may be considered. Skogerboe et al. (1974) chose a figure of 75 percent in their study of the Grand Valley.

Evapotranspiration

Of the water which is used consumptively within the farm subsystem, by far the largest portion is released to the atmosphere as water vapor by plant, soil, and water surfaces. Another component is utilized in metabolism and growth, although in all common circumstances this is an insignificantly small amount. The sum of water transpired by the plant, evaporated from adjacent soil and water surfaces, or evaporated from the surfaces of leaves of the plant, then, comprises evapotranspiration (Hansen, 1963).

Operational definitions of ET usually speak of the amount of water evolving from a fully vegetated surface which is amply supplied with water. A commonly used reference crop is alfalfa with 12-18 inches of top growth. This is a potential ET (PET) rate that is not always reached in actual practice. It implies a dependency on (1) climatological factors, and mentions explicitly dependencies on (2) the type of crop being grown and its stage of growth, and (3) availability of water to the crop. These three groups of variables will be dealt with in more detail in following sections.

Transpiration, far from being a wasteful loss of water from the system, is a vital plant process that permits the absorption of CO_2 to occur in small pores on the undersides of leaves. Since these small, moist pores must be open to the atmosphere to permit the gas assimilation process, evaporation from the pores to the atmosphere is a necessary concomitant. The means whereby the liquid water is changed to a vapor and released to the atmosphere is simply an evaporative process and, as such, is subject to the physical laws governing evaporation from an open water surface.

An important difference is that where a small area of water surface will have a specific evaporation rate that is easily extrapolated to nearby areas, a small volume of a vegetated surface (the plant surfaces must be considered in three dimensions) will be composed of moist plant surfaces, dry vegetative material, and air. In addition, since transpiration is a function of a living plant, plant-related seasonal and diurnal fluctuations will be superimposed on meteorologically-induced variations in transpiration rate. Relations describing this process are thus semi-empirical in character.

Practically, however, these difficulties are less serious than they at first seem. By combining appropriate empirical coefficients with some measure of evaporation, good predictions of ET over both the short and long run can be made.

Pan Evaporation

The evaporation pan provides a means of measuring evaporation rates directly. Several standard pan designs have evolved and are regularly used by different organizations engaged in collecting meteorological information. Essentially, pans provide a known water surface area from which evaporation can take place and a means to accurately measure water depth, and hence volume of water evaporated, over a given length of time.

Pans integrate all of the variables involved in the evaporation process into a single measurement and are quite accurate when used to indicate evaporation over a period of a month or a season. Because the mass of water in the pan is subject to substantial response lags, however, pans are not suitable for estimating ET on a daily or a weekly basis (Hart, 1975).

Furthermore, because of differing rates of heat storage and exchange, a correction coefficient must be applied to pan evaporation to relate it to evaporation from a larger natural body of water or transpiration from a crop. This coefficient is strongly influenced by the size and type of pan, its placement above or in the ground, vegetation surrounding the pan, exposure, and the fetch conditions of the location. For best accuracy, the pan must be calibrated in its actual location (Pruitt, 1960). The advantages of pan evaporation measurements are the simplicity of a single measurement and the wide availability of pan evaporation data for different locations, with respect to any other type of direct or indirect evaporation measurement.

The Penman Equation

The most successful methods for predicting PET over short periods of time are based on energy balance principals. The prime consideration here is that plants take up water as a liquid and release it as a vapor. This change of state requires about 585 calories of heat per gram of water at ordinary air temperatures. The source of this energy is radiant sunshine varying with season and latitude according to site and with cloudiness, slope, and aspect according to local weather and topography (Penman, 1963).

In addition, there must be some mechanism for removing the vapor from the vicinity of the leaf surface. That is, there must be a sink for the vapor. The basic equation for this process was set down by Dalton over a hundred years ago as $E_a = (e_s - e_d)\ f(u)$, where E_a is the vapor transported per unit time, e_s is the vapor pressure at the evaporating surface, e_d is the vapor pressure in the atmosphere above, and $f(u)$ is a function of the horizontal wind velocity.

H. L. Penman was the first to combine both of these ideas into a single equation for predicting the rate of evaporation from open water, bare soil, and vegetated surfaces (Penman, 1948). In its various incarnations, his equation is still one of the most theoretically satisfying and computationally accurate available for the purpose.

The combination equation of Penman is

$$E = (H'\Delta + E_a\ \gamma)/(\Delta + \gamma)$$

where E is the energy available for evaporating water, H' is the net of short and long wave radiant energy available for evaporation, Δ is slope of the saturation vapor pressure curve at mean air temperature, E_a is an expression for the "drying power" of the air based on Dalton's equation, and γ is the psychrometric constant.

While the basic form of the Penman equation stands, methods of computing the various component functions have undergone some change.

In view of the fact that the equation now is most often run through a digital computer or a programmable calculator, many of the constants are approximated by polymonials rather than taken from tables.

An equation and methodology given by Kincaid and Heerman (1974) is based on the following rearrangement of the Penman formulation: $E = (\Delta / \Delta + \gamma) H' + (\gamma / \Delta + \gamma)(e_s - e_d) f(u)$. The complementary constants $(\Delta / \Delta + \gamma)$ and $(\gamma / \Delta + \gamma)$ are treated as dimensionless weighting factors and, as functions of temperature alone, are approximated by a second order polynomial. The saturation vapor pressure constants e_s and e_d are likewise functions of temperature alone and are calculated by a third-order polynomial.

H' is a somewhat complicated function of thermal back-radiation, maximum possible incoming solar radiation, and actual solar radiation received. The first two terms are calculated using date, maximum and minimum temperatures, and saturation vapor pressure at mean dewpoint temperature data. A measured value is used for actual solar radiation received. The vapor transport function, f(u), is calculated from total daily wind movement. The data thus required for the use of the equation are daily maximum and minimum temperatures, mean dewpoint temperature, total solar radiation received, and total wind movement at an altitude of 2 meters. (See Kincaid and Heerman, 1974, for actual formulae, units, and techniques.)

As originally developed, the Penman equation applied to evaporation from open water surfaces only. In 1944 and 1945 Penman conducted a series of experiments designed to test the equation for open water, bare soil, and turf. From the results of these experiments, he developed empirical coefficients relating evaporation from open water surfaces to

ET from the bare soil and grass-covered surfaces. This approach is widely used today although much progress has been made in refining the coefficients for various crops.

In this regard, the problem of a three-dimensional, discontinuous evaporative surface is less serious than it might seem. In a horizontal direction, plant phototropic responses might be expected to tend toward a uniform lateral distribution of leaf surfaces. In the vertical direction, as the leaf-area index (leaf area/ground area occupied) increases, the separation between the leaves decreases and mutual interference becomes more effective. This results in reduced ventilation and inhibits vapor transport. It also decreases the amount of radiant energy available per leaf because of shading effects.

Qualitatively, one might expect that, as the leaf-area index increases from zero, the transpiration rate will increase in proportion over the early range of the index. The rate of increase then becomes smaller and smaller until it becomes effectively constant. Some data indicate that this point is reached at a leaf-area index of about 2 or 3 (Penman, 1963). If soil is wetted frequently by rainfall or irrigation, evaporation from the soil surface may make the total ET loss quite insensitive to the leaf-area index.

<u>The Jensen-Haise Equation</u>

In 1963, after an exhaustive review of consumptive use measurements from the western United States, Jensen and Haise presented a simplified PET formula based on the two key variables of temperature and solar radiation (Jensen and Haise, 1963). After examining historical records dating from the first "duty of water" measurements made by Elwood Mead in Fort Collins, Colorado, in 1887, they found about one-thousand measurements of ET for individual sampling periods to be useful for reevaluation. Following the same basic line of theoretical reasoning as did Penman 15 years earlier, they arrived at a dimensionless energy balance equation for predicting PET.

Feeling that in arid and semi-arid regions, the mechanism for removing water from the vicinity of evaporative surfaces was seldom a limiting factor, they ignored direct consideration of vapor transport in their treatment. Taking solar radiation as the most significant independent variable, they developed a series of dimensionless ratios of ET, also written E_{tp}, to estimated incoming short wave radiation, R_s for given crops at a rationalized stage of growth. By analyzing their historical data using this technique, they developed the following empirical equation for a reference crop of alfalfa:

$$E_{tp} = (0.014\ T - 0.37)\ R_s.$$

The main advantage of the Jensen-Haise equation is found in its simplicity and in the fact that good predictions of PET can be made using only two variables, mean air temperature and radiation flux. If sufficient data are available, however, even Jensen prefers to use the Penman equation (Hart, 1975).

Because Jensen-Haise is an empirical equation, the constants in it may not be applicable to other climatic regions without recalibration. The major climatological factor in the equation is solar radiation, and the magnitude of deviation of daily solar radiation from the long-term mean has been found to be different for different locations (Jensen, 1966). This calibration can be done using climatological data where such data are available.

The Jensen-Haise equation is first presented in a generalized form as $E_{tp} = C_T (T - T_x) R_s$ where:

E_{tp} = the potential ET for the reference crop in inches/day,

C_T = an air temperature coefficient which is constant for a given area,

T = the mean daily air temperature,

T_x = a constant for a given area and is the linear equation intercept on the temperature axis in the solar radiation-air temperature relationship, and

R_s = the daily solar radiation expressed as the equivalent depth of evaporation in inches/day.

The two parameters C_T and T_X are evaluated as follows:

$$C_T = \frac{1}{C_1 + C_2 C_H}$$

where C_H is the humidity index calculated by the following expression:

$$C_H = \frac{50 \text{ mb}}{e_2^o - e_1^o} .$$

In this expression, e_1^o and e_2^o are the saturation vapor pressures in millibars at the mean minimum and mean maximum air temperatures respectively during the warmest month of the growing season. For air temperatures in degrees Fahrenheit, $C_1 = 68°F - 3.6°F \frac{(\text{elevation in feet})}{(1{,}000 \text{ feet})}$ and $C_2 = 13°F$. For air temperatures in degrees Celsius, $C_1 = 38°C - 2.0°C \frac{(\text{elevation in meters})}{(305 \text{ meters})}$ and $C_2 = 7.6°C$. For Fahrenheit temperatures, $T_X = 27.5°F - 0.25\ (e_2^o - e_1^o)°F/mb - \frac{(\text{elevation in feet})}{(1{,}000 \text{ feet})}\ °F$. For temperatures in degrees Celsius, $T_x = -2.5°C - 0.14\ (e_2^o - e_1^o)\ °C/mb - \frac{(\text{elevation in meters})}{(550 \text{ meters})}\ °C$.

The above discussion draws on formulae presented in Jensen (1973). A detailed example of such a calibration process for Pakistani conditions is found in Clyma and Chaudhary (1975) though several of the calibration equations for Celsius temperatures are given incorrectly in that publication.

Lysimeters

All of the methods mentioned above determine PET as referenced to a well-watered crop which fully covers the ground surface. Lysimeter methods can be used to assess directly the effects of crop growth stage and limited water supplies as well as PET.

A lysimeter consists of a tank with a closed bottom set in the ground and surrounded by a guard region of the reference vegetation. Measurements of ET are based on gravimetric or volumetric measurement of water actually transpired by a growing crop. Provision is made for weighing the entire tank to determine evaporative water loss or the addition of known quantities of water and measurement of percolation losses to arrive at ET as a residual. Since the water budget of the tank can be accurately calculated, lysimetry is the most accurate means available of determining actual ET and is usually the standard by which predictive equations are calibrated and evaluated.

While the measurement accuracy of lysimeter studies is high, great care must be taken to insure that the small vegetated area being measured is representative of larger cropped areas. According to Penman (1963) there is no place in open air research where edge effects are more important than in ET studies. The test plot should be as nearly indistinguishable from the surrounding area of the same crop as is possible to minimize the effects of increased radiation interception surface, air turbulence, and vapor pressure gradients.

The Dependence of ET on Crop and Crop Growth Stage

Since it is often impractical to conduct lengthy lysimeter studies for determining actual ET rates, one of the predictive equations is often coupled with empirical parameters to convert PET rates to rates of actual expected ET. As mentioned previously, this requires correction for the type of crop and its stage of growth and for availability of water to the crop root system.

Total ET is then determined by the formula: $E_t = K_c (E_{tp}) + E_{tr}$ where E_t is actual evapotranspiration; E_{tp} is potential evapotranspiration; K_c is a crop coefficient determined by the crop, stage of growth, and soil water depletion; and E_{tr} is additional evaporation occurring from the soil surface before effective cover has been reached. The values of the coefficients K_c used will depend, to some extent, on which predictive equation is used. Even though the value of PET for grass might be only 80-87 percent of that from alfalfa under arid conditions, traditionally nc attempt has been made to correct ET measurements to a common base (Jensen, 1973). The Penman equation, for example, is calibrated for short grasses, while the Jensen-Haise equation uses alfalfa as a reference crop, yet crop coefficients have been used for both equations interchangeably. This difference in base rates should be considered when calculations of actual ET rates are made.

The crop coefficient K_c can be broken down into two components such that $K_c = K_{co} K_s$, where K_{co} depends on crop and stage of growth, and K_s depends on the availability of water to the crop. First taking the growth stage coefficient K_{co} and assuming a well-watered crop, it is evident that the rate of actual ET will be restricted to some proportion of the PET rate by the vegetated surface area available for radiation interception. During the initial period between planting and emergence, however, ET will not be zero, as evaporation will take place from the soil surface. The rate of ET during this time will be controlled largely by the moisture present in the upper portion of the soil profile and hence by the frequency of soil wetting.

Since growing seasons of specific crops vary according to variety, planting date, and climate, it is useful to rationalize the first part of the crop growing season, from planting to effective cover, on a percentage basis. It should be pointed out that, in this context, effective cover does not necessarily imply complete canopy cover, but only that sufficient evaporative and transpirational surfaces exist to use all of the available heat energy in the ET process (Jensen and Haise, 1963).

The functional relationship between percent of time until full cover and the ratio ET/PET is available in tabular, graphical, and regression equation form for a number of common crops. This data, while developed in the western United States, should have wide applicability. Ideally, however, it should be validated for the specific region being investigated. The tabular format of the relationship, useful for hand calculations, and the regression equation coefficients, useful for computer analysis, are listed in Appendix A. The actual length of the growing season in days for a given crop must be determined locally and converted to a percentage basis before the coefficients can be used.

During the maturation period following the attainment of effective cover, the ET rate of some crops, such as small grains, declines sharply as plant activity falls off. For others, such as sugar beets and fodder crops, no such specific maturation period exists. For these crops, the ratio of ET/PET remains essentially constant after full cover has been achieved. The calculation of K_{co} for this period is treated separately and related simply to the number of days following effective cover. Data for computing K_{co} during the maturation period are also given in Appendix A.

The Dependence of ET on Soil Moisture Content

The second component of K_c is K_s, the water stress coefficient. It is used to adjust the values of PET downward in cases where the assumption of a well-watered surface does not hold. For the purpose of the following discussion, a fully vegetated surface is assumed. That is, ET will be at the PET rate unless the amount of water available to the crop is limiting.

Agricultural soils have, as a limit to the amount of water they will hold, a certain porosity or scaled volume of space between solid soil particles. This space is almost completely filled with water during an irrigation. When irrigation ceases, however, a certain portion of that water will drain rapidly from the soil under the influence of a potential gradient dominated by a gravitational component. After several days, this rapid drainage will cease as capillary and surface forces assume the dominant role in the potential function. Drainage will continue after this time but at a much lower rate. The soil moisture content (SMC) at the end of this period of relatively rapid drainage is commonly referred to as field capacity (FC). Until FC is reached, SMC has no influence on the rate of ET.

As plants continue to withdraw moisture from the soil reservoir, the SMC falls below FC and eventually reaches what is termed the permanent wilting point (PWP). It is unfortunate that this point is defined in terms of plant function rather than in reference to soil properties. The term does indicate, however, the shared inability of a large number of plant varieties to withdraw water from the soil reservoir at moisture contents below this point.

The actual percentage values of FC and PWP vary from soil to soil and are largely a function of the soil physical properties which determine the capillary pressure distribution within the soil profile. This subject will be discussed in more detail in the following section. Here, the important point is that as the moisture content falls from FC to PWP the ET/PET ratio decreases from 1 to 0.

This decrease has profound importance for both the farmer in scheduling irrigations and the researcher in computing water budgets. Only by knowing the shape of this available water versus ET/PET curve, can rational decisions be made regarding optimal irrigation with limited water and costly labor. In this connection, it should be noted that the stage of crop development at which water stress occurs is also of great importance in determining final crop yields, as some stages are more sensitive to stress than others.

For our purpose here, calculating the actual amount of water transpired by a crop, the effect of water stress on crop yield as such is not significant. In order to model the ET process, however, a knowledge of the shape of the curve is important. Though studies of ET as a function of SMC have seldom shown consistent generalizable results, most indicate that the curve is concave downward. One method, therefore, of adjusting PET for the effects of limited soil moisture is to use an empirical relation such as the one developed by Kincaid and Heerman (1974). That curve is described by the expression:

$$K_s = \frac{\log\,(1 + 100\,(W_A/W_T))}{\log\,(101)}$$

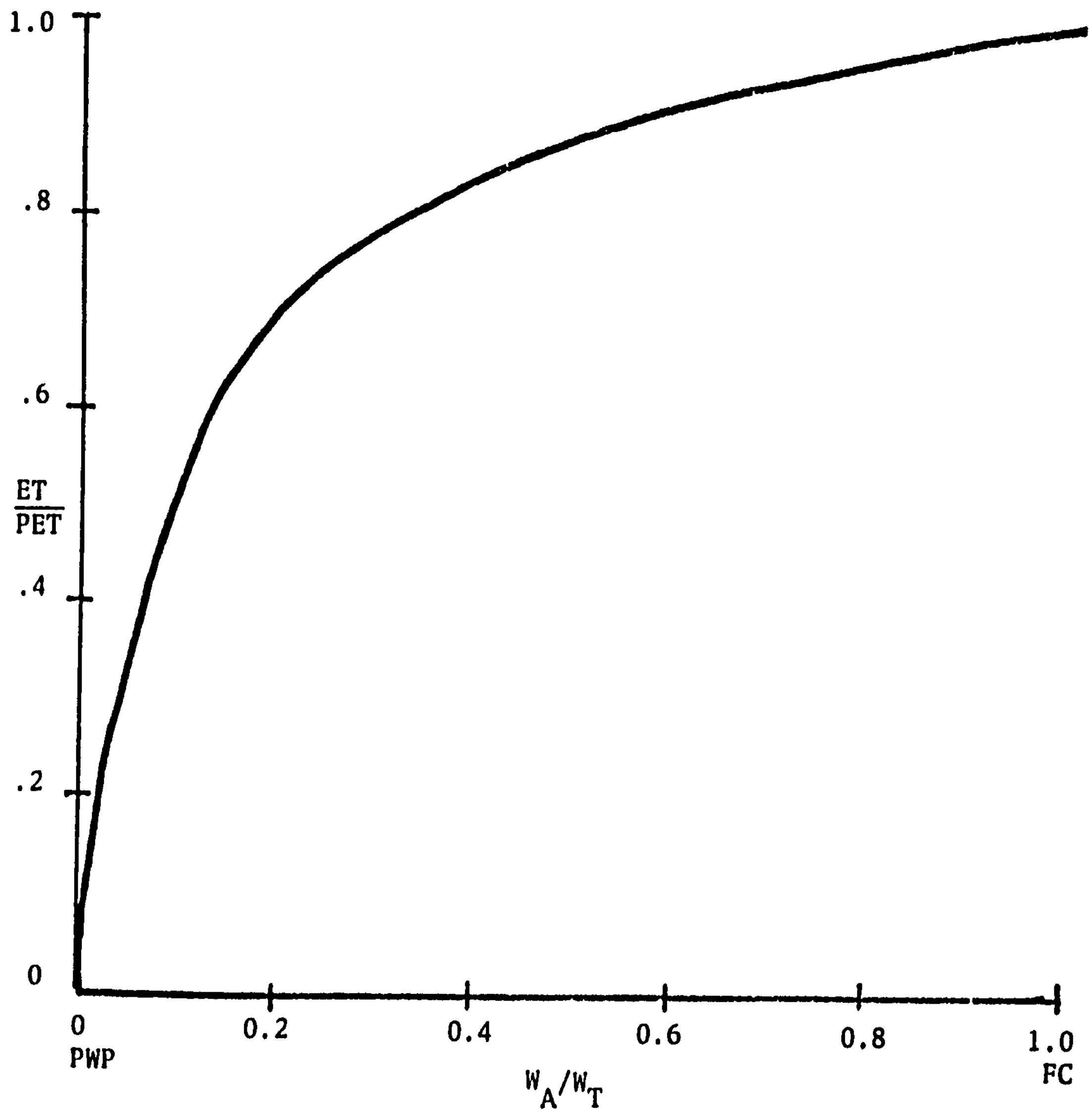

Figure 4. Empirical K_s Function.

where K_s is the water stress coefficient, and (W_A/W_T) is the fraction of the total available water between FC and PWP in the root zone which remains at a given time. The shape of this curve is shown in figure 4. The data analyzed by Denmead and Shaw (1962) indicate that this curve is a good approximation under "usual" weather conditions.

Denmead and Shaw (1962) were able to explain almost all of the variance in ET/PET versus soil moisture (SMC) relationships by parameterizing data curves in terms of a measure of PET (figure 5). In their terminology T_{FC} indicates transpiration at field capacity or PET.

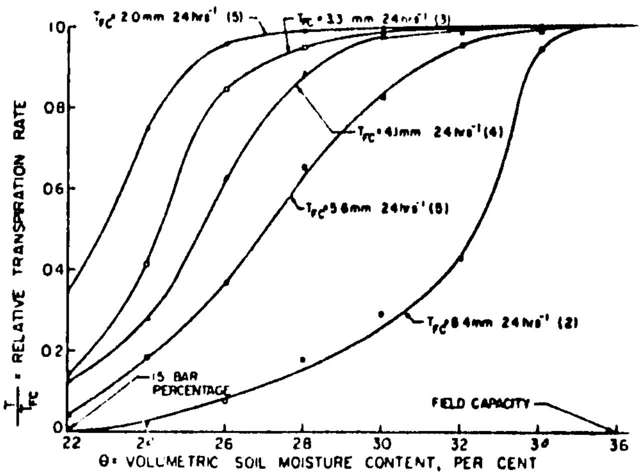

Figure 5. Relative Transpiration Rate as a Function of Soil Moisture Content for Different Potential Transpiration Conditions. The Numbers in Parentheses Refer to the Number of Days of Observation Represented by Each Curve.

Their results indicate that on a cool, cloudy, humid day, for example, where the PET rate is low, actual ET will approach PET (ET/PET ≈ 1) even at substantially reduced SMC percentages. Conversely, on a hot dry day, where PET is high, ET/PET would be near unity only at SMC levels very near field capacity.

Minhas, et al. (1974) developed a similar family of curves for the same purpose using empirical fitting techniques. They suggest that their parameter r, which defines individual curves, when multiplied by Θ_{FC}, where Θ is volumetric water content and FC indicates field capacity, might be a constant. In that case, their relationship for ET/PET depends only on the ratio Θ/Θ_{FC}. They do not, however, relate their parameter, r, to PET or to climatic factors.

Combining these approaches suggests a K_s function of the form $(W_A/W_T)^\lambda$, where $\lambda = f(PET)$. A family of curves showing this relationship is shown in figure 6. Ignoring K_{co} for the moment, the ET equation in the budgeting process might take the form

$$(ET)_i = (W_A/W_T)^\lambda_{(i-1)}(PET)_i$$

where i is a time step and the parameter λ is a function of $(PET)_i$.

Since both W_A/W_T and ET/PET are scaled dimensionless variables, ranging from 0 to 1, they should have wide applicability. It must be assumed that the response of different crops will be similar between SMC's of FC and PWP. Apart from the lack of a detailed theoretical justification for the form of the function, the major difficulty with this approach will be in finding a suitable empirical relationship between λ and PET. Still, a parameterized K_s coefficient of this form would be expected to give significantly better results than one based on a single curve.

The final term in the ET equation is E_{tr}. This is an empirical factor developed by Kincaid and Heerman (1974) to account for evaporation taking place from the soil surface following an irrigation or rain when the crop has not yet achieved full cover. This coefficient is determined in the following way:

$E_{tr} = 0$ if $K_c \geq 0.9$

$E_{tr} = 0$ if there has been no rain or irrigation in the past three days

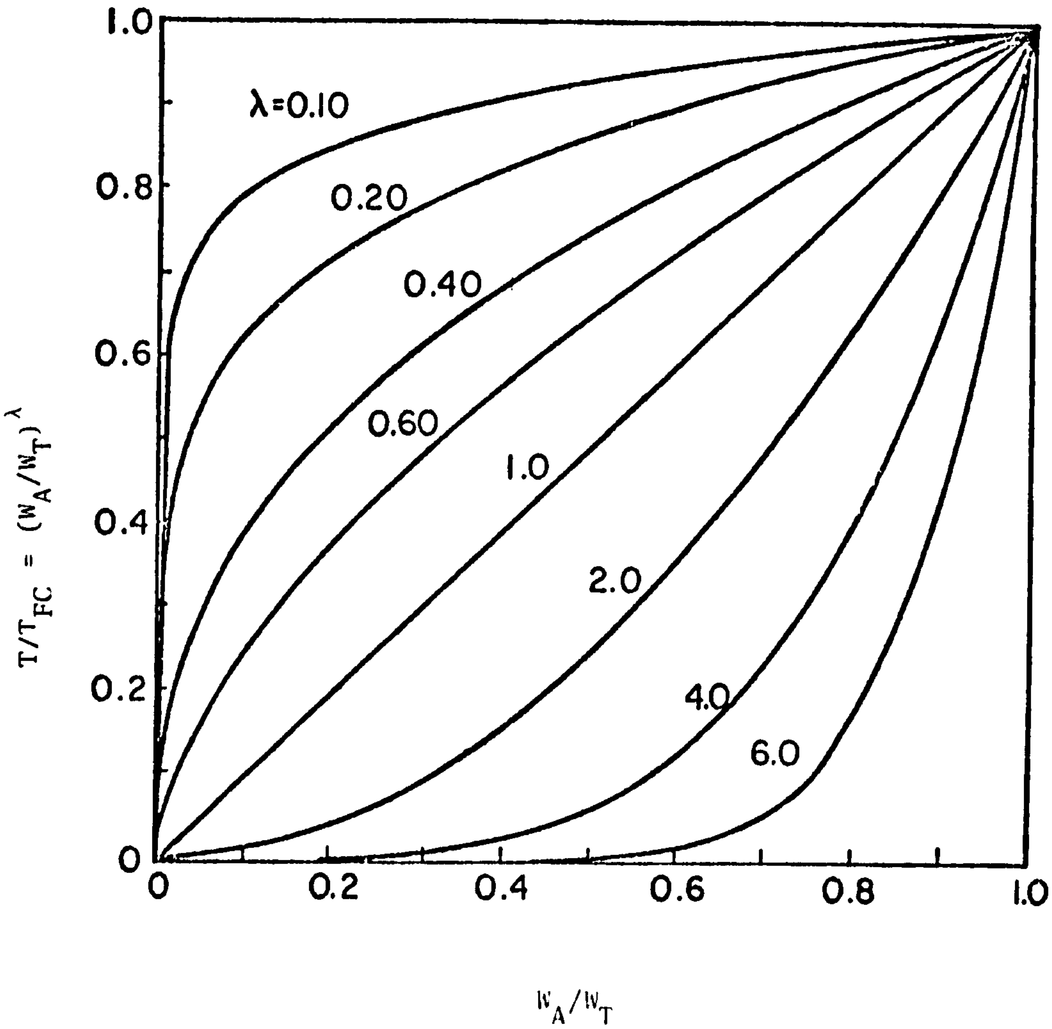

Figure 6. Relative Transpiration as a Function of Available Soil Moisture with Climate Parameter λ (from Blank, 1975).

$$E_{tr} = K_r\ (0.9 - K_c)\ E_{tp} \quad \text{otherwise.}$$

The coefficient K_r is defined as follows:

K_r = 0.8 for the first day after the event

K_r = 0.5 for the second day after the event

K_r = 0.3 for the third day after the event.

Root Zone Storage

The quantity of water stored in the soil will vary with time as water is consumptively used by the growing crop and replenished by irrigation and rainfall. The amount of storage at a given time will have a significant effect on the farm water budget and is an important consideration in determining the fate of the applied water.

To evaluate the amount of storage at any given time, it is first necessary to determine the volume of soil available for holding water. The farm-use subsystem was defined earlier as extending to the bottom of the root zone. This depth varies both among crop varieties and throughout the growing season. Usual practice is to assume a constant depth through the growing season for a given crop and to multiply that depth by the area of the field containing the crop. Average depths for a number of different crops are given in Appendix B. It is possible to consider the root zone dynamically if the rate of downward root extension is known, although this complicates the analysis somewhat.

Once the total volume of soil available for storage is known, the average water holding capacity of the soil must be determined. The soil porosity, ϕ, defined as the ratio of the void space in the soil to the bulk volume of the soil, serves as an upper limit to this quantity and typically falls in the range of 40-50 percent. In the field, water will seldom fill this void space completely. As soil imbibes water, air becomes entrapped in some of the pores and prevents the entry of water into them. Nevertheless, soil which has ceased to imbibe water during an irrigation is often spoken of as being "saturated." At such a time, the actual saturation, S, defined as the fraction of pore space which is water-filled, is often about 85 percent.

The actual amount of water a volume of soil contains is expressed as volumetric water content, θ, or gravimetric water content, W. Volumetric water content is defined as the volume of water present in a given volume of soil, while W is the mass of water present in a given mass or dry soil. The quantities described above are related by the expression

$$\theta = S\phi = \gamma_s (1 - \phi) W$$

Where γ_s is the specific gravity of the solid soil grains, and the other variables are as previously defined. An average value of γ_s is about 2.65.

As noted in the previous section, water will drain rapidly from the soil under the influence of a combined potential gradient for a period of about 1 to 3 days following the disappearance of water from the surface. The moisture content of the soil at the end of this period is traditionally termed field capacity. This water by definition can be held by the soil for long periods of time without significant drainage losses. Water contained in the soil at field capacity, however, can be readily removed by growing plants. Extraction by plants will continue until the soil water content reaches the so-called permanent wilting point, at which time it essentially ceases.

These definitions of FC and PWP are admittedly imprecise. FC and PWP have been defined more precisely (but less accurately) in terms of the water content of the soil at various pressures. The commonly accepted reference points are pressures of 1/3 atmosphere, corresponding to FC, and 15 atmospheres, corresponding to PWP. The error associated with this approach is much more significant for the FC measurement. Because of the lower SMC of PWP, this value is relatively insensitive to changes in capillary pressure. In practice, water in a soil sample is allowed to approach equilibrium at a given pressure and the gravimetric water content determined. This procedure gives a precise and reproducible indication of the SMC's at FC and PWP for a particular soil. From a practical standpoint, FC is often roughly twice PWP.

The amount of water held in the soil between FC and PWP, on a volume basis, is called total available water, TAW, and is defined mathematically as

$$TAW = (FC - PWP)\ A_s\ Z$$

where TAW is given in units of depth of water, FC and PWP are given as fractional water contents on a dry weight basis, A_s is the bulk specific gravity of the soil (dimensionless), and Z is the depth of the root zone in units of length. If the soil in the root zone is layered, the TAW of each layer must be computed separately and summed. Approximate values of TAW for different soils are shown in Appendix B.

Because crop growth rates fall off when the plant is not adequately supplied with water, an additional quantity, readily available water, is sometimes defined. Readily available water, or RAW, indicates some arbitrary fraction of TAW, often 1/2, above which crop growth and yield are considered normal. The connection of RAW with the more descriptive parameter K_s should be noted.

Having determined the parameters PWP, A_s, and Z in the above expression, the volume of water stored in a sub-region at any given time can be calculated by substituting the actual SMC into the expression in place of FC and multiplying the result by the area of the sub-region, in compatible units. This quantity is termed simply available water (AW).

$$AW = (FC - PWP)\ A_s\ Z$$

If periodically collected soil moisture data for the entire root zone soil profile are available, a more precise graphical method may be used to determine changes in root zone storage. Moisture content data in units of (length/length) are plotted against depth for SMC measurements after and before successive irrigations. By integrating the area between the curves with a planimeter, the change in storage during this time is determined. While requiring more extensive data, this method can give good values for a difficult-to-measure quantity.

Measurement of Soil Moisture Content

Soil moisture is subject to so many modifying factors that the area of representation by a particular site is often extremely limited. The slope of the land, through its effect on surface runoff and lateral soil water movement; the depth and duration of overland flow; soil profile characteristics; and exposure all affect the variability of SMC. Because of this, a number of sampling sites and replication of data is necessary within a given field. This is especially true when the goal is to determine the actual amount of water stored in the root zone of the field. It is suggested that analysis of data be kept current so that the adequacy of the sampling procedure used may be determined (USDA, 1962).

Gravimetric Analysis

The simplest and most direct means of measuring the moisture content of a soil is by gravimetric analysis. In this method, a soil sample is weighed at its field moisture content, oven dried, and reweighed. The gravimetric moisture content is then expressed as a fraction of the weight of the oven dry soil. This fraction can be converted to a volumetric basis for use in water budget calculations by multiplying it by the bulk density of the soil. The method does have the disadvantage of ultimately destroying a small sampling site.

Another problem encountered in this method is that in addition to water held in the soil by capillary forces, structural and adsorbed water is also present. Since the potential energy of the water in these three cases may be similar, the dehydration versus temperature curves may not reach a definite plateau. The result will be that water loss in the drying process will continue over an indefinitely long period.

For some soils composed of such minerals as illite, montmorillonite, vermiculite, kaolinite, gibbsite, and chlorite, the change in water content with temperature is at a minimum in the range of 165 to 170 degrees Celsius. At drying temperatures in excess of 70 degrees C, however, organic soils will continue to lose weight for long periods of time due to the oxidation of organic matter. For typical soils with moderate amounts of organic matter, a temperature range of 105 to 110 degrees C, is a good compromise. For maximum precision, however, close temperature control is required and samples should be of equal size and should be dried for the same length of time (FAO/UNESCO, 1973).

This method of analysis can be applied to composites of samples taken throughout the root zone as well as to samples from individual depth horizons. It can be used to determine prevailing moisture status in the root zone periodically and for ascertaining SMC at field capacity by sampling several days after a thorough wetting of the soil profile.

In this latter application, it is the method most consistent with the actual definition of field capacity. Gravimetric analysis usually serves as the standard against which other techniques are measured and calibrated.

"Feel Method"

A simple method of estimating SMC is the "feel" method used by the Soil Conservation Service of the U.S. Department of Agriculture. A person experienced in this method can make surprisingly accurate estimates of soil moisture content using the guidelines shown in table 1. Some technicians can consistently estimate soil moisture deficiencies within 0.2 inches on soils with which they are familiar (Merriam, 1960). It is, nonetheless, a low precision measurement and of limited usefulness in water budget studies. Still, there may be occasions when no other data are available and in such cases, an estimate based on the feel method might prove useful.

To use the guidelines, a handful of soil is squeezed very firmly and its appearance compared with the description given. If free water appears when the soil is squeezed, the moisture content is greater than field capacity.

Neutron Scattering

A more recent and highly accurate method of obtaining SMC data is through neutron probing. A radioactive source emitting fast neutrons is lowered into a thin-walled aluminum or stainless steel access tube emplaced in the soil. Slow neutrons are scattered back to a detector located in the probe in direct proportion to the number of water molecules encountered in the soil volume surrounding the access tube. Signals from the detector are relayed through a cable to portable counting

Table 1. Guide for Judging SMC by the "Feel" Method (from USDA, 1959)

Available soil moisture remaining	Feel or appearance of soil			
	Coarse texture	Moderately coarse texture	Medium texture	Fine and very fine texture
0 to 25 percent...	Dry, loose, single grained, flows through fingers.	Dry, loose, flows through fingers.	Powdery dry, sometimes slightly crusted but easily broken down into powdery condition.	Hard, baked, cracked, sometimes has loose crumbs on surface.
25 to 50 percent..	Appears to be dry, will not form a ball with pressure.[1]	Appears to be dry, will not form a ball.[1]	Somewhat crumbly but holds together from pressure.	Somewhat pliable, will ball under pressure.[1]
50 to 75 percent..	Appears to be dry, will not form a ball with pressure.	Tends to ball under pressure but seldom holds together.	Forms a ball somewhat plastic, will sometimes slick slightly with pressure.	Forms a ball, ribbons out between thumb and finger.
75 percent to field capacity (100 percent).	Tends to stick together slightly sometimes forms a very weak ball under pressure.	Forms a weak ball, breaks easily, will not slick.	Forms a ball, is very pliable, slicks if relatively high in clay.	Easily ribbons out between fingers, has slick feeling.
At field capacity (100 percent)	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand.	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand.	Upon squeezing, no free water appears on soil, but wet outline of ball is left on hand.	Upon squeezing, no free water appears on soil but wet outline of ball is left on hand.

[1]Ball is formed by squeezing a handful of soil very firmly.

and timing circuitry. The number of neutrons scattered back to the detector during a given time interval, usually 30 or 60 seconds, can then be related to the soil moisture content of the soil. This method samples a larger volume of soil than the other techniques discussed in this section and for that reason must be regarded as a more satisfactory representation of soil moisture status. For this reason also, it requires less replication than other methods.

In use, the probe is lowered in increments of 6" or a foot and a count taken at each elevation. In this way a complete mapping is made of the SMC throughout the soil profile. It should be noted that neutron probe measurements are not reliable within 6" or so of the soil surface and other sampling procedures may be necessary to supplement probe data in this region. This type of data is amenable to the graphical method of determining changes in root zone storage discussed earlier.

The counts obtained in the probing process are indirect measurements and must be related to actual moisture contents by means of a calibration curve. Calibration is done by taking soil samples simultaneously with neutron probe readings and determining the moisture content of the samples by gravimetric analysis. SMC is then related to the ratio of the actual counts obtained and a standard count taken with the probe inside its traveling shield.

Tensiometers and Resistance Blocks

Another indirect method of determining SMC utilizes tensiometer readings at various locations and depths throughout a field to obtain values of prevailing capillary suctions. These values can then be converted to soil moisture percentages using the soil moisture characteristic curve which relates capillary suction to moisture content.

The tensiometer consists of a porous ceramic cup placed in the soil at some depth. This cup is attached to an inverted U-tube manometer above the ground surface by a length of tubing. The cup and tubing are filled with water and the open end of the U-tube carefully inserted into an open reservoir of mercury, excluding all air. Water will then flow out of the porous cup and into the soil and mercury will rise in the tube until pressure inside and outside the cup are equal. Suction readings can then be calculated from the height of the mercury column and the depth of the cup. This suction is then related to moisture content by means of a previously developed curve.

The major drawback of the tensiometer method is that, because of dissolved gasses in the water in the tensiometer, the water column tends to break at suctions above about 0.8 atmospheres. This limits the usefulness of the tensiometer to a fraction of the range of TAW, albeit the most important fraction.

Another in situ method employs a pair of electrodes embedded in a porous block of gypsum, nylon, or fiberglass and buried in the soil. The matric potential of the soil solution is then inferred from electrical conductivity readings. These readings are indirect measurements and the block must be calibrated to read capillary suction or moisture content.

This method constitutes the only available technique for determining capillary suction in situ at suctions greater than 1 atmosphere. It is, however, of relatively low precision and unreliable in the presence of salts in the soil water solution. The calibration curves of the blocks also tend to shift with time. It is more useful as an indicator of soil moisture status than as a measure of actual SMC.

In Situ Soil Salinity Measurements

As a complement to laboratory determinations of soil solution salinity, an in situ soil salinity sensor has been developed by Kemper (1959) and Richards (1966) and evaluated by Oster and Ingvalson (1967). It consists of a thin ceramic plate about 1.0 mm thick which separates a pair of platinum screen electrodes connected to a resistance bridge. The sensor is buried in the soil at the desired depth and readings taken of the resistance to a small alternating current which passes through the ceramic between the electrodes. This resistance is inversely related to the salt concentration of the soil solution which occupies the ceramic. The sensor must be calibrated in the laboratory with salt solutions of known concentration. Oster and Ingvalson estimated, in evaluating the sensor's performance, that it was accurate to $\pm$ 0.5 mmho/cm. This does not match the accuracy of laboratory conductivity measurements, but it is sufficient for many purposes.

The single overriding advantage of the in situ sensor, apart from the simplicity of making measurements, is that it measures the conductivity of the soil water solution at the prevailing moisture content of the soil. The measurement thus avoids the problem of redissolution of precipitated minerals associated with the saturation extract method. This makes it a valuable supplement to laboratory determinations even when the greater precision of the latter is necessary.

Measurement of Surface Runoff

Surface runoff, or field tailwater, is water that is applied to a field but which does not infiltrate into the soil profile. Usually it appears at the lowest corner of the field and is lead, via a ditch, to a drainage channel. This outflow must be measured carefully for inclusion into the water budget. The most convenient way to do this is by placing small portable flumes in the outflow channels.

Since the flow may change quickly in magnitude during an irrigation or precipitation event, it is most desirable to equip the flume with a stilling well and stage recorder. If this is not possible, frequent manual readings should be taken during this period. With basin irrigation systems, the irrigation technique is usually to pond the water on the soil surface and allow it to infiltrate completely into the soil. In this case, of course, there would be no runoff.

The surface drainage water should be measured in the same manner near its outflow into a natural water course and sampled for laboratory quality analysis. This will permit a partition of surface drainage outflows into field runoff and ground water infiltration components by the use of a dilution equation.

Direct Measurement of Deep Percolation

In addition to surface runoff and ET, a certain fraction of the water applied to the field will move below the root zone and thus leave the farm use subsystem. This water will eventually reach a water table and then flow laterally in the direction of the prevailing hydraulic gradient.

Leaching Requirement

Not all of the water percolating below the root zone can be considered wastage or loss. Because plant roots extract relatively pure water from the soil moisture reservoir, the salt concentration of the water that remains will inevitably increase. This increasingly saline water must be flushed out of the root zone if agriculture is to be practiced on a continuing basis. This is done by allowing controlled deep percolation to take place, thus removing accumulating salt from the root zone. The quantity of deep percolation necessary to accomplish this depends on the quality of the applied irrigation water; the allowable quality of the leachate; and, to some extent, soil type and the type of crop being grown.

Determination of the quantity of water necessary for leaching is usually based on the requirement that the quantity of salt leaving the root zone must be at least as great as that entering in the irrigation water. That is,

$$EC_i\ Q_i = EC_d\ Q_d$$

where EC_i and EC_d represent the electrical conductivity of the irrigation and drainage water respectively, and Q_i and Q_d are the quantities of irrigation and drainage water added to and removed from the root zone. Electrical conductivity is an easily measured parameter that represents the concentration of salts dissolved in a water sample. It will be discussed in more detail in Chapter VII.

A quantity prescribing the amount of drainage necessary to achieve this balance was defined as the leaching requirement (LR) by the U.S. Salinity Laboratory in 1954 (Richards, et al., 1954). By rearranging the above equation, the leaching requirement is shown to be,

$$LR = \frac{Q_d}{Q_i} = \frac{EC_i}{EC_d}$$

This quantity has practical significance only when applied to relatively long time periods that can be measured in months or even years. The quantities involved must thus be weighted averages and should include effective precipitation. Over the long run, it can be assumed that the quantity of water draining from the root zone is the net of water applied less that consumptively used, or

$$Q_d = Q_i - Q_{et}.$$

Combining this expression with the original equation results in an expression for the amount of water which should be applied relative to the amount consumptively used,

$$Q_i = Q_{et}\left(\frac{EC_d}{EC_d - EC_i}\right).$$

Unfortunately, there are no universally accepted standards for allowable quality of drainage water. This topic will be discussed in Chapter VII.

Tile Drainage

Measuring the magnitude of deep percolation flows is difficult. One way around the measurement problem is to calculate deep percolation as a residual in the water budget. If possible, however, it is desirable to have some independent measurement of this quantity also. If an impermeable barrier is located near the bottom of the root zone, a tile drainage network can be installed on the barrier and assumed to collect all of the downward flow from the root zone. To eliminate the influence of horizontal flows from upslope, it may be necessary to install a vertical barrier, such as a plastic membrane, from the soil surface to the impermeable barrier, to block these inflows. Alternatively, the drainage outflows from upslope tile lines can be ignored and drainage data from the remainder of the field extrapolated to the entire area. Drainage outflow should be sampled for qualitative laboratory analysis.

If no impermeable barrier exists, such a system becomes unworkable. In this case the flow into the drains assumes a radial character and the amount of drainage water collected will not be representative of the downward flow from the root zone. It then becomes extremely difficult to separate out the fractions of the drainage flow resulting from downward percolation, horizontal inflows and change in storage.

Soil Water Extractors

A practical method for measuring the rate of downward percolation in such cases has been recently perfected (Duke and Haise, 1973). The device, called a vacuum or soil water extractor, permits the collection and measurement of unsaturated downward flow occuring between the bottom of the root zone and the water table, regardless of water table depth. Since water flowing downward under unsaturated conditions is at a pressure less than atmospheric (negative gage pressure) suction is necessary to create a potential gradient in the direction of the extractor. Because a vacuum is used to induce flow, the device is limited to a range of suctions below about 0.8 atmospheres.

The extractor system consists of a field measuring unit and a vacuum control system which can be located some distance from the measuring unit. The field measuring unit comprises a trough approximately 11 feet long, 6 inches wide, and 8 inches deep containing a finely porous hollow ceramic "candle". The trough functions to limit the convergence of flow lines caused by the candle acting as a line sink. The candle is kept in a saturated condition and is connected to the control system via a collection bottle. A second line is also fitted to the candle to permit rewetting of the ceramic, should that be necessary.

In use, the trough is filled with soil and buried beneath the plant root zone. Two tensiometers are provided, one in the upper portion of the trough and a second in undisturbed soil outside the trough and at the same elevation but some distance away. Experimental evidence indicates that by periodically adjusting the applied suction so that the two tensiometer readings are similar, the soil near the top of the trough can be maintained within 5 cm water suction of that outside the trough, thus minimizing convergence (Duke and Haise, 1973). The quantity of leachate collected is relatively insensitive to the applied suction so long as excessive convergence is avoided.

In soils with little or no structure, the trough can be placed in the bottom of a trench dug to the desired depth and the trench backfilled. A hydraulic-powered horizonatal boring machine has been developed to create a cavity under undisturbed soil from an access pit for use in more structured soils where backfilling could change hydraulic properties of the soil significantly. The trough, filed with soil, is then inserted into the cavity. A pneumatic pillow is placed under the trough and inflated to press the soil in the trough firmly against the roof of the cavity insuring intimate hydraulic contact.

Initial experiments indicate that, with proper vacuum control, interception within ± 15 percent of the ambient flux can be achieved. The trough samples a large area relative to earlier devices, and since the same vacuum control system can be used for a number of different field measuring units, economical and accurate measurements of deep percolation flows are possible. The sample extracted can also be used for qualitative laboratory analysis. Before this is done however, it is necessary to flush the candles with an acid solution to reduce their high initial pH.

Subsystem Outputs

Having measured the amount of water applied to the prototype farm water-use subsystem as irrigation inflows and precipitation, an apportionment must be made to surface runoff and deep percolation, which comprise the removal and drainage subsystem, and to evapotranspiration. The amount of water incorporated into the plant material is assumed to be negligibly small.

Evaporation can be determined with reasonable accuracy with one of the predictive equations based on climatological data. Surface runoff is easily measured with small portable flumes placed in the outflow channels at the lower end of the field. Deep percolation can then be calculated as a residual or measured independently with a tile drainage system or through soil water extractor measurements.

Chapter V

THE WATER DELIVERY SUBSYSTEM

Description and Boundary Definition

The water delivery subsystem can be defined in a number of ways. As it is used here, it comprises the surface channels used by the water as it enters the system and is transported to the most distant farm turnout on each branch. If ground water is also used for irrigation, the ground water flow system could conceivably be included as a part of the water delivery subsystem. While this would be conceptually satisfying, it would present complicated practical problems of measurement and definition. Since ground water would necessarily be treated separately from the surface delivery portion anyway, it seems most reasonable to frame a general definition of the delivery subsystem in terms of above ground flows.

The water delivery subsystem then, comprises the natural and artificial channels which carry water across the system boundary and transport it to smaller canals or laterals from which a single farmer or a small number of farmers obtain irrigation water. This definition is not as precise as would be desired but must depend to a certain extent on the configuration of the irrigation system in a particular locale. The delivery subsystem usually, though not always, is under public or collective ownership and, because of the number of people depending on it, has qualities of a public good.

In a vertical direction, the subsystem extends downward from the water surface only to the bottom of the channel. Water which evaporates or seeps out of the channel is considered to have left the subsystem. If the delivery subsystem consists of several main canals leaving the natural stream at different points, the natural stream is included in the delivery subsystem to the point of the last diversion within the system. This raises the possibility of overlap as some return flows may enter the stream above the last diversion.

Mapping the Water Delivery Subsystem

To know with some certainty the source and fate of the water entering the system, it is necessary to map the delivery subsystem to scale. This is most conveniently done in conjunction with the mapping of the surface drainage system and the land use survey. Unless accurate up-to-date maps exist for the study area, it will be necessary to update existing maps or to prepare new ones. Aerial photography is one convenient way to do this. If aerial photographs are unobtainable, however, the mapping can be carried out on the ground using standard surveying techniques.

Quantitative Surface Flow Measurement

Method

In arid regions, surface flow measurements will usually be made on a small number of large natural watercourses and a much larger number of smaller artificial ones. This is in contrast to a more humid region where local watersheds might contribute substantial amounts of water to the system, necessitating a larger number of measurements of natural flows. In arid regions, the source of the irrigation water will usually be mountain watersheds substantially removed from the study area and will often consist of a single river.

Most common techniques used to measure both small and large volume flows are based on simple depth of flow measurements. The depth measurement, or stage, is then related to the volume of flow, or discharge, by a stage/discharge relationship or rating curve. For these correlations to be accurate, it is necessary to measure stage within a stable channel configuration called a control and to eliminate the possible influence of downstream conditions on the stage reading. In this way, a monotonic relationship can be assured between stage and discharge.

The period over which measurements must be taken will vary with the type of flow involved. In most cases, a period of record covering a water year or, at the least, a cropping season will be required. Longer term studies are more desirable but also more expensive.

Stage measurements can be made either manually with a staff gage or automatically with a data recording device. Normally, the recorder is preferred as it gathers a continuous record rather than a set of periodic but discrete readings. For studies of short duration, however, this may be impractical. The higher cost of the automated measurements is another consideration.

The most common type of stage recording instrument consists of a pen which is moved at a constant rate by clockwork or a suspended weight across a drum covered by a paper chart. The drum rotates under the pen resulting in a continuous record of water level heights. The motion of the drum is controlled by a float in a stilling well located directly below the recorder and connected hydraulically to the control section. The purpose of the stilling well is to eliminate the influence of waves and other small period fluctuations in water surface elevation. Variations include a continuous-roll chart for longer periods of recording in which the motion of the pen is controlled by the float and a gas bubbler system which eliminates the need for the stilling well and float mechanism.

Control Sections

The control section for stage measurements can be either natural or artificial. A control section is defined by the USGS as "a natural constriction of the channel, a long reach of the channel, a stretch of rapids, or an artificial structure downstream from a gaging station that determines the stage-discharge relation at the gage." (Langbein and Iseri, 1960). The conditions stated in the description of a natural control imply a combination of length and grade that prevents downstream conditions from exerting excessive influence on the velocity of flow at the gaging point.

If this criterion is met, the key to location is the stability and impermeability of the channel section. All natural channels shift to some degree as a result of aquatic vegetation, debris lodging on the control, and scour and deposition in the channel. It is desirable, however, that such changes in a control section be small over time.

If the channel bed is not reasonably impermeable, subsurface flow may account for a substantial portion of the water moving past a particular point. Limestone or permeable gravel beds are examples of such conditions. These subsurface flows can be measured, but greater accuracy will be achieved if they can be measured as surface flow.

To eliminate problems of shifting controls and downstream influence, artificial control sections are often used. Commonly used artificial controls fall into two categories - weirs and flumes. Both are open channel structures containing a constricted section. If the constriction is formed by raising the channel floor, the structure is classed a weir. If the constriction is caused by reducing the width between the sidewalls, it is considered a flume. By knowing the geometry of the constriction and the height of the water surface upstream, and in some cases downstream, from the constriction, the flow rate can be determined with reasonable accuracy.

Weirs

The weir is, in general, the more accurate of the two types of artificial controls. On the negative side, it causes large head losses and is highly susceptible to silting which can diminish its accuracy. A weir consists of a wall or dam containing a notch of regular form which impounds water in a basin. A staff gage or stage recorder is provided to measure water surface height in the basin, often in an adjacent stilling well. The notch or crest over which the water flows to leave the basin may be either sharp or smooth and flat, giving rise to the terms sharp-crested and broad-crested weirs.

The most common types of sharp-crested weirs are the rectangular, the trapazoidal, and the v-notch. As the names imply, the first two consist of sharp horizontal crests with either vertical or sloping ends. The flow over them is a function of the crest length and the 3/2 power of the head over the crest. They are used mostly for larger discharges as they are not particularly accurate at low flows.

V-notch or triangular weirs employ a notch having 60, 90, or 120 degrees between the sides. Flow is a function of the 5/2 power of the head above the bottom of the notch. These weirs are extremely accurate in measuring small flows and can cover a fairly wide range of flows.

Where the flow over a sharp-crested weir is contracted and springs free of the weir crest immediately upon leaving the basin, the broad-crested weir supports the flow leaving the basin for a short distance before it springs free. Broad-crested weirs may have a variety of cross sections and may be horizontal or sloping with sharp or rounded corners.

Stage height is not sensitive to flow volume at low flow and broad-crested weirs are, in general, less accurate than sharp-crested weirs. One big advantage is that the crest is not as susceptible to damage by water-borne silt and debris. They are also less likely to snag floating debris, a situation which makes stage readings meaningless. Discharge is proportional to crest length and the 3/2 power of the head.

Knowing the geometry of all of these weirs, theoretical formulae can be derived relating head above the crest to discharge. The general form of all of these equations is $Q = C\ L\ H^b$, where Q is the discharge, C is a constant, L is the crest length, H is the upstream head, and b is an exponent. The theoretical exponents given above for various weirs are usually quite accurate, but C must usually be determined empirically.

The preceding discussion assumes that free-flow conditions exist over the crest of the weir. If there is insufficient fall below the weir crest, or if the channel below the weir cannot carry the flow away rapidly enough, the discharge may become partially submerged or drowned. When this occurs, the flow will be unstable and stage readings must be considered approximate (Thomas, 1957).

Flumes

While slightly less accurate than weirs, flumes have a number of advantages that recommend them, particularly in measuring small agricultural flows. One of these advantages is the relatively low head loss which occurs across the flume. As a result, flumes can be used in channels with very flat gradients. Head loss can be reduced still further by operating the flume in a submerged mode, though this will require measurement at two points rather than one. A second important attribute of flumes is their self-cleaning property. Finally, they are simple to construct and can be moved readily from site to site.

A flume is a stabilized channel section with contractions in its sidewalls. Commonly used types consist of a converging entry section, a throat section, and a diverging exit section. The types most often encountered in measuring agricultural flows are the Parshall flume, the trapezoidal flume, and the Cutthroat flume.

The Parshall flume, developed in 1926 by Ralph Parshall at Colorado State University, has long been one of the most popular flow measuring devices used in agricultural work. It is a parallel-sided flume with a downward-sloping throat floor and an upward sloping exit section. It operates under both free-flow and submerged conditions, the former occurring when critical depth is exceeded in the throat. Under free-flow conditions, a single measurement of water stage in the entrance section is sufficient to define the flow volume. Under submerged flow conditions, an additional depth measurement in the throat (or exit) section is required. The ratio of the second of these values H_b to the first H_a is termed the submergence, and the point at which free-flow conditions no longer hold is termed the transition submergence. For the Parshall flume,that value is approximately 0.7. The discharge Q is a function of the width of the throat W_t and H_a. The actual formula given by Parshall is $Q = 4\ W_t^{1.026}\ H_a^{1.522}$. The geometry of the flume is complicated and varies considerably as throat width is change.

The trapezoidal flume is an outgrowth of the Venturi flumes pioneered by V. M. Cone during the early part of the century. It has a flat floor and includes a converging entry section, throat, and diverging exit section. Because of its trapezoidal cross section, however, its geometry is quite complicated and varies considerably for different sized flumes. One main advantage is that it can be constructed or placed in existing trapezoidal channels. It can be operated under both free flow and submerged conditions with transition submergence ranging from 0.80 to 0.85. Because of the geometry, the equation relating stage to flow is somewhat complicated. A general equation for the free flow mode developed by A. R. Robinson (1964) is:

$$Q = C_a H_a^{2.5} + C_b H_a^{1.5} + C_c$$

where Q is the discharge in cfs; C_a , C_b , and C_c are experimental coefficients; and H_a is the upstream head measured in feet.

The third type of flume grew out of research conducted by Skogerboe at Utah State University in the mid-sixties. It consists of a flat floor, vertical sides, and a throat length of zero. Because of this latter characteristic, it was named the Cutthroat flume (Skogerboe et al, 1967). This design has two important advantages over previous designs which should secure for it an increasingly important place in the measurement of agricultural flows. The first is its extreme simplicity and consequent ease of construction. The second related advantage is that all flumes of this type have constant convergence and divergence ratios, and families of flumes with differing throat widths have the same entrance and exit section lengths. This permits the development of generalized discharge relations applicable to continuous ranges of flume sizes.

It also shares the advantages of earlier designs in its low head loss, ability to operate under either free flow or submerged conditions, and placeability in lined channels. Transition submergence is variable but in the group of flumes rated by Bennett (1972) which varied in length from 1.5 to 9 feet, it varied from about 0.6 to 0.8. Rating curves and parameters can also be found in Bennett (1972).

Stage/Discharge Relationships

To be useful, stage measurements in a control section must be converted into discharge or flow measurements. This involves developing a rating curve or equation for the control, using an independent measurement of flow and relating it to observed stages in the control. Independent flow data can be obtained in a number of ways.

The simplest method for measuring small flows is to collect the outflow from a control in a flask, bucket, tank, or other appropriate container during a selected time interval. The actual flow rate is then easily determined. A flume or weir with a known stage discharge relation placed just upstream or downstream from the control to be rated can also be used, though this technique will compound the uncertainty in the rating.

For measuring larger flows, a Price current meter or its smaller cousin, the Pygmy meter, is often used. These meters, employing a set of cups rotating around a vertical axis, measure current velocity. Measurements are made in a number of vertical sections across the channel with the total flow computed by summing the products of the mean sectional velocity and the sectional area. Sections are drawn so that no one areal element accounts for more than about ten percent of the total flow.

Since the vertical velocity distribution in a channel is approximately parabolic, depths of velocity measurement must be selected carefully. It has been found that, for most channels, the average of the velocities at 0.2 and 0.8 depth below the surface equals the mean velocity in the vertical. The velocity at 0.6 depth below the surface is also nearly equal to the mean in the vertical. The later point is usually used in more shallow water.

When a current meter cannot be used because of high stream velocities or rapidly changing flows, floats can be introduced into the stream at regular intervals across the channel and their travel timed over a known distance. The velocities so determined are used in place of the current meter readings as above. Since the surface velocity is usually higher than the mean velocity by a factor of about 1.2, the calculated velocity must be corrected by this factor.

Moderate flows with velocities in the range of 1 to 10 feet per second can also be measured with a velocity-head rod. This device, which was developed in the early 1940's at the San Dimas Experimental Forest in California, is simple, dependable, and rugged. It consists simply of a rod, calibrated to measure depth, with a sharp, wedge-shaped leading edge and flat surface on the opposite side. It is used to determine stream velocity in a number of vertical sections. Total flow is then calculated as in the current meter method.

Stream depth is first measured with the sharp edge of the rod facing upstream, neglecting the ripple or "bow wave." The rod is then rotated 180 degrees so that the flat edge faces upstream causing an hydraulic jump. The height of the jump measures the total energy content of the stream at this point. The difference between the total head and the stream depth is the velocity head of the flow. Velocity can then be computed from Bernouilli's equation: $v = \sqrt{2gh}$, where v is the velocity, g is the acceleration due to gravity, and h is the velocity head. In measuring turbulent flows, there will be some uncertainty associated with the height measurements. This error, however, will propagate only as the square root of the velocity head. In evaluating the results of flow measurements using the velocity-head rod, Wilm and Storey (1944) found average errors on the order of a few percent.

Another way of measuring discharge which has been known for many years, but not widely used, is the dye dilution method. It has become more popular in the last 15 years because of the development of stable fluorescent dyes and instruments capable of detecting these dyes in extremely low concentrations, i. e., as low as 0.5 ppb. It is particularly useful as a complement to the simpler current meter method in situations where current meter measurements are difficult to make or inaccurate. Such situations arise where streams are shallow and slow moving, turbulent, heavily laden with sediment and debris, ice covered, rough bottomed, or unstable.

In the dye dilution method, a fluorescent dye, such as one of the Rhodamines, is introduced into a channel and allowed to mix thoroughly with the flow in the channel. Injection can be either continuous at a constant rate or instantaneous as a "slug" of dye. At some point downstream, the stream flow is sampled and the dye concentration determined with a fluorometer.

In the continuous injection method, concentration at the sampling point rises to some plateau value and remains constant until injection is discontinued. Channel flow is calculated simply by multiplying the ratio of the initial to the downstream concentration by the injection rate, assuming that the volume of solution injected is a negligible addition to the stream flow.

In the total recovery method, the entire slug of dye must be accounted for. Sampling downstream continues until the dye concentration, having risen to some peak value, declines again to the background concentration of the stream. Data are then plotted on a concentration versus time curve and the total quantity of dye injected is divided by the area under the curve to give the discharge.

Dye dilution has been used successfully both in natural channels and for the in-place rating of orifices, weirs, and flumes (Kilpatrick, 1968). While the results obtained have shown impressive accuracy, they must be balanced against the cost of the equipment required for injection and concentration measurement.

Once independent determinations of flow have been made, they must be related to observed stages in the control. For most natural controls, a simple plot of stages versus discharge is satisfactory. Resulting curves are essentially parabolic but often show irregularities if the control changes with flow or if the cross section is irregular. The basic equation is of the form $Q = p(G - e)^b$ in which Q is the discharge and G is the gage of stage height. The parameters p, e, and b can be determined from a log/log plot of the stage vs. discharge data (Carter and Davidian, 1965). Rectangular coordinate paper can also be used for the plot but is most useful for representing the lower part of the rating and for final display after curve shape has been determined (Carter and Davidian, 1965). If the slope of the energy line through the control section is variable, more complex relations can be developed, including curves defining discharge in terms of slope, rate of change of stage, and other variables.

In developing rating curves for flumes and weirs, log/log plots of stage versus discharge data can be used to determine the coefficients in the general formulae given earlier. With the smaller portable devices, rating can be done in the laboratory under more carefully controlled conditions. For the Cutthroat flume with its generalized discharge relations and simple geometry, preliminary rating can be done analytically using the dimensions of the particular flume. The rating should be checked, however, for at least a few actual data points.

Measurement of Inflows Across System Boundaries

All flows of water and dissolved solids which enter the system must be measured. These include surface flows, groundwater flows, precipitation, and imported water. In addition, some measure of their variability over time is necessary. The following three sections discuss techniques for making these measurements.

Surface Flows

Surface flows entering an irrigated arid region will usually consist of one or two major natural streams and possibly tributaries which join the main streams within the study area. All of these flows must be measured. Usually this will be done using natural control sections rated with a current meter.

Gaging points should be located near the point where the stream enters the study area. Existing gaging stations either inside or outside of the system boundary may be utilized if the quantity and quality of the flow is not altered appreciably between the gaging station and the system boundary. Water samples for laboratory analysis of dissolved solids, pH, temperature, sediment and other quality characteristics should be taken at the same location periodically.

If water is imported to the study area, the imported flow should be measured, analyzed and treated as tributary flow. The quantity and quality of exported water should also be determined so that it can be deducted from the conveyance subsystem at the appropriate point.

Sub-surface Flows

Groundwater flows are measured with greater difficulty and less precision than are surface flows. This is because the measurements are indirect; depend on sensitive, hard-to-determine parameters; and cover wide geographical areas. To get a complete picture of the quality and quantity of groundwater inflows and outflows for a region requires an extensive and expensive program of test drilling and groundwater contour mapping. Procedures for this are outlined in Chapter VI.

A thorough knowledge of the subsurface geology of the region simplifies this task as it permits the identification of impermeable barriers which would prohibit flows across particular system boundaries. Probably the best solution would be the selection of system boundaries which coincide with a groundwater basin that drains via effluent surface streams. While the identification of the basin would require some investigation itself, the need for monitoring of inflows and outflows across the boundaries would be eliminated. If this is not possible, attempts should be made to minimize the extent and distribution of subsurface flow by judicious boundary selection. For this reason, it is important to begin groundwater investigations early in the project to provide as much information on the groundwater regime as possible before definite boundaries are drawn.

Precipitation

Although less significant in arid regions than in humid ones, precipitation may nonetheless be a significant factor in the hydrologic budget of a region. Its measurement is relatively straightforward and can be done with a number of different types of manual and recording rain gages (see for example, Linsley et al, 1958).

At least one such gage will be required for the calculation of ET and the farm water budget studies described in the preceeding chapter. The need for additional precipitation gages will depend on the size of the study area, the precipitation expected during the period of study, and its areal variability.

Precipitation can contribute to surface flows in rivers, canals, laterals, and drainage channels; to subsurface flows by direct deep percolation; and to ET losses via crops and natural vegetation and from the soil surface. Since inland rainfall is quite low in dissolved solids content (on the order of 10 mg/liter), it will have a negligible effect on the total amount of salt in the system. If added to surface or groundwater flows, however, it will reduce the concentration of the salts already in solution.

In the fields selected for farm water budget studies, most rainfall will have a significant effect and must be considered in the budget. When considering the system as a whole, if individual rainfall events are brief and of low intensity, it may be possible to assume that all of the precipitation is returned to the atmosphere via evapotranspiration. Deep percolation and surface runoff are then ignored. If this is not the case, it may be necessary to estimate allocations of precipitation to the various components of the system.

Measurement of Inflows to the Artificial Conveyance System

The preceding section has outlined the determination of the quantity and quality of all water entering the system. We now need to focus on the portion of that inflow which is diverted from natural watercourses to irrigate fields of agricultural crops.

Since water taken from rivers and streams in developing arid regions almost always flows in open, unlined channels, we will restrict discussion to measurement of such flows. These channels are man-made and function effectively only for a limited range of flows. Because of this, the amount of water entering them must be more or less carefully controlled. The transport of water in these man-made canals can contribute directly to problems of waterlogging and salinity. Because of the comparative regularity of both the canal cross sections and the flows they carry, however, there is the possibility for control of these harmful effects. For this reason, a more thorough investigation of artificial channels is justified than was made of the natural watercourses.

Water can enter the artificial conveyance system either through pumping or by gravity flow. In either case, measurement of both quantity and quality of water withdrawn from the watercourse is necessary. Water quality at the diversion point will often be unchanged from that of the water entering the system. Nonetheless, water quality samples should be taken at the point of diversion for laboratory analysis until this is solidly established.

Pumped Discharges

In the less common situation of pumped withdrawal, quantity can be determined in several ways. The most direct method, applicable for small flows, is a timed volumetric measurement, in, for example, a 55 gallon oil drum. A commercial water meter can also be inserted in the discharge pipe to measure discharge over a specified length of time. The time in this case may be a matter of days or weeks, giving a record of the total quantity of water pumped from the watercourse rather than a flow rate.

If the pumpage period is known to be regular, accurate measurements of flow rates obtained from rated circular orifices can be used to calculate total discharge. One type commonly used to measure steady flows is an orifice plate attached to the end of the pump discharge pipe coupled with a piezometer (figure 7, from Johnson, 1975). A rating curve for the orifice is shown in figure 8 (from Johnson, 1975). Measurements made on the flatter part of the curve can be accurate to within 2 percent if the device is properly constructed and installed. Note that the discharge pipe must be straight and level for a distance of at least 6 feet behind the orifice plate and that valves and similar flow obstructions should be located at least 10 pipe diameters upstream from the piezometer tube connection.

Another device which is useful in measuring flows up to about 150 gpm is the orifice bucket, developed by the Illinois State Water Survey (Johnson, 1975). The construction is shown in figure 9 and consists simply of a variable number of circular orifices in the bottom of a small drum. Provision, such as an external water level gage, is made to measure the head on the orifices and a rating curve developed for a single orifice. The total flow is then determined by multiplying the number of openings by the value obtained from the head/discharge curve. Some of the openings can be plugged to permit measurement of a wide range of flows. This device is particularly useful in measuring variable flows such as might result from a positive displacement pump.

A final technique, useful in obtaining rough estimates of discharges with a minimum of equipment, is to measure the dimensions of a stream flowing from an open pipe, oriented either vertically or horizontally. The technique for measuring the height of the crest of vertical jet flow is shown in figure 10 (from Johnson, 1975). Table 2 (from Johnson, 1975) gives the flow rate for various crest heights above the top of the pipe.

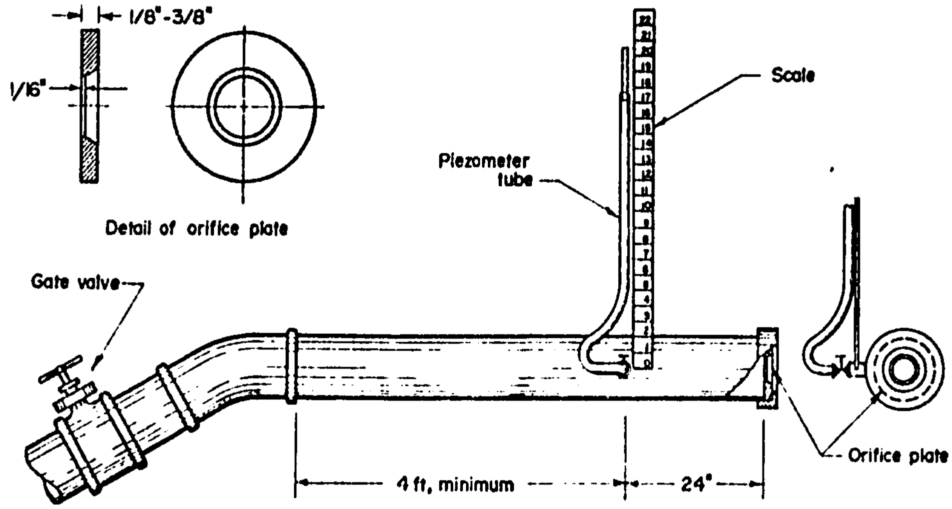

Figure 7. Circular Orifice Weir Used for Measuring Pumping Rates When Pumping with a Turbine Pump. Discharge Pipe Must be Level.

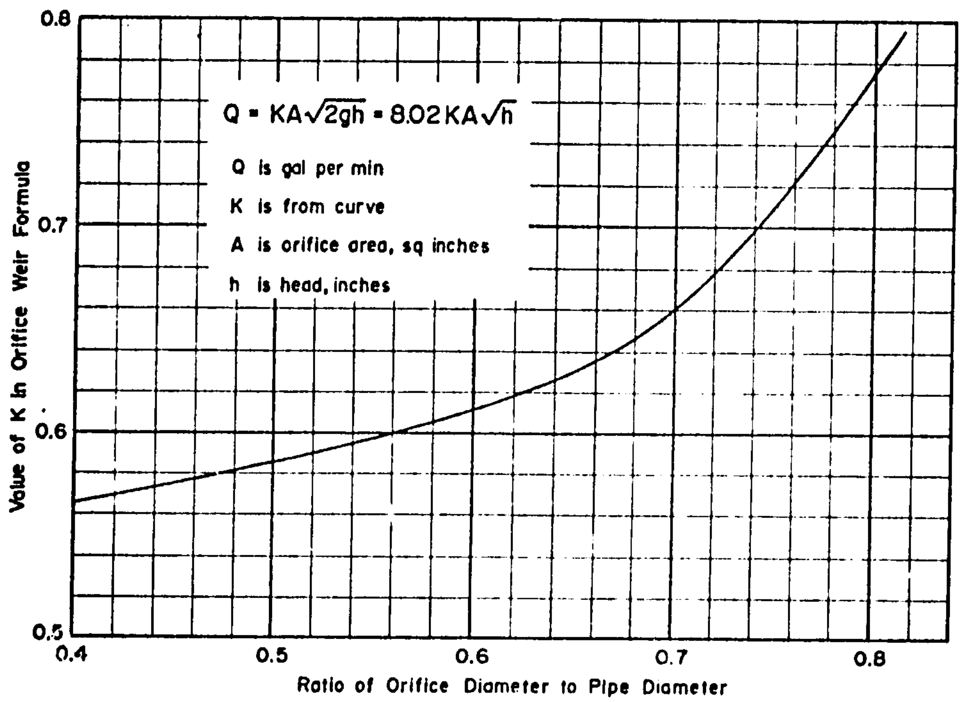

Figure 8. Value of Discharge Factor, K , in the Orifice-Weir Formula.

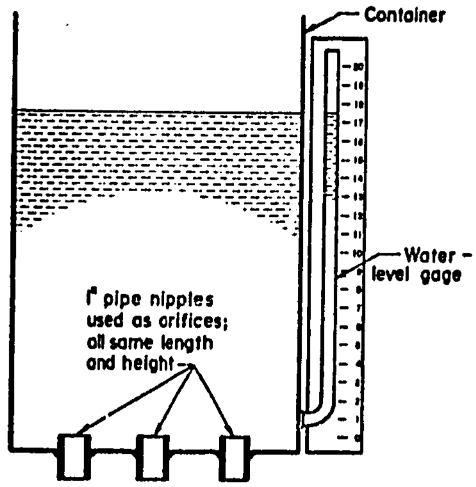

Figure 9. Orifice Bucket With Multiple Openings, Water Level Gauge Shows Head in Inches of Water During Operation.

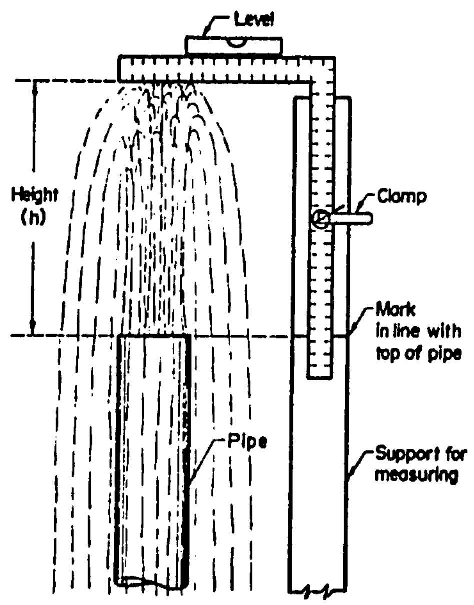

Figure 10. Measuring Height of Crest of Jet Flow From a Vertical Pipe.

Note that the flow must be jet-type discharge and reasonably steady. The vertical pipe should be a straight length, not less than three feet long.

Height of Crest, in inches	Nominal Diameter of Pipe					
	2"	3"	4"	5"	6"	8"
1 ½	22	43	68	85	110	160
2	26	55	93	120	160	230
3	33	74	130	185	250	385
4	38	88	155	230	320	520
5	44	99	175	270	380	630
6	48	110	190	300	430	730
8	56	125	225	360	510	900
10	62	140	255	400	580	1050
12	69	160	280	440	640	1150
15	78	175	315	500	700	1300
18	85	195	350	540	780	1400
21	93	210	380	595	850	1550
24	100	230	400	640	920	1650

Table 2. Discharge From Vertical Pipe, in gpm

Figure 11 (from Johnson, 1975) shows the method for obtaining discharge from the dimensions of the flow from a horizontal pipe. The theoretical equation, based only on inertial and gravitational forces, is $Q = 2.828\ D^2\ X/Y^{.5}$ where Q is the discharge in gpm, D is the inside diameter of the pipe in inches, X is the horizontal distance from the end of the pipe to the center of the stream in inches, and Y is the vertical distance from the center of the pipe to the point P in inches. Table 3 (from Johnson, 1975) shows a number of discharges for a set drop of 12 inches.

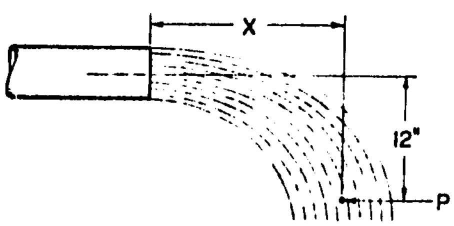

Figure 11. Measuring Rate of Flow From a Horizontal Pipe.

Table 3. Discharge From Horizontal Pipe Flowing Full, in gpm

Distance, X in inches, at 12" drop	Pipe diameter					
	2"	3"	4"	5"	6"	8"
6	21	46	80	125	181	312
7	24	54	93	146	211	364
8	28	61	106	167	242	416
9	31	69	119	188	272	468
10	35	77	133	208	302	520
11	38	84	146	229	332	572
12	42	92	159	250	362	624
15	52	115	199	313	453	780
20	70	154	265	417	604	1040

In some cases it may be desirable to place point P at the outer margin of the stream. In this case, the vertical reference should be the top of the stream at the pipe. In all cases the discharge pipe should be a straight length at least 5 feet long.

Gravity Flows

In most cases, water will enter the artificial conveyance system by gravity flow. If there is a permanent structure controlling the flow into the canal system, it can often be rated to relate gate position and head to flow. If this is not possible, any of the techniques described in the previous section can be used to determine the inflow.

For higher flow volumes, the canal velocity profile can be measured using a current meter and used to compute the flow into the canal from stage readings. If greater accuracy is desired, a permanent weir or flume can be constructed in an upper reach of the canal though this will be somewhat costly. Dye dilution methods can also be used. For measurement of smaller flows, portable flumes are relatively inexpensive and give good results.

Measurement of Conveyance Losses

Water losses from the conveyance system can take place through evaporation, spillage into the drainage system, or by movement into the soil profile beneath the canal. In the latter case, water may subsequently be taken up by phreatophytes and transpired or it may move downward to the water table. Such seepage losses may significantly reduce the quantity of water delivered to the farm turnout and can contribute directly to water logging and salinity problems.

Seepage

Seepage from unlined canals is governed by a number of interrelated factors including the characteristics of the canal bed, sediment content of the water, length of time the canal has been in operation, depth to ground water, depth of water in the canal, soil and water temperatures, percentage of entrained air in the soil, capillary pressure in the soil, and the wetted perimeter of the canal cross section (Robinson and Rohwer, 1959). Because of this plethora of variables, no satisfactory analytic formula for computing seepage losses has been developed. There are, however, several more or less successful empirical techniques for determining these losses.

Simple and inexpensive tests can be made with a seepage meter. In its simplest form, it consists of a bell-shaped housing which is connected by a length of tubing to a plastic bag full of water suspended above it. In use, the housing is pressed into the bed of the canal, isolating that small section of the bed. The amount of water which then flows out of the suspended reservoir, under pressure gradients similar to those of adjacent sections of canal bed, is a measure of the seepage occurring from a given area over a given length of time.

Unfortunately, results are difficult to reproduce accurately, although the average of a number of separate determinations does indicate correctly the order of magnitude of the losses occurring. Best accuracy is achieved when seepage rates of less than 1 ft^3/ft^2/day are measured at least a week after emplacement. Measurements should also be made on the sides of the canal as seepage is often higher here than through the canal bot.om.

In an extensive series of tests made in the early fifties, Robinson and Rohwer (1959) found that seepage can vary from 26 ft^3/ft^2/day in clay loam to 0.01 ft^3/ft^2/day in silt loam. In view of this wide range of seepage rates, seepage meter measurements establishing an order of magnitude are clearly useful in the absence of more accurate determinations.

Another relatively simple method of measuring seepage losses is the inflow/outflow technique. As the name implies, this method consists of measuring, as accurately as possible, all of the water entering and leaving a given reach of canal over a given time interval. In addition to the canal inflow and outflow, all diversions, leaks, and drainage inflows must be measured. Rainfall and evaporation should also be determined. During the course of the test, the water stage in the canal must be held constant to eliminate the effects of bank and channel storage. Measurement of large flows such as canal inflow and outflow can be made with a current meter or a rated control structure. Smaller flows such as leaks and diversions can be measured with weirs and flumes or volumetrically.

This method has the advantage of being relatively simple and can be used without disrupting the operation of the canal. Unfortunately, the seepage losses are often of the same order of magnitude as the uncertainty involved in measurement. It is most successful when used for long sections of canal with few diversions and with appreciable seepage.

A modification of this method which, at present, is not widely used is the substitution of fluorescent dye injection at the upper end of the reach for the current meter rating. By comparing the results of dye sampling and current meter ratings at the outflow end of the reach, losses can be determined.

A third method of determining seepage losses is the ponding method. Temporary dams are constructed at either end of a stretch of canal and water ponded between them. Hook or staff gages are used to measure the drop in water surface elevation over given time periods, and knowing the geometry of the canal, seepage rates per unit wetted surface area can be computed. Stage measurements should be made at both ends of the canal section to eliminate wind effects.

This method is the most accurate of the three and is the standard by which other procedures are evaluated. It does, however, have disadvantages. It can only be used when the canal is not in use, and at such times obtaining water to fill the pool may be difficult. Constructing the temporary dams, particularly in larger canals is expensive, and high channel gradients may limit the reach of canal which can be isolated. Still, when affordable, it is the best available method for accurately determining canal seepage losses.

Phreatophytes

Indigenous vegetation in arid areas often is composed largely of phreatophytes, or plants which habitually obtain their water supply from the zone of saturation, either directly or through the capillary fringe. The term,phreatophyte, is a hybrid one, created by O. E. Meinzer from the Greek roots "phreatos" meaning a well, and "phyte", a combination form denoting a plant having a particular characteristic or habitat. It first appeared in published form in USGS Water Supply Paper 494 in 1923 (Meinzer, 1923), and has since come into common usage. It overlaps, to some extent, the traditional ecologic groupings of halophytes, which can tolerate high concentrations of salts in the soil water, and hydrophytes, or plants which grow with their roots wholly or partially submerged.

The importance of phreatophytic vegetation to irrigated agriculture stems from its consumptive use of ground and, indirectly, of surface water which would otherwise be available for more beneficial uses. The roots of some phreatophytes can tap ground water at depths of over 100 feet and many are heavy users of water, with annual transpiration rates ranging as high as 9 acre feet/year/acre. The actual rate of water use by these plants depends upon a number of factors, including climatic conditions, depth to groundwater, groundwater quality, volume of vegetation per unit area, mix of species, and the expanse of vegetated area (Hughes and McDonald, 1966).

The primary effect of transpiration by phreatophytes is to deplete groundwater supplies and, as a result, to increase the concentration of dissolved solids in the remaining water. As a consequence of these groundwater withdrawals, the water table drops and induced recharge, in the form of seepage from nearby canals and streams, is increased. These effects are shown clearly by the seasonal and diurnal fluctuations in both groundwater levels and stream flows in areas inhabited by phreatophytes which correlate closely with periods of plant activity (Robinson, 1958).

The subject of phreatophytes is introduced here because of the influence these plants exert on seepage losses from the canal system. Quantitatively, ET by phreatophytes is considered as a withdrawal from ground water and does not enter into a consideration of canal losses directly. Methods for determining phreatophyte ET are considered in Chapter VI.

Spillage and Bypass Water

Bypass water is water which passes through an entire canal and is returned directly to the river. Its purpose is to regulate flow in the canal. Intentional spillage is also used at times to regulate canal flow and prevent canal bank overtopping. Both of these practices, while wasteful of water, have little effect on water quality. Their quantities, however, must be measured using flumes or rated control structures for consideration in the water and salt budgets.

Unintentional spillage as a result of breaks and overtopping can also occur and, if allowed to continue, cause substantial errors in later calculations. The conveyance system should be monitored closely for such spills and repairs effected promptly. If the break is a major one, an estimate can be made of the volume of the spill flow and the length of time it had been taking place. Discharge could be measured with a portable flume, or, in the worst case, estimated visually.

Evaporation

Evaporation taking place from canal water surfaces can best be handled using one of the empirical relations discussed in the following chapter. These equations use climatic data to determine the volume of water evaporated daily per unit surface area. A corrected value of pan evaporation can also be used for this purpose. The free water surface area needed to calculate total evaporative losses from a reach of canal can be determined from the average canal width at the average depth of flow and the length as determined from the earlier mapping of the canal system.

Dead Storage

The best means of accounting for canal storage is to eliminate it as a factor by beginning and ending data collection when the canal system is full.

Subsystem Outputs

Having measured the quantity and quality of diversions to the water delivery subsystem and the losses from it, we are able to determine the subsystem outputs. The residual of water diverted, less losses, is the delivery to the farm-use subsystem. This is water which is delivered to farm turnouts for use in irrigating crops. It is possible to check this value independently by summing the measured flow of such diversions directly, but if the number of turnouts is large, this is a difficult and expensive task.

The sum of spillage and bypass water and seepage is the delivery to the drainage and removal subsystem. These flows are handled separately as surface and sub-surface components.

Evaporation comprises water lost from the system entirely. It evaporates as pure water and increases the concentrations of dissolved solids in the remaining fluid components proportionately. This will be discussed in greater detail in Chapter VII.

Chapter VI

THE DRAINAGE AND REMOVAL SUBSYSTEM

Description and Boundary Definition

The drainage and removal subsystem comprises both surface and subsurface flows. Surface flows are derived from field runoff or tailwater, canal spillage, and bypass water. Subsurface flows result from canal seepage and deep percolation. River and aquifer outflows may also be considered a part of the drainage and removal subsystem.

Defining boundaries for this subsystem is somewhat complicated. Surface drainage channels are obviously included. Subsurface drainage flows, vertically from the bottom of the root zone to the water table and horizontally to an effluent water course, would also seem to be necessary components. The lower portion of the river which receives these inflows and the subsurface flows taking place toward the system boundary must be included also.

This means that both the river or rivers flowing through the system and, in the case of conjunctive use of ground and surface waters, the groundwater aquifer, are serving as both delivery and removal agents. Furthermore, in some locations they may serve both functions simultaneously. While inelegant from an organizational point of view, this overlapping does not cause serious practical problems. The subsystem can be defined as comprising the surface drainage channels, the river from the point of the first runoff inflow to the lower system boundary, and virtually the entire subsurface flow regime from the bottom of the root zone to the bottom of the groundwater aquifer.

Mapping the Drainage and Removal Subsystem

The surface drainage channel system must be mapped, at least for the intensive study area and preferably for the entire system, as described in Chapter V. This is most conveniently done in conjunction with the mapping of the water delivery subsystem and the land use survey.

Measurement of Outflows Across System Boundaries

Surface Flows

All surface outflows of water and dissolved solids across system boundaries must be measured. Often in arid irrigated regions, surface outflow will consist of a single river, which simplifies this task considerably. The quantity of outflow can be measured at the system boundary by establishing gaging stations and rating control sections of the rivers involved, or by utilizing data from a nearby existing gaging station. Water samples for laboratory analysis of dissolved solids, pH, temperature, sediment, and other quality characteristics should also be taken at the same locations periodically.

Subsurface Flows

As described in the section on measuring inflows in Chapter IV, groundwater flows are immensely more difficult to measure than are surface flows. If groundwater outflows from the system are considerable, a complete water budget analysis requires that they be measured or estimated. Measurement will require a program of test drilling at the boundaries where the outflows occur to determine hydraulic gradients, aquifer conductivities, and cross-sectional areas of flow. This is an expensive and time-consuming task.

In many cases, the magnitude of such outflows will be small with respect to the groundwater outflows to effluent drainage channels and rivers within the system. In these cases, groundwater outflows across the system boundary can be ignored with little loss in budgeting accuracy. In any event, the measurement of groundwater flows is sufficiently imprecise that a non-steady state analysis is unwarranted unless a groundwater study is the specific objective of the project (Skogerboe and Walker, 1972).

Subsurface Investigations

Stratigraphy and Groundwater Contours

To gain some quantitative understanding of the occurrence, distribution, and flow of subsurface water, it is necessary to assemble a number of indirectly acquired data. Although groundwater occurs under both saturated and unsaturated conditions, consideration is restricted to the zone of saturation. The existence of subsurface water at pressures less than atmospheric is recognized by assuming that the amount of water held in the soil between the bottom of the root zone and the water table is constant throughout the period of study.

The first step in any groundwater investigation is an analysis of published geologic data for the study area supplemented by geologic field reconnaissance. Such an analysis can indicate the extent, regularity, continuity, and interconnection of aquifers, and the existence of aquifer boundaries. It can also suggest the nature and thickness of overlying beds as well as the dip of aquifer formations (Todd, 1967).

Additionally, existing information relating to groundwater and subsurface geology should be sought out. Such information includes drillers' logs; drilling time logs; previously determined values of aquifer constants; data on groundwater levels, pumping records, pumping tests, and artificial recharge data that can be correlated or interpreted to yield information on aquifer properties. Drillers' logs are an extremely useful aid in determining stratigraphy and the extent, thickness, and location of water-permeable formations.

In conducting a steady state analysis of groundwater storage and flow, it is necessary to learn the prevailing vertical and horizontal hydraulic gradients, the hydraulic conductivity and saturated thickness of the aquifer, and its specific yield or storage coefficient. Much of this information can be derived by putting down a number of piezometers or small bore observation wells and conducting appropriate tests. These wells can also be used for collecting groundwater samples for quality analysis.

Observation wells and piezometers can be emplaced by jetting, in the absence of rocks and heavy clay formations, or by cable-tool rig. If existing data is limited and the scope of the project warrants, the wells can be placed in a regular grid pattern and supplemented with additional wells in areas of special interest. Additional information on stratigraphy will be obtained in the drilling process which will enable location of impermeable layers and the later determination of saturated thicknesses. In applying the method used by Walker (1970), a double line of wells along the boundary of groundwater outflow into an effluent water course is required.

By placing a number of piezometers terminating at different depths at the same location, vertical hydraulic gradients can be measured. Comparison of water level elevations, taken periodically, in piezometers of the same depth but from different clusters will indicate the horizontal gradients.

The existence of vertical gradients indicates the presence of confining strata which should then be investigated further with respect to extent and continuity. Horizontal gradients can be used to plot lines of equal potential by triangulation. Flow lines can be drawn in orthogonally to indicate the direction of subsurface water movement. The magnitude of the horizontal gradient in a given region, together with the hydraulic conductivity and the saturated thickness, can be used to determine the magnitude of the flow. If the scope of the investigation warrants, a finite difference model can be used to model changes in groundwater storage and flow. Methods of obtaining hydraulic conductivity measurements, the most difficult parameter to determine, are discussed in the following section.

Hydraulic Conductivity Measurements

The method selected for measuring hydraulic conductivity, K, should be such that the soil region and flow direction used for the measurement adequately represent the soil and flow direction of the actual system. In layered soils, the K of each layer should be determined separately. The most commonly used techniques for determining horizontal conductivities are, in order of increasing volume of soil sampled, the piezometer method, the auger hole method, and the multiple well method. All of the techniques discussed assume the presence of a water table near the ground surface.

In the piezometer method, proposed by Kirkham in 1946 (Bouwer and Jackson, 1974), a small bore tube is installed to some point below the water table and a cavity of height h_c created beneath it. After the water level in the piezometer has come to equilibrium with the water level in the soil, the water in the piezometer is quickly withdrawn by suction or bailing. The rate at which it again rises in the tube is then measured. The geometry and symbols for the piezometer are shown in Figure 12.

The hydraulic conductivity is determined with the formula

$$K = \frac{r^2 \pi}{A(t_2 - t_1)} \ln(y/y_2)$$

where K has the same units as those selected for the time and length factors, t represents time, and A is a factor depending on the geometry of the system. Values for the ratio A/r, determined by electric analog, are given in Table 4. The method measures K in an essentially horizontal direction if h_c is large compared to r. The volume of soil sampled is about 10^3 cm^3.

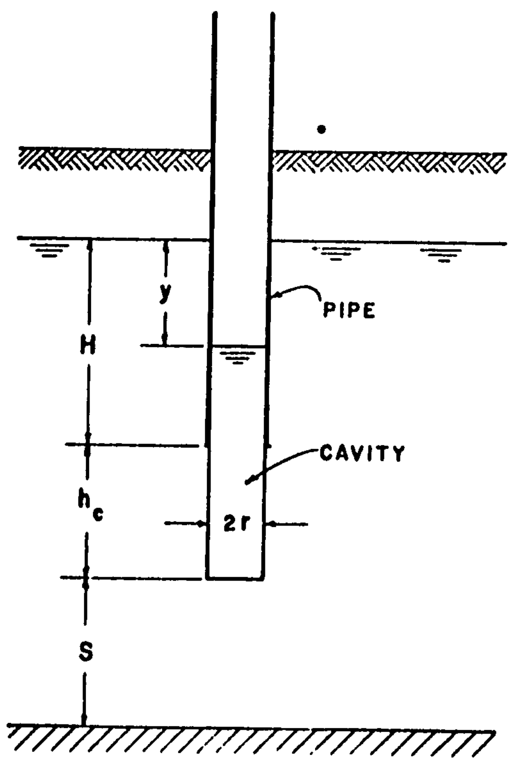

Figure 12. Geometry and Symbols for the Piezometer Method (from Bouwer and Jackson, 1974).

Table 4. Values of A/r for Piezometer Method with Cylindrical Cavities (Youngs, 1968)

h_c/r	H/r	S/r for impermeable layer							S/r for infinitely permeable layer						
		∞	8.0	4.0	2.0	1.0	0.5	0	∞	8.0	4.0	2.0	1.0	0.5	0
0	20	5.6	5.5	5.3	5.0	4.4	3.6	0	5.6	5.6	5.8	6.3	7.4	10.2	∞
	16	5.6	5.5	5.3	5.0	4.4	3.6	0	5.6	5.6	5.8	6.4	7.5	10.3	∞
	12	5.6	5.5	5.4	5.1	4.5	3.7	0	5.6	5.7	5.9	6.5	7.6	10.4	∞
	8	5.7	5.6	5.5	5.2	4.6	3.8	0	5.7	5.7	5.9	6.6	7.7	10.5	∞
	4	5.8	5.7	5.6	5.4	4.8	3.9	0	5.8	5.8	6.0	6.7	7.9	10.7	∞
0.5	20	8.7	8.6	8.3	7.7	7.0	6.2	4.8	8.7	8.9	9.4	10.3	12.2	15.2	∞
	16	8.8	8.7	8.4	7.8	7.0	6.2	4.8	8.8	9.0	9.4	10.3	12.2	15.2	∞
	12	8.9	8.8	8.5	8.0	7.1	6.3	4.8	8.9	9.1	9.5	10.4	12.2	15.3	∞
	8	9.0	9.0	8.7	8.2	7.2	6.4	4.9	9.0	9.3	9.6	10.5	12.3	15.3	∞
	4	9.5	9.4	9.0	8.6	7.5	6.5	5.0	9.5	9.6	9.8	10.6	12.4	15.4	∞
1.0	20	10.6	10.4	10.0	9.3	8.4	7.6	6.3	10.6	11.0	11.6	12.8	14.9	19.0	∞
	16	10.7	10.5	10.1	9.4	8.5	7.7	6.4	10.7	11.0	11.6	12.8	14.9	19.0	∞
	12	10.8	10.6	10.2	9.5	8.6	7.8	6.5	10.8	11.1	11.7	12.8	14.9	19.0	∞
	8	11.0	10.9	10.5	9.8	8.9	8.0	6.7	11.0	11.2	11.8	12.9	14.9	19.0	∞
	4	11.5	11.4	11.2	10.5	9.7	8.8	7.3	11.5	11.6	12.1	13.1	15.0	19.0	∞
2.0	20	13.8	13.5	12.8	11.9	10.9	10.1	9.1	13.8	14.1	15.0	16.5	19.0	23.0	∞
	16	13.9	13.6	13.0	12.1	11.0	10.2	9.2	13.9	14.3	15.1	16.6	19.1	23.1	∞
	12	14.0	13.7	13.2	12.3	11.2	10.4	9.4	14.0	14.4	15.2	16.7	19.2	23.2	∞
	8	14.3	14.1	13.6	12.7	11.5	10.7	9.6	14.3	14.8	15.5	17.0	19.4	23.3	∞
	4	15.0	14.9	14.5	13.7	12.6	11.7	10.5	15.0	15.4	16.0	17.6	20.1	23.8	∞
4.0	20	18.6	18.0	17.3	16.3	15.3	14.6	13.6	18.6	19.8	20.8	22.7	25.5	29.9	∞
	16	19.0	18.4	17.6	16.6	15.6	14.8	13.8	19.0	20.0	20.9	22.8	25.6	29.9	∞
	12	19.4	18.8	18.0	17.1	16.0	15.1	14.1	19.4	20.3	21.2	23.0	25.8	30.0	∞
	8	19.8	19.4	18.7	17.6	16.4	15.5	14.5	19.8	20.6	21.4	23.3	26.0	30.2	∞
	4	21.0	20.5	20.0	19.1	17.8	17.0	15.8	21.0	21.5	22.2	24.1	26.8	31.5	∞
8.0	20	26.9	26.0	25.5	24.0	23.0	22.2	21.4	26.9	29.6	30.6	32.9	36.1	40.6	∞
	16	27.4	26.3	25.8	24.4	23.4	22.7	21.9	27.4	29.8	30.8	33.1	36.2	40.7	∞
	12	28.3	27.2	26.4	25.1	24.1	23.4	22.6	28.3	30.0	31.0	33.3	36.4	40.8	∞
	8	29.1	28.2	27.4	26.1	25.1	24.4	23.4	29.1	30.3	31.2	33.8	36.9	41.0	∞
	4	30.8	30.2	29.6	28.0	26.9	25.7	24.5	30.8	31.5	32.8	35.0	38.4	43.0	∞

Since the exact diameter and length of the cavity formed beneath the piezometer are often difficult to determine, particularly in unstable soil, the lower section of the piezometer is sometimes perforated and screened. This creates a "cavity" of known dimensions and can be used to measure K as outlined above. The value of A in this case depends on the geometry of the well point. For a standard 1/4 inch "Pomona" well point with a 40 mesh brass screen, the value of A is 19 cm (7.5 inches).

Alternatively, a suction tube can be lowered into the piezometer to a certain depth below the water table and continuous suction applied. An equilibrium flow rate is determined and the hydraulic conductivity determined from tables given in Donnan and Aronovici (1961).

The auger hole technique was first applied by Diserens in 1934. It is similar in principal to the piezometer method, but employs a somewhat larger augered hole, 4 to 8 inches in diameter, and thus samples a larger volume of soil. Geometry and symbols are shown in Figure 13.

Boast and Kirkham (1971) developed an exact solution for the flow into the hole with the depth of the lower boundary as a variable. This lower boundary was taken to be either an impermeable layer or a layer of infinite permeability. They used an expression of the form

$$K = C(\Delta y/\Delta t)$$

and presented values of C in tabular form as shown in Table 5. In the table, y is expressed in centimeters and t in seconds with K given in meters/day. Interpolation should be done logarithmically. The region of soil sampled is of the order of $0.4H\ m^3$, where H is in meters.

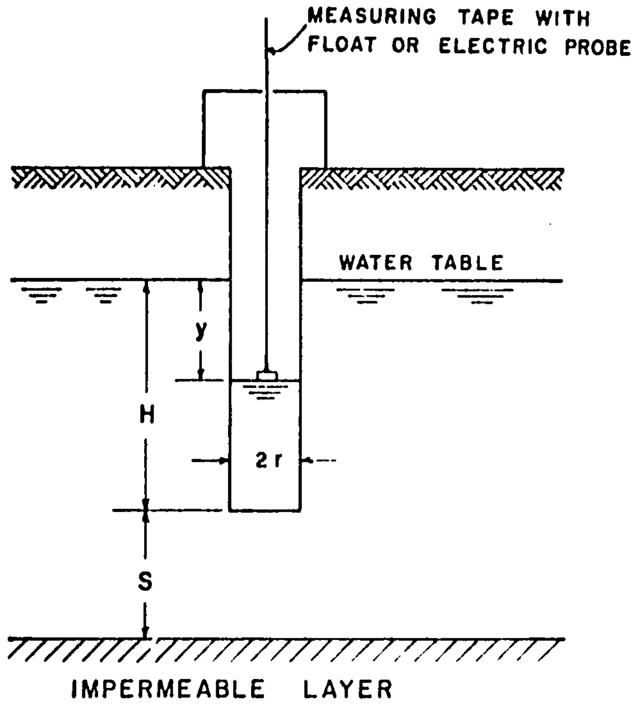

Figure 13. Geometry and Symbols for the Auger-Hole Method (from Bouwer and Jackson, 1974).

Table 5. Values of C for an Auger Hole Underlain by Impermeable or Infinitely Permeable Material (Boast & Kirkham, 1971)

		S/H for impermeable layer								S/H	S/H for infinitely permeable layer			
H/r	y/H	0	0.05	0.1	0.2	0.5	1	2	5	∞	5	2	1	0.5
1	1	447	423	404	375	323	286	264	255	254	252	241	213	166
	0.75	469	450	434	408	360	324	303	292	291	289	278	248	198
	0.5	555	537	522	497	449	411	386	380	379	377	359	324	264
2	1	186	176	167	154	134	123	118	116	115	115	113	106	91
	0.75	196	187	180	168	149	138	133	131	131	130	128	121	106
	0.5	234	225	218	2 7	198	175	169	167	157	166	164	156	139
5	1	51.9	48.6	46.2	42.8	38.7	36.9	36.1		35.8		35.5	34.6	32.4
	0.75	54.8	52.0	49.9	46.8		41.0	40.2		40.0		39.6	38.6	36.3
	0.5	66.1	63.4	61.3	58.1	53.9	51.9	51.0		50.7		50.3	49.2	46.6
10	1	18.1	16.9	16.1	15.1	14.1	13.6	13.4		13.4		13.3	13.1	12.6
	0.75	19.1	18.1	17.4	16.5	15.5	15.0	14.8		14.8		14.7	14.5	14.0
	0.5	23.3	22.3	21.5	20.6	19.5	19.0	18.8		18.7		18.6	18.4	17.8
20	1	5.91	5.53	5.30	5.06	4.81	4.70	4.66		4.64		4.62	4.58	4.46
	0.75	6.27	5.94	5.73	5.50	5.25	5.15	5.10		5.08		5.07	5.02	4.89
	0.5	7.67	7.34	7.12	6.88	6.60	6.48	6.43		6.41		6.39	6.34	6.19
50	1	1.25	1.18	1.14	1.11	1.07	1.05			1.04			1.03	1.02
	0.75	1.33	1.27	1.23	1.20	1.16	1.14			1.13			1.12	1.11
	0.5	1.64	1.57	1.54	1.50	1.46	1.44			1.43			1.42	1.39
100	1	0.37	0.35	0.34	0.34	0.33	0.32			0.32			0.32	0.31
	0.75	0.40	0.38	0.37	0.36	0.35	0.35			0.35			0.34	0.34
	0.5	0.49	0.47	0.46	0.45	0.44	0.44			0.44			0.43	0.43

The two-well technique, proposed by Childs (1952) consists of two auger holes of equal dimensions set about 1 meter apart. Water is pumped from one hole and into the second at a constant rate. When equilibrium is reached, the water level in each hole is measured and the difference taken. The hydraulic conductivity, K, is obtained from the equation

$$K = \frac{Q}{\pi \Delta H (H + L_f)} \cosh^{-1} (D/2r)$$

where Q is the pumping rate, ΔH is the equilibrium water level difference, D is the distance between the centers of the auger holes, r is the radius of the holes, H is the average depth of water in the holes, and L_f is an end correction to be applied if the average height of the flow system between the wells exceeds H. It accounts for partially saturated flow above the water table and for non-linear flow through the bottoms of the holes. The former is sometimes taken to be one-half the height of the capillary fringe and the latter about 20 cm for holes of about 10 cm diameter. The head difference, H, should be small but measurable to validate the assumption of horizontal flow.

The multiple-well technique is an extension of the two-well technique and increases the volume of soil sampled. It consists of a radially symmetrical array of pumping and receiving wells arranged in alternate and symmetrical fashion on the circumference of a circle. Hydraulic conductivity is calculated from the formula

$$K = \frac{Q}{n \pi \Delta H (H + L_f)} \ln \frac{4D}{nr}$$

where Q is the total flow rate in the system, n is the number of auger holes in the circle, H is the average value of the head difference between alternating holes, and the other terms are as defined above. Since the volume of soil sampled is roughly equal to the total volume of the auger holes, sampled volume increases with the number of holes. The two- and multiple-well techniques are suitable for use in stony soil (Bouwer and Jackson, 1974).

The Fate of Subsurface Water

Water leaves the system groundwater regime by phreatophyte uptake, by drainage channel or water course interception, or by outflow across system boundaries. The latter of these routes has already been discussed.

It is also possible for water tables close to the surface to lose water by direct evaporation from the soil surface through the mechanism of capillary rise. Consistent with the system of definitions and measurements thus far developed, however, it is assumed that the water table lies below the bottom of the root zone. In this case, such direct evaporation should be minimal. If this is not the case, the water budget may have to be modified to employ measured groundwater flows and to treat direct surface evaporation as a residual. This will result in increased complexity and reduced accuracy in the budgeting process.

Interception

Interception by drainage channels and water courses is often a significant factor in the groundwater budget. It can be accounted for quantitatively by measuring the quantity and TDS concentration of all surface flows into a portion of the drainage subsystem and the quantity and quality of the drainage outfall. Ignoring evaporation from drainage channel water surfaces, any difference between the sum of surface inflows and the surface outfall can be attributed to groundwater interception. This can be varified by a simple salt balance using the quantities and concentrations of the surface inflows and outfall and the known concentration of the groundwater to arrive at the quantity of groundwater intercepted.

Phreatophytes

Water used by phreatophytes is considered in water budget calculations as a direct withdrawal from groundwater. This is not entirely correct as water use by phreatophytes can cause increased seepage from canals by lowering the water table locally as discussed in Chapter V.

Of greater difficulty, however, is the problem of determining the actual quantity of phreatophyte water usage. As pointed out in Chapter V, actual water usage depends on climatic conditions, depth to groundwater, groundwater quality, volume of vegetation per unit area, mix of species, and the expanse of vegetated area. The problem is thus somewhat more difficult than measuring ET from a given area of a single species of an agricultural crop, which is usually well supplied with water and of uniform plant density.

One approach is to assume that phreatophytic vegetation uses water at the PET rate. This ignores, however, all but the climatic factors. If water use by phreatophytes is a significant portion of the water budget, this approach, in many cases, will give an accurate estimate of ET only fortuitously. The major variable, volume density of vegetation, was found by Gatewood et al. (1950) to be linearly related to ET. This should certainly be considered in estimating the amount of water withdrawn from groundwater by phreatophyte ET. Some data on water use for various species of phreatophytes, usually parameterized by depth to water table, have been collected and tabulated (see for example Robinson, 1958).

Existing data, however, is generally insufficient to make more accurate estimates of phreatophyte water use based on measurable field variables. At present, the only practical means of estimating phreatophyte ET with reasonable accuracy is through lysimeter studies which match existing field conditions of water table depth, water quality, and volume density of vegetation as closely as possible. Guidelines for surveying phreatophytic vegetation can be found in USDA (1964).

Storage

The groundwater regime is not a simple input-output system but has significant storage capability as well. To account for this storage in a water budget, it is necessary to determine the specific yield of the soil comprising the shallow groundwater aquifer. Specific yield is defined, on a fractional basis.as the ratio of the volume of water which drains from an initially saturated section of aquifer under the influence of gravity to the bulk volume of the soil initially containing that water. It is the complement of residual saturation. Specific yield can be approximated by the porosity of the soil but differs from it by the volume of water held in place by molecular and surface tension forces. Specific yield can be determined in the field or in the laboratory from an undisturbed core sample of the aquifer material.

Chapter VII

ANALYZING DATA

The Nature of the Problem

Keeping in mind the overall goal of the investigation, most probably the increase of agricultural production on a regional or national basis, there are two important problem impacts to be considered. The first is the nature of the adverse conditions caused by waterlogging and soil salinization in the plant root zone. The second is the external effect on agricultural and other users down slope from the system under investigation. The relative importance of these two considerations must be related to national or regional goals and conditions specific to the situation. External effects are usually considered most conveniently as constraints on the quantity and quality of surface and groundwater flows out of the system.

Waterlogging

Although we know that waterlogging affects crops primarily through its influence on gas diffusion, soil microflora, and soil temperature, it is at present difficult to separate these factors and to predict their individual effects on growing plants. In addition, the determination of basic data such as soil aeration and thermal capacity is difficult. Finally, soil properties and conditions vary over depth and time throughout the growing season, requiring non-steady-state solutions. As a result, use is often made of water table depth as an easily measured substitute variable. Values for acceptable water table depths commonly given range up to three and five meters. Significant amounts of water also exist above the water table held in place by capillary forces; this water must also be considered. The distribution of this so-called capillary fringe is dependent primarily on pore size and distribution within the soil profile but its effect on a crop depends also on the rooting depth and tolerance of the crop to the effects mentioned earlier. As a crude rule of thumb, FAO/UNESCO suggests the following depths to the water table not be exceeded: clay soils, 1.50 meters; loamy soils, 1.20 meters; sandy soils, 0.8 meters (FAO, 1973). The variation with soil type illustrates the importance of the water held above the water table.

Under conditions of irrigated agriculture, the water table depth will probably not be static, as implied above, but will fluctuate through the irrigation cycle and the cropping season. Sieben (quoted in Wessling, 1974) proposes an index to indicate the number of days per season that the water table depth is less than some specified value, in his case 30 cm. While a step in the right direction, this concept ignores such significant variables as the amount of excess water over threshold value, the effect of consecutive days of waterlogging, crop related factors, and soil type (and hence the amount and distribution of water above the water table). Presumably these last two factors could be integrated into the threshold value.

The water table elevations throughout the study area can be taken from the observation wells and piezometer clusters installed in the subsurface investigations. In general, it is safe to say that water tables below 5 meters (16.4 feet) will not result in waterlogging problems. Water tables closer than this to the surface must be examined for possible influence, at least in the transient state. Tensiometer readings, gravimetric sampling, or neutron probe data can be used to determine whether the SMC within the root zone at various times during the irrigation cycle is at or near saturation.

The tolerance or sensitivity of crops to waterlogging depends on 1) plant species, 2) air temperature, 3) duration of flooding, and 4) stage of plant growth (FAO/UNESCO, 1973). Alfalfa is among the most sensitive crops and can be permanently damaged by periods of flooding of 24 hours or less on hot summer days. Tolerance to waterlogging for a number of common, actively growing crops is shown in Appendix C. The times indicated can be lengthened considerably by cool temperatures. As far as stage of growth is concerned, most crops are least tolerant during the flowering stage and most tolerant during the fruit stage of growth (FAO/UNESCO, 1973).

Salinity

With the exception of boron, little is known about the toxic influence of specific ions on agricultural crops. Boron has been the subject of considerable research and crop-specific tolerances are given in Appendix C.

Present U.S. standards for trace elements are written in terms of the permissible concentrations of potentially toxic trace elements in irrigation water. If a specific toxicity is suspected, both the applied water and tissue of affected plants can be analyzed.

Since little is known about the concentration and storage of these trace elements in the soil, an intervening variable which should be examined is trace element concentration in the soil water solution. By conducting controlled experiments with soil water solutions of known specific ion concentrations, crop response functions to these ions can be determined. The resulting set of criteria based on soil water concentrations would seem to be of more use to the agriculturist than standards based on irrigation water quality.

Approaching the system from the other end, measuring soil water concentrations in fields which have been irrigated over long periods of time with waters high in specific ions would provide information on storage and concentration effects. This is potentially a more difficult problem since soil physical and ion exchange characteristics would be significant varying parameters.

Nutritional imbalance is a related though uncommon problem. Its existence is suggested by characteristic plant injury symptoms and verified by chemical analysis of plant tissue. Effects of nutritional disturbances vary widely among crops and among individual crop varieties, and a problem can often be solved by a switch to a better adapted variety (Bernstein, 1964).

The harmful osmotic effect of saline soil water solutions is due almost entirely to the total amount of solids dissolved in them. To evaluate this effect it is necessary to obtain and analyze samples of these solutions. It would be most desirable to extract samples at moisture contents normally found in the field; that is, those moisture contents bounded by the field capacity (FC) and the permanent wilting point (PWP) of the soil.

This can be done using displacement or suction techniques, but it is a difficult and time-consuming process. Consequently, the technique normally used in the laboratory is to obtain the soil water solution sample at saturation moisture content since this is the lowest moisture content at which the sample can conveniently be extracted from the soil.

In obtaining a saturation extract for analysis, distilled water is added to a soil sample until a pre-determined end-point consistency is reached (see Richards et al, 1954). A portion of the soil water is then drawn off under vacuum and analyzed for common ions using standard laboratory techniques. Ions ordinarily included in such an analysis are the cations calcium, magnesium, sodium, and potassium and the anions carbonate, bicarbonate, chloride, sulfate, and nitrate. Silicates are also sometimes included.

The difficulty in this is that at saturation, the moisture content of the sample is several times greater than field moisture contents. This requires that the concentrations of the various ions be adjusted mathematically to the moisture contents typical of the field if actual root zone conditions are to be described.

Fortunately, while the end points of the field moisture range vary from soil to soil, the saturation percentage is reasonably related to them. As a general rule, Richards et al. (1954) found that the saturation moisture content is approximately twice the moisture content of a given soil at field capacity and four times the value at the permanent wilting point. Corresponding ion concentrations should therefore be increased by factors of 2 and 4. By operationally defining these points at suctions of 1/3 atmospheres and 15 atmospheres respectively, the adjustment can be made more precisely.

The second and more serious problem connected with the saturation extract technique is the dependence of the amount of total dissolved solids (TDS) and of relative ionic composition on soil moisture content before extraction. Some minerals, such as the alkaline-earth carbonates, which precipitate out of solution at field moisture contents, may re-dissolve at the higher saturation percentage. This can lead to the over-estimation of the concentrations of such ions as calcium, magnesium, sulphate, carbonate, and bicarbonate.

This type of error, while in a conservative direction, can be serious. Attempts have been made to model such changes in TDS, but they are complicated and depend on a wide range of variables. An empirical measure, the Langier Saturation Index, is sometimes used to predict the direction and approximate magnitude of the solution reaction for carbonates in irrigation water under various irrigation management regimes (McNeal, 1974).

Additional problems attend the saturation extract technique. In the process of saturating the soil sample, soil structure is destroyed, and thus the extract does not indicate exactly soil salinity under field conditions. It also does not show salinity gradients resulting from water extraction by roots. This problem can be partially alleviated by taking soil samples from various depths within the profile. In spite of these drawbacks, the saturation extract technique provides the basis for a number of parameters useful in assessing the effects of salinity on agricultural systems.

TDS can be determined directly in the laboratory by summing the concentrations of ions found in the saturation extract. This process, however, is time-consuming and expensive if the number of samples is large. As a result, the electrical conductivity (EC) of the saturation extract solution (EC_e) is often used instead.

Electrical conductivity is measured by passing a current through a known distance of solution and obtaining the reciprocal of the specific resistance to the current flow. The unit used for conductance is the mho, "ohm" reversed. The mho is usually subdivided into 1000 parts and the unit millimho used. The measurement is standardized by dividing by the distance the current travels in the solution, resulting in millimhos/centimeter. Since the current flow is directly related to the number of ions in the solution, EC_e is a measure of the TDS of the solution. Such measurements are simple and relatively cheap.

Unfortunately, EC values also vary with ionic composition, although in the range of concentrations which permit plant growth, the variance is not excessive. Better results are achieved by expressing concentrations in chemical equivalents as can be seen by comparing figures 14 and 15 (from Richards et al, 1954).

An equivalent is the atomic or formula weight of an ion divided by its charge. This way of expressing concentrations eliminates the variance due to ion mass and charge. Because the concentrations found are usually much less than an equivalent, the smaller unit milliequivalent is used.

Figures 16 and 17 show the results of regression analyses conducted at the U.S. Salinity Laboratory in Riverside relating EC_e to TDS and osmotic potential respectively. Whenever possible, sufficient concurrent TDS and EC_e data should be taken initially to allow a regression analysis for the area under study to be done. Subsequently, TDS can be inferred from EC_e readings.

In figure 17 osmotic pressure determinations were made by measuring the freezing point depression of salt solutions of varying concentrations. Within the range of EC_e values that permit plant growth, osmotic potential can be obtained from EC_e values with the relation $OP = 0.36 \quad EC_e$, where EC_e is measured in millimhos/cm and OP is measured in atmospheres.

In spite of the greater explanatory value of criteria based on osmotic potential, the standards used in practice are generally

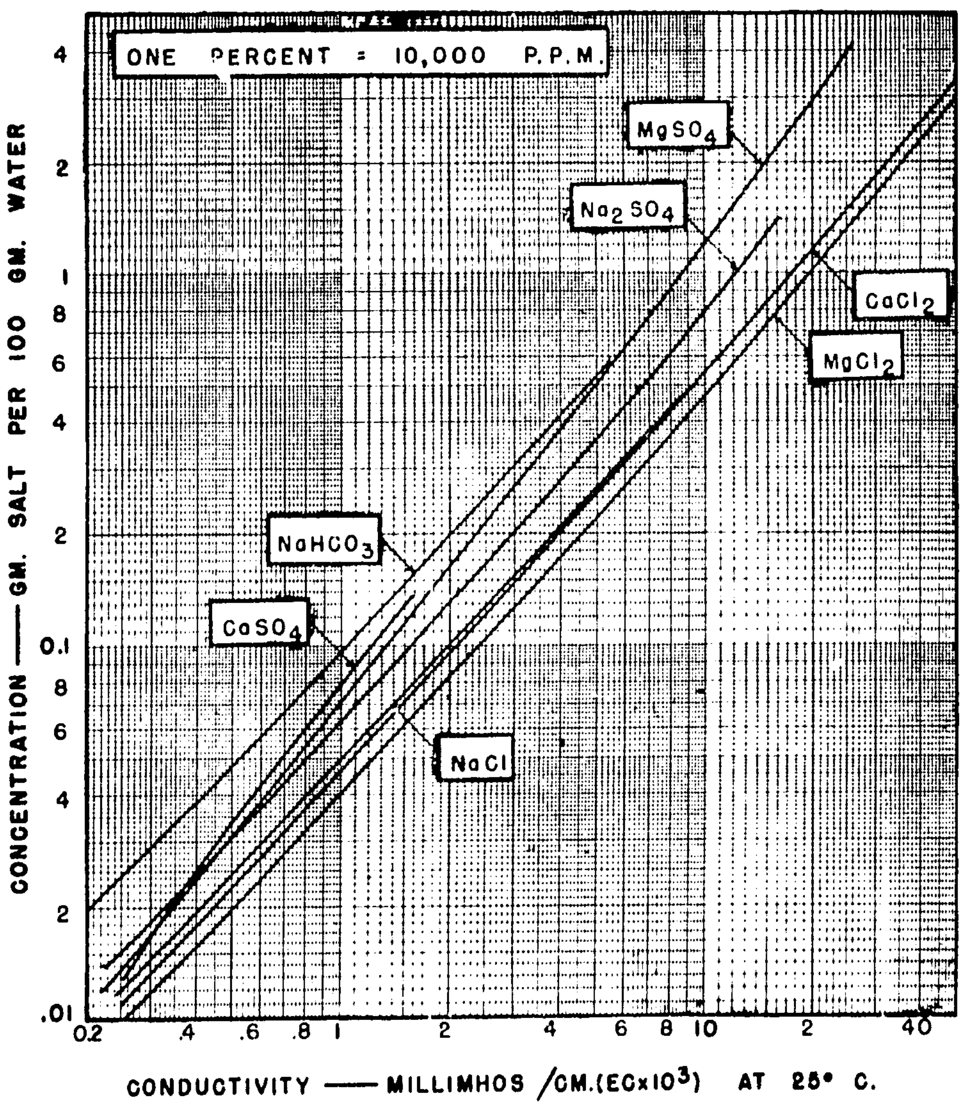

Figure 14. Concentration of Single-Salt Solutions in Percent as Related to Electrical Conductivity.

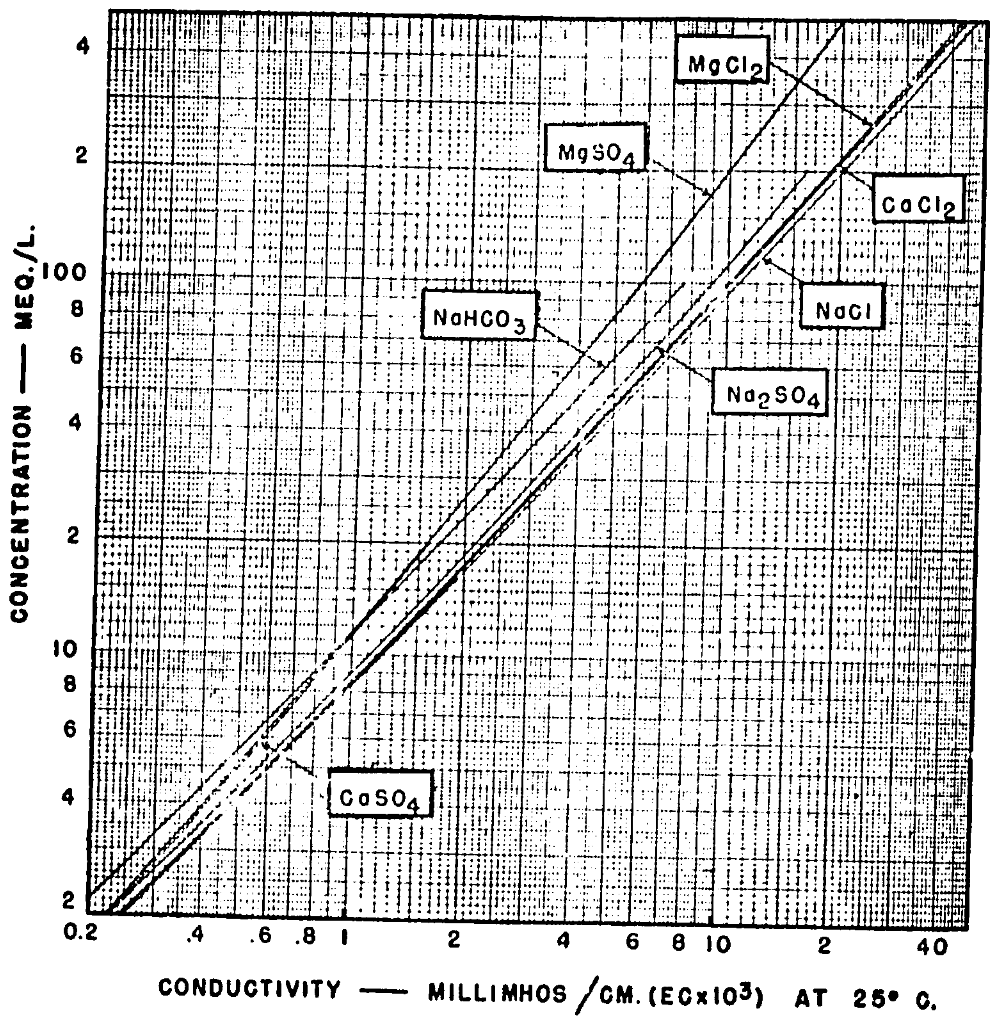

Figure 15. Concentration of Single-salt Solutions in Milliequivalents Per Liter as Related to Electrical Conductivity.

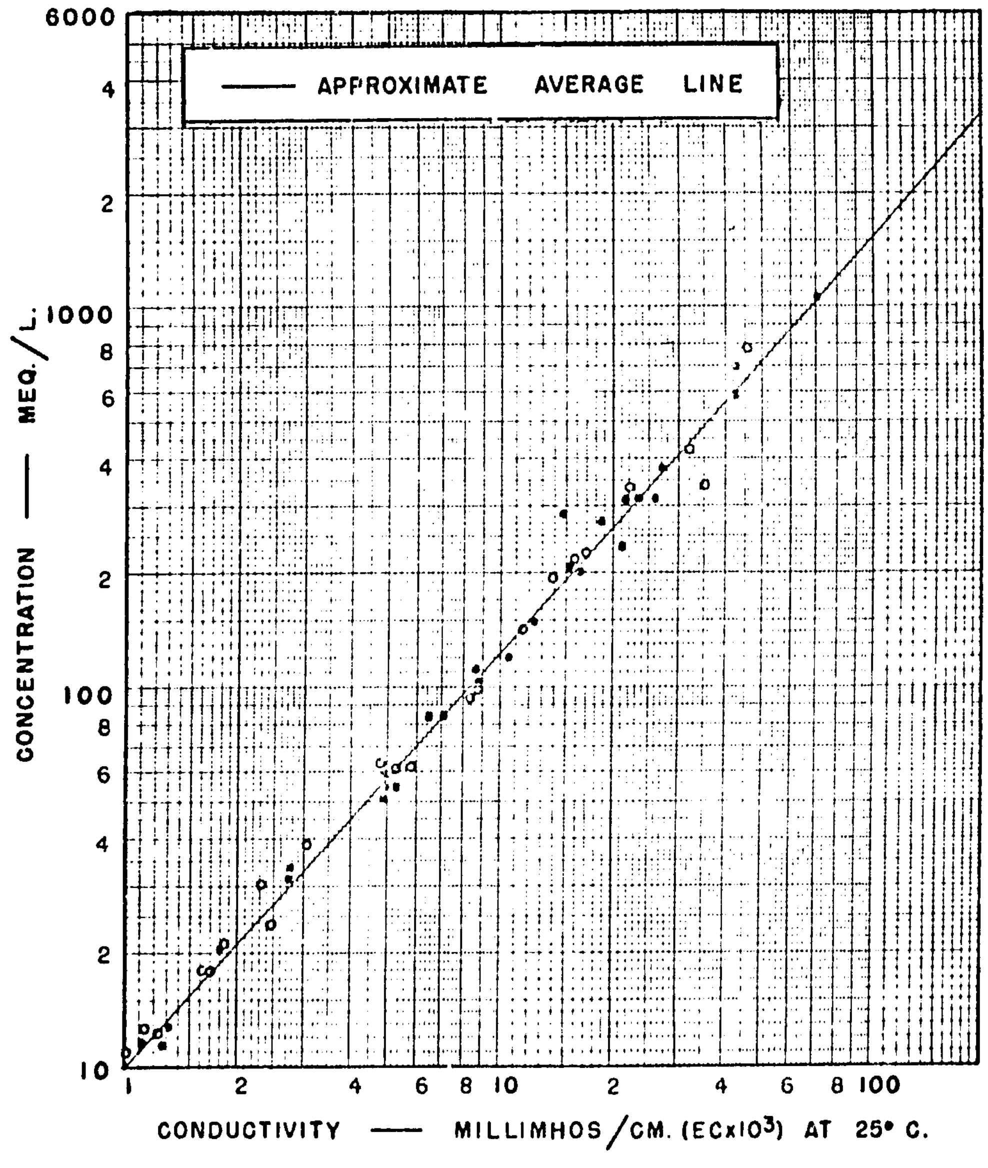

Figure 16. Concentration of Saturation Extracts of Soils in Milliequivalents Per Liter as Related to Electrical Conductivity.

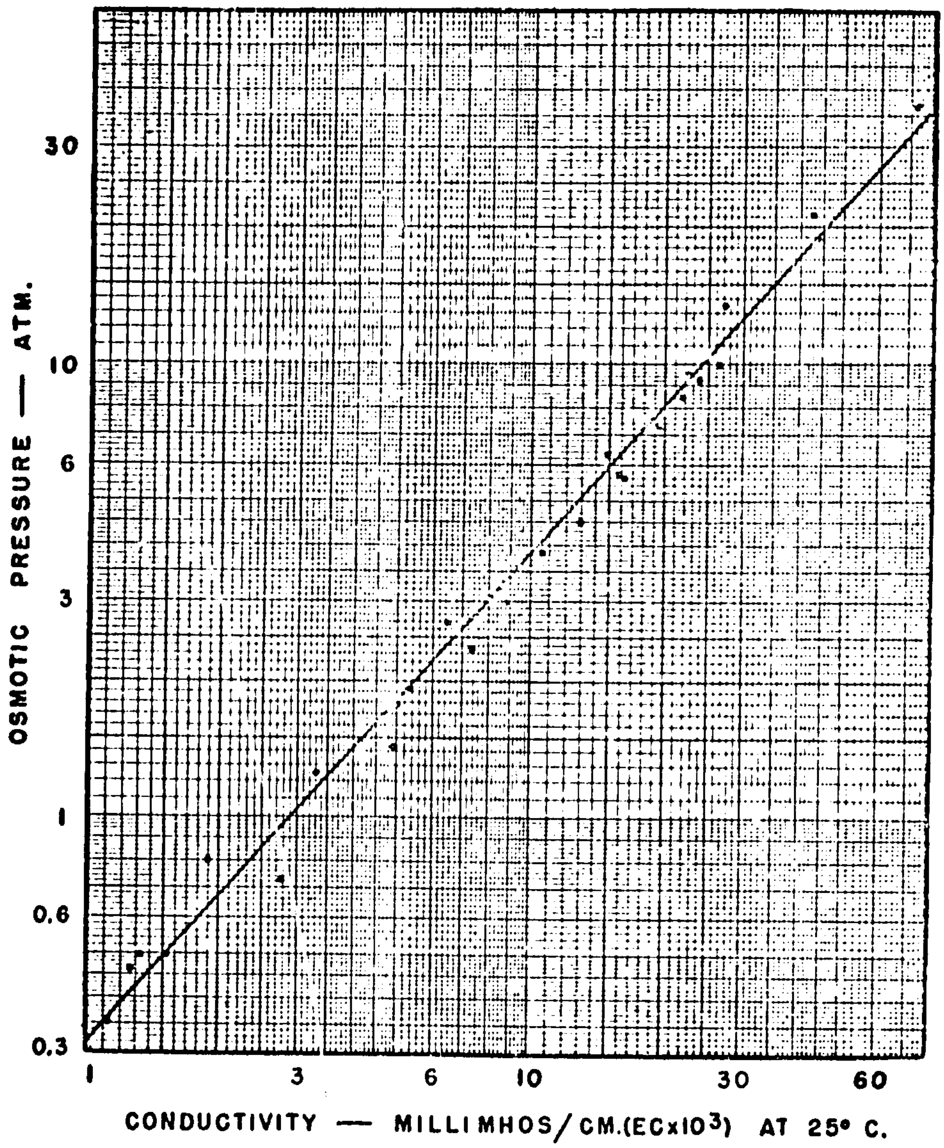

Figure 17. Osmotic Pressure of Saturation Extracts of Soils as Related to Electrical Conductivity.

referenced directly to EC_e values. There seems to be no readily observable threshold TDS concentration where growth or yield is initially affected or becomes markedly more severe. The harmful effect of salt in the soil water seems to increase in a fashion that is continuous, though not necessarily linear, with TDS or EC_e. Richards et al, (1954) developed the following scale to apply to all crops.

Table 6. Effects of Salinity on Crop Yields (from Richards et al, 1954)

Salinity effects mostly negligible	Yields of very sensitive crops may be restricted	Yields of many crops restricted	Only tolerant crops yield satisfactorily	Only a very few tolerant crops yield satisfactorily
0	2	4	8	16

Millimhos/cm at 25°C.

Note that 25°C is specified for EC_e readings. This is important, for in the neighborhood of 25°C (15°C - 35°C) there is a 2 percent change in EC for each degree Celsius above or below 25°C (Richards et al, 1954).

The preceding scale has been replaced by Bernstein's (1964) response functions with data points at 10, 25, and 50 percent yield reductions. These graphs are reproduced in Appendix C.

Bernstein (1964) suggests choosing allowable drainage water salinity to be the EC at which a 50 percent reduction in yield is indicated. This high salinity occurs in the soil water solution only at the bottom of the root zone and the real reduction in yield will be slight. Yields are more influenced by the minimum soil water salinity than by higher salinities occurring elsewhere in the root zone (Bernstein, 1974).

The primary significance of sodium in the root zone results from its effect on soils. As described in Chapter II, the proportion of the total cation exchange capacity (CEC) which is occupied by sodium ions is the key determinant of the degree to which soil dispersion takes place. The exchangeable sodium percentage (ESP) is a measure of this tendency.

$$ESP = \frac{Na^+}{CEC} 100\%$$

The CEC of a soil is determined in the laboratory by saturating the exchange somplex with sodium ions and then replacing them with ammonium ions. The amount of sodium removed from the soil sample in this way is expressed in milliequivalents per 100 grams of soil and represents the cation exchange capacity.

The composition of the naturally occurring exchangeable cations in a soil, i.e., those actually adsorbed on the cation exchange complex, can be determined by a related procedure (Richards et al, 1954). The ESP is then calculated from the above formula.

Since exchangeable cation composition is in equilibrium with the ionic composition of the soil solution, a knowledge of the latter offers an indirect pathway to ESP. As described in Chapter II, the effect of sodium on soils depends both on the proportion of Na^+ present and on the total cation concentration of the soil solution. The U.S. Salinity Laboratory has combined these parameters into a sodium adsorption ratio (SAR) defined as follows:

$$SAR = \frac{Na^+}{\sqrt{(M_g^{2+} + Ca^{2+})/2}}$$

where all concentrations are expressed in meq/liter. Although other minor ions could be added to the formulation, their effects are usually quite small. The SAR, while somewhat less precise than a determination of the actual ESP, is vastly easier to obtain, requiring only a standard composition analysis of the saturation extract. It can be used directly to describe soil status or converted to ESP. The nomograph shown in figure 18 can be used for this purpose as can the following formula on which the nomograph is based:

$$ESP = \frac{100\ (-0.0126 + 0.01475\ SAR)}{1 + (-0.0126 + 0.01475\ SAR)}$$

The U.S. Salinity Laboratory defined a tentative cut-off for acceptable ESP values at 15, while stressing the modifying influence of such parameters as soil texture, amount and type of clay minerals present, and the presence of potassium, soluble silicates, and organic matter. Indeed, crops of alfalfa, cotton and olives are grown in the San Joaquin Valley where ESP values range as high as 60 and 70. This is probably possible because of the absence of swelling clay minerals (USDI, 1968).

The SAR and ESP then are valuable parameters describing soil conditions, but must be evaluated together with information on the texture and compostion of the soil and infiltration data to determine their real significance.

Areal Extent

Within relatively small well-defined areas, ground sampling methods are the most convenient and reliable methods of determining the areal extent of waterlogging and salinity problems. In arid regions, high water tables are usually manifested by readily visible surface accumulations of salts. Water table height can be measured directly in existing wells and in observation wells placed for that purpose. Soil salinity can be determined by soil sampling and laboratory EC_e measurements.

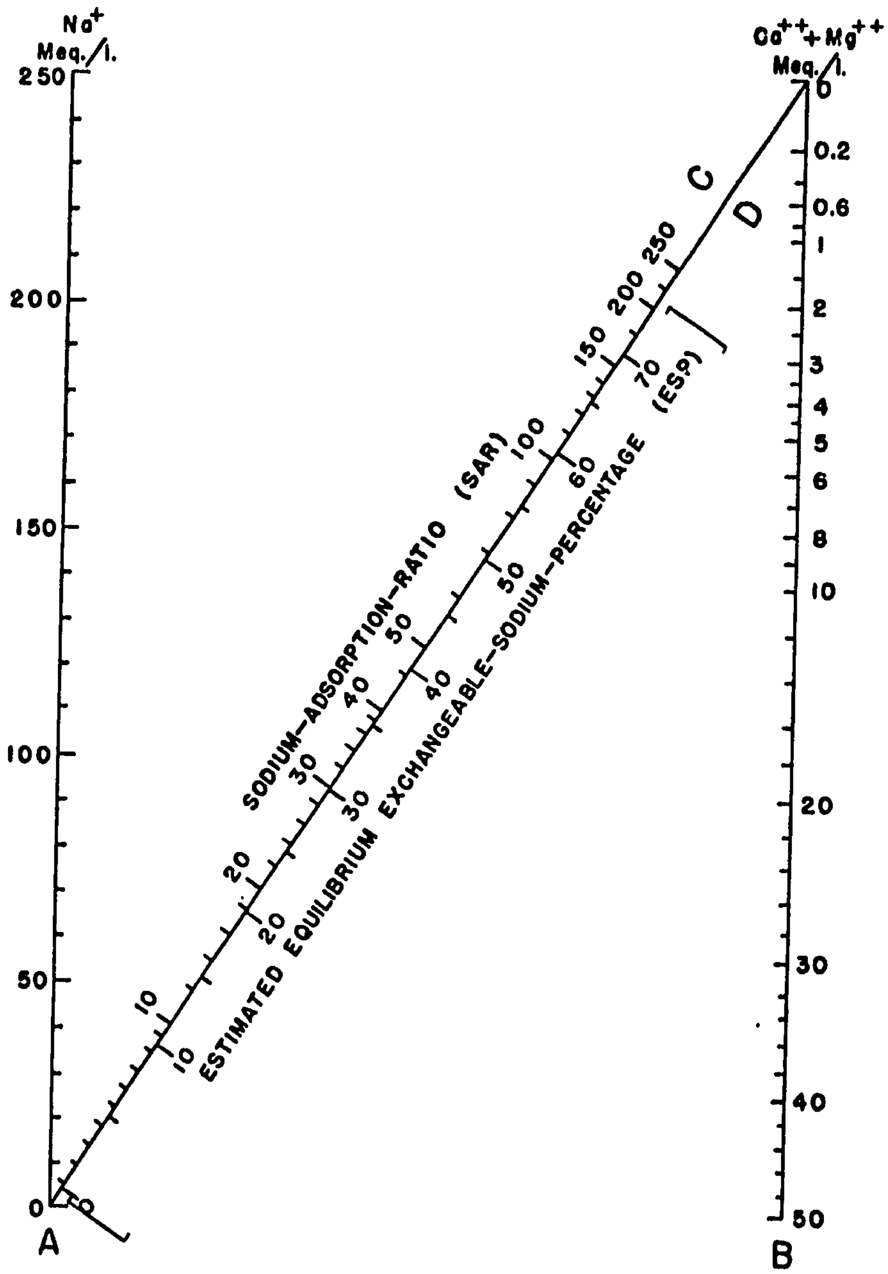

Figure 18. Nomogram for Determining the SAR Value of a Saturation Extract and for Estimating the Corresponding ESP Value of Soil at Equilibrium with the Extract.

It is likely, however, that the problem which first claimed investigative attention is not in stasis. More probably, it is a problem growing in extent and severity. It is therefore important to try to locate the problem area within a larger region which, because of physical, geologic, or climatological characteristics, wholly contains it. It is only by studying this larger area and understanding its relationship with the immediate study or problem area that optimal solutions can be found.

For surveying large and less well-defined areas, remote sensing may prove a useful and inexpensive tool. Although techniques are not well-developed at present, a number of different plant and soil properties can be exploited in differentiating problem areas.

Remote sensing can be accomplished from aircraft and satellites. Satellite imagery covers large areas in individual passes and is widely available at low cost. NASA presently has arrangements with a number of developing nations through which it supplies them with data from NASA's LANDSAT satellites. Under this program, imagery obtained over the particular country is provided, along with ground equipment and personnel training necessary for data interpretation. The program could be easily expanded to include waterlogging and salinity mapping as techniques are refined.

While providing broad and rapid coverage, the resolution of satellite imagery is necessarily less fine than that of aerial photographs and sensor readings. A pixel, the smallest area over which energy is integrated, for LANDSAT's multispectoral scanner covers about 1.13 acres (Ragan and Jackson, 1975). Although this would seem to be excellent performance from an altitude of 910 km. (565 miles), higher resolution may be necessary. This can be obtained from aerial coverage, though at a higher cost.

Satellite mapping with radiation in the 0.8-1.1 micron range has been effective, especially in areas with sparse vegetation. Variations in reflectivity in these areas appear to be related to moisture in the near surface soil (Rango et al, 1974) and might serve to identify areas of high water tables. Scanners in this range are on board the LANDSAT satellites.

Microwaves at the 1.55 cm wavelength have also been successful in monitoring soil moisture status. Since the microwaves penetrate the soil surface, reflectivity seems to be governed by the moisture in the layer just below the surface (Rango et al, 1974).

The high thermal capacity of wet soil can also be used to advantage. Satellite scanning in the 10.5-12.5 micron thermal infrared range has revealed temperature differences which are inversely proportional to soil moisture content (Rango et al, 1974). In general, the 8 to 14 micron range provides a good window through the atmosphere for infrared scanning.

Myers and coworkers have also used remote sensing to detect salinity problems in fields of growing crops. Aerial photographs were used to measure salinity-induced water stress in cotton plants through its effects on leaf reflectance (Myers et al, 1963) and plant leaf temperature (Myers et al, 1966). Leaf reflectance was measured in the near infrared (0.7-0.8 micron) and plant leaf temperatures in the 8-14 micron range mentioned earlier. Both were found to have reasonably good correlations to EC_e measurements made on soil samples. A significant problem with this technique would seem to be separating the effects of osmotic and matric potentials in producing the observed water stress.

Input-Output Analysis

The purpose of the input-output analysis is to compute budgets of gross water and salt flows into and out of the region. The water budget will verify the magnitude of the measurements taken during the investigations. The salt budget reveals whether the salinity of the region as a whole is increasing or decreasing and gives useful information on the source of the salinity in the drainage outflows from the system.

The water budget is computed with the expression

$$SWI + GWI + PPT = SWO + GWO + ET$$

where SWI and GWI are surface and groundwater inflows, PPT is effective precipitation, SWO and GWO are surface and groundwater outflows, and ET is evapotranspiration. If approximate equality is not achieved in the above equation, its terms should be reevaluated, beginning with the most uncertain, i.e., groundwater inflows and outflows. The efficiency of irrigation water use for the entire system can be calculated by dividing the crop ET use plus the computed leaching requirement by the amount of water diverted from the surface inflows plus any groundwater pumped for irrigation use.

In terms of salt flows, the overall budget can be written

$$C_{SWI}\ SWI + C_{GWI}\ GWI = C_{SWO}\ SWO + C_{GWO}\ GWO + SSC$$

where C is the concentration of TDS in the water and the subscripts are as previously defined. The term SSC represents a salt storage change. These terms are all weighted averages over some long period, a growing season, for example.

Following the completion of the subsystem investigations, all of the terms except SSC should be known, and the equation can then be solved for SSC. If SSC = 0 , salt inflow is equal to outflow and the region is in rough overall balance. This simple conclusion is complicated, however, by the possibility that less soluble salts are being precipitated out in the root zone and that other salts are being picked up at some other point in the system. A comparison of the constituent compositions of the irrigation and drainage waters would shed light on this possibility.

A significant positive value for SSC indicates that the salinity of the region is increasing and that agricultural salinity problems will probably become increasingly severe. If the SSC term is significantly negative, more salt is being removed from the region than is being imported. This can indicate that a past accumulation of salt in the root zone and the groundwater aquifer is being flushed out, or that original salts present in the soil are being picked up and removed. The first situation indicates that agricultural conditions are likely to improve if the trend continues. The second may or may not indicate a pending improvement, depending on the quantity of original salts present. In either case, the increased quantity of salts in system drainage outflows may bode salinity problems for down slope users of ground and surface waters.

Water and Salt Budgets

The basic principal behind water and salt budgeting was exposed in the preceding input-output analysis. Essentially, it involves a mass balance, accounting for flows into and out of a system and the changes which occur within the system.

The principal budget employed in this type of analysis is the water budget, since all salt flows occur as dissolved constituents in the water flow regime. Salt flows are thus accounted for by multiplying the appropriate water flow by the concentration of dissolved solids which it contains.

Exceptions to this general procedure are encountered when changes in TDS concentration occur within a particular subsystem. In the water delivery subsystem, this happens as water evaporates from free water surfaces and increases the salt concentration in the remaining water. Since the amount of this evaporation can be calculated, the concentration of the remaining water, less seepage losses, can be readily determined.

In the farm-use subsystem, the concentration effect due to ET can likewise be accounted for. Both the total quantity of salt present and its concentration can change, however, as less-soluble salts, such as calcium sulfate, are precipitated out of solution in the soil and other salts are picked up. These changes in concentration and composition of the root zone soil solution can be dealt with in various ways. A complete accounting of both the change in composition and the change in total quantity of salt requires a complicated modeling process such as that proposed by Dutt and coworkers (See Dutt and Tanji, 1962, Tanji et al, 1967, and Dutt et al, 1972). A simpler procedure ignores the exact nature of the chemical interactions taking place and deals only with the total amount of salts entering and leaving the root zone on an input-output basis.

The same comments apply to interactions occurring in the subsurface drainage flow regime. In this case, phreatophyte transpiration can be accounted for, but salt deposition and pick up below the water table are treated only in input-output terms. If the time-to-equilibrium of these interactions is short compared to the length of time that a given fluid partical is present in the groundwater flow regime, equilibrium values of groundwater TDS concentration can be used.

In the remaining three subsections of this chapter, water and salt budgets for individual subsystems will be developed. This process will give more detailed information on the fate of applied water and salt and the source of any salt pick up.

Budgeting the Water Delivery Subsystem

The delivery subsystem water budget can be written as

$$QI - QS - EV - QSP = QO$$

where QI is the inflow to the canal system, QS is the total seepage loss, EV is the evaporation loss, QSP is the spillage loss, and QO is the distribution subsystem output. The inflow, QI , has been measured at the point of diversion. Seepage, QS, was determined for sample canal sections and can be extrapolated to the entire canal system utilizing map and wetted perimeter data. Evaporation, EV , can be computed from climatic or pan evaporation data. Spillage, QSP , should also have been measured at the point of occurrence. The delivery to the farm-use subsystem, which is usually composed of a large number of small flows, can then be computed as a residual. If this quantity is also known by direct measurement, the least precise terms of the budget can be adjusted accordingly.

When QO is determined, distribution subsystem efficiency can be calculated as

$$(QO/QI)\ 100 \text{ percent.}$$

If there is considerable variance from point to point in canal seepage rates, physical dimensions, or canal bed and bank material, it may be worthwhile to compute canal seepage losses for various sections separately.

In this way, sections making the largest contribution to waterlogging and salinity problems can be identified for future remedial action.

The salt budget for the subsystem can be written as

$$C_I\ QI - C_S\ QS - C_{SP}\ QSP = C_O\ QO$$

where C_{sub} indicates concentration of TDS and other symbols and subscripts are as previously defined. In this expression, the concentrations, C_{sub}, will often be very nearly equal. Exact concentrations of specific flows will depend on the length of time the water has been in the conveyance system. Inspection of individual terms in the expression will indicate the allocation of salt inflows to the various recipient subsystems. The most important of these will be the product $C_O\ QO$, the amount of salt added to the farm-use subsystem.

Budgeting the Farm Water Use Subsystem

Water and Salt Budgets

The amount of water delivered to the entire farm water-use subsystem is the amount of the output, QO , of the delivery subsystem. To determine the fate of that water, it is necessary to take the data obtained from the intensive studies conducted on the water-use subsystem prototypes and extrapolate it to the entire subsystem. This is done using the land use information developed early in the investigations.

The water budget expression for the subsystem is

$$QI + PPT - WSC - ET - QDP - QRO = 0$$

where QI is the input to the farm-use subsystem (equivalent to QO in the delivery water budget), PPT is effective precipitation, WSC is the water storage change in the root zone which is positive for an increase in storage and negative for a decrease, ET is evapotranspiration, QDP is the deep percolation flow below the root zone, and QSR is the surface runoff or field tailwater. These terms must all sum to zero. If their sum is substantially non-zero, the quantities known with the least certainty may be adjusted so that a budget balance is achieved.

The subsystem salinity budget is calculated as

$$C_I\ QI - C_{DP}\ QDP - C_{RO}\ QRO = SSC$$

where C_{sub} represents a concentration as defined earlier and SSC is the salt storage change. If the value of SSC is positive, the salinity of the root zone is increasing. If SSC is negative, root zone salinity is decreasing. If SSC is zero or negligibly small, a balance in net salt flow exists. This budget gives a more accurate representation of the type of salt balance existing in the root zone than the value of SSC found in the input-output analysis since that budget included the effects of storage changes in the groundwater aquifer as well.

For this type of analysis, it is necessary to measure both the quantity and quality of the deep percolation flow and to compute SSC as a residual. The aim of the type of root zone salinity model developed by Dutt and coworkers is to derive an independent value of SSC by modeling the chemical reactions taking place there. If this is done, the value of SSC calculated as a residual can be verified, and information on the changes in composition of the soil solution can be obtained.

From the analyses conducted so far, the nature of the waterlogging and salinity problems affecting the study area have been determined and the relative magnitudes of the various components of the water and salt flows calculated. To define "causes" of these problems, it is necessary to examine the efficiencies with which the various subsystems perform their intended functions.

Problems identified may have a number of causes. Since the end goal of waterlogging and salinity investigations is to find practical solutions to these problems, the causes most amenable to amelioration must be found. Before system changes are actually undertaken, economic and social studies will be needed to determine the economic feasibility and social feasibility and impact of the proposed solutions. It is to provide input data for these second-stage investigations, as well as for more detailed technical studies, that information on efficiencies must be developed.

As pointed out earlier, the problems identified may have a number of causes. By determining the degree of ameliorative change possible for each of the causative factors, and the effect of such changes on the actual problem, e.g., lowering a water table, subsequent consideration can be limited to measures with the greatest potential effectiveness. The efficiency with which the delivery subsystem operates was computed in the previous section. In the following section, methods of measuring the efficiency of the farm water-use subsystem are examined.

Irrigation Efficiencies

There is no single figure which measures adequately the efficiency of on-farm irrigation. To evaluate the adequacy and efficiency of irrigation water use it is necessary to combine several measures judgementally.

Probably the most-used measure is application efficiency. Defined most generally, it is the ratio of the amount of useful water applied to a field to the amount of water delivered to the field. Useful water would comprise water stored in the root zone for crop use, the minimum amount of water necessary to leach accumulating salts from the root zone (the LR), and water used by the crop during the period of irrigation and drainage to FC. This ratio measures the proportion of the water applied to the field which is used beneficially, but says nothing about the adequacy of that application in meeting crop needs. An application efficiency of 100 percent could be achieved, for example, by sprinkling one gallon of water lightly over a portion of the field.

To meet this inadequacy, a requirement efficiency can also be calculated. Requirement efficiency is the ratio of the water available for plant use to the amount of water required by the crop during the period between irrigations. Again it is possible to achieve 100 percent efficiency by applying large quantitites of water to the field. This figure gives useful information about the adequacy of the irrigation in meeting crop ET requirements, but says nothing about over-irrigation and non-beneficial use.

Although the definition of requirement efficiency implies that crop requirements are met over the entire field, measurement is often made only of the water applied to the field and an even distribution assumed. In practice however, this is seldom a realistic assumption. If requirement efficiencies are less than 100 percent, the efficiency figure tells us nothing about the localized existence of over- or under-irrigation. To have meaning in this context, the figure assumes that crop response is directly and linearly related to water adequacy. In other words, it assumes a linear 45 degree crop response function with respect to water with a zero intercept.

Hall (1960) has combined these ideas into a system application efficiency, defined as the application efficiency of the system when at least 95 percent of the field has received an adequate irrigation. This parameter combines the three aspects of efficiency of use, adequacy of application, and uniformity of areal distribution into a single figure. The percentage given (95 percent) is an arbitrary example and is actually a variable function of production factor costs and market prices.

One problem with this concept is that if water distribution fails to reach the cut-off percentage, the definition does not apply. It might, however, give some indication of the ideal efficiency of the system if conscious attempts are made to match the required irrigation distribution and adequacy through what might normally be considered over-irrigation. It also provides a basis for comparison among different farm systems.

A further word on the distribution of applied irrigation water is in order. Hall's system application efficiency requires some measure of such a factor. This can be obtained, for surface irrigation systems, by measuring SMCs in some regular pattern over the entire field by gravimetric sampling, neutron probing, or other appropriate means, both before and after the irrigation.

A simple parameter for representing such a distribution is the Christiansen uniformity coefficient. It is defined as one minus the ratio of the sum of the magnitudes of the deviations to the mean value of the uniformity function.

$$UCC = 1 - \sum_{i=1}^{n} |x_i - \bar{x}| / (n\bar{x})$$

where UCC is the uniformity coefficient, n is the number of observations, x_i is an individual observation of depth of water applied, and $\bar{x}$ is the average depth of water applied. On the average, about 75 percent of the area irrigated will have received a depth of applied water of (UCC) $\bar{x}$. This coefficient serves as a simple and useful measure of uniformity of distribution.

Other measures of irrigation efficiency have been proposed (see, for example Hall, 1960 and Hansen, 1960) which may have utility under some circumstances. In general, however, evaluating the above mentioned efficiencies of an irrigation will supply sufficient information for a general evaluation. A low distribution index, for example, might indicate the need for system improvements such as land leveling, while a high application efficiency and a low requirement efficiency point toward under-irrigation.

It is informative also, to examine the temporal changes which occur in the efficiencies over the growing season. Any definite trends which emerge in this examination may be useful in ascertaining the effects of correlated variables such as soil infiltration rates and irrigation water availability on water management practices and water use efficiencies.

In applying these efficiency measures, the leaching requirement must be caluclated, based on the allowable concentration of subsurface drainage water, and included in the quantity of water beneficial to the farming operation. The method for accomplishing this is found in Chapter IV.

<u>Budgeting the Drainage and Removal Subsystem</u>

The drainage and removal subsystem water budget is most conveniently written in two parts. The first, describing surface drainage flows, is written as

$$QSP + QIA + QRO = QO + EV + QS\ X$$

where QSP is spillage from the canal system, QIA is subsurface drainage interception by surface channels, QRO is runoff inflows (including those from precipitation), QO is the outflow of the drainage network into a natural water course or other sink, EV is free water surface evaporation, and QS is drainage channel seepage. This last term can usually be ignored.

Subsurface drainage flows are considered in the expression

$$QI + QDP = QO + TR + QIT + WSC$$

where QI is the sursurface inflow to the system, QDP is deep percolation accretions, QO is the subsurface outflow from the system, TR is phreatophyte transpiration, QIT is total drainage interception by surface channels and watercourses, and WSC is water storage change.

All of the terms in the first equation can be measured or computed independently of the budget equation and hence the budget serves chiefly as a verification. The budget of subsurface flows is composed of difficult to measure terms and hence has a large measure of uncertainty associated with it. If system subsurface inflows and outflows are nil or negligibly small, the equation reduces to

$$QDP = QIT + TR + WSC$$

In this case, the inflows consist only of deep percolation flows from irrigation and precipitation. Outputs are phreatophyte transpiration and groundwater interception. The storage change can be either positive or negative. The interception term, QIT , is composed of intercepted outflows to surface drainage channels, QIA , and flows to the natural watercourses draining the system.

By solving the equation for QIT and deducting the computed value of QIA , the drainage flow out of the agricultural area is determined.

This can be compared to values of drainage outflow across a vertical plane parallel to the natural watercourse determined using the steady state groundwater flow equation

$$Q = - K A' \frac{\Delta H}{\Delta X}.$$

In this equation, Q is the outflow rate, K is the hydraulic conductivity of the aquifer, A' is the cross-sectional area of flow, and $\frac{\Delta H}{\Delta X}$ is the hydraulic gradient. In the method used by Walker (1970), the value of Q is first found using measured hydraulic conductivities. The value of K , used as a surrogate parameter, is then adjusted iteratively by comparison with (QIT - QIA) computed as a residual, until it has a constant value over several time periods.

The salt budget for surface drainage flow is written

$$C_{SP}\ QSP + C_{GW}\ QIA + C_{RO}\ QRO = C_O\ QO$$

whrer SP indicates spillage, GW indicates groundwater, QIA is the groundwater intercepted by drainage channels, RO indicates runoff, and O is outfput from the subsystem. The salt budget for subsurface drainage flow is written

$$C_I\ QI + C_{DP}\ QDP + SSC = C_{GW}\ QO + C_{GW}\ QIT$$

where I indicates subsurface inflows to the system, DP indicates deep percolation, SSC is the salt storage change in the aquifer, O indicates system outflows, GW indicates groundwater and QIT is the total groundwater interception.

C_{GW} represents an average equilibrium groundwater TDS concentration at a given time. It is usually safe to assume that equilibrium is reached in a length of time that is short compared to the time water is in the aquifer. The surface salt flow equation again serves as a verification of the magnitude of measured quantities. The subsurface salinity budget can be solved for SSC. When this salt storage change is added to that determined for the root zone, the result should be approximately equal to the total salt pick up determined in the input-output analysis. A comparison of the magnitudes of the two component terms should indicate where the bulk of the salt pick-up occurs.

The efficiency of the drainage and removal subsystem is a relative concept. The capacity of the subsurface flow system depends primarily on the hydraulic conductivity of the aquifer materal and the naturally existing hydraulic gradients. The system is self-adjusting in that the gradient and hence the outflow increases in response to additional inflows. The system will tend toward a steady state where inflows equal outflows regardless of the amount of water added to it. In that sense its efficiency can be considered to be a natural and continuous 100 percent. In practical terms, however, whether or not the system is adequate to carry away the seepage and deep percolation flows depends on the magnitude of these flows and the proximity with which the water table can be allowed to approach the ground surface.

In many cases, the tendency of farmers to over-irrigate, even when the water supply for the region as a whole in inadequate, provides for adequate leaching of the root zone. Both salinity and waterlogging problems are thus often associated with high water tables. The solution to both problems then involves the lowering of the regional groundwater table.

Before measures are undertaken to accomplish this, it is desirable to determine the effect which various system and water management changes might have on the water table. If the changes contemplated are small, steady state equations are adequate to model them. If the proposed changes are large, the assumptions made in employing the steady state equations are no longer valid and a more complex model must be developed.

Chapter VIII

SUMMARY

In the final quarter of the twentieth century, the world's agricultural systems will be called upon to double their production of food and fibre. Because of its greater potential for increased production and because of its central position in the hungriest regions of the world, irrigated agriculture will be asked to provide the bulk of this increase.

A major constraint which must be overcome if this is to happen is the twin problem of waterlogging and salinization of agricultural lands. The practice of irrigated agriculture changes the hydraulic regime of a region significantly. Drainage systems which were adequate to handle natural flows of water and salt become inadequate when faced with the greatly increased flows resulting from artificial irrigation. As time passes, pressures to increase production bring marginal lands under the plow for the first time. Lands presently producing a single annual crop are subject to increased cropping intensity. Increasingly extensive and intensive agriculture can only exacerbate existing problems of waterlogging and soil salinization.

By their very nature, systems of irrigated agriculture require a system of social organization and collective action. The practice of irrigated agriculture may well have given rise to the earliest systems of extensive social organization, and it continues to provide an imperative for their existence (see Wittfogel, 1957). The advent of waterlogging and salinity problems date back nearly to the establishment of such hydraulic societies, and their solution likewise requires collective action.

Just as individual cultivators are unable to establish and maintain the complex water supply systems necessary for the practice of irrigated agriculture, it is usually impossible for them to act individually to solve problems resulting from such cultivation. It is necessary, therefore, to deal with these problems on a regional basis and to center an understanding of their causes and solutions squarely on the farmer's conception of his own self-interest.

Solutions to waterlogging and salinity problems will often involve substantial expenditures of scarce resources. At the same time, the regional and national benefits derived from the resultant production increases are potentially enormous. To insure that proposed solutions will have the desired effect, therefore, a necessary first step is to determine the nature, seriousness, extent, and sources of the waterlogging and salinization problems. Because of the large investment required for problem solution and the large potential gains to be achieved, a thorough investigation of these four problem dimensions would normally seem to be warranted.

Before summarizing the steps involved in such an investigation, it is essential to point out what has been omitted from this discussion. It is to be emphasized that the purpose of this paper was not to propose solution technologies but to provide a methodology for investigating waterlogging and salinity problems. The investigations described are technical in nature and do not include vital and equally important economic and social considerations. Information on farm and system improvement economics, on farmer attitudes and practices, and on overall social and institutional structure and dynamics is essential for any meaningful evaluation. Since technical, social, and economic factors interact at a large number of points in the agricultural system, the investigations must also interact. For this reason, the technical investigations outlined above are only one aspect of the organically interrelated research effort necessary to adequately understand and solve waterlogging and salinity problems.

To investigate an agricultural system in terms of the four technical dimensions, a system boundary must be drawn to isolate the region to be studied. This is done in accordance with the basic principal of minimizing interconnections. In the general case, it is most useful to partition the system into a water delivery subsystem, a farm water-use subsystem, and a drainage and removal subsystem. While overlaps in subsystem definition do result from this scheme, in most instances they will cause only minor difficulties.

Within individual subsystems, measurements are made to permit the calculation of subsystem hydrologic budgets. Salinity budgets are developed by multiplying the appropriate water flow by its salinity concentration and adding algebraically a term representing the net of salt pick up and deposition.

The water delivery subsystem takes water from a source of supply, a river for example, and transports it to the small private canals irrigating individual fields. This is probably the simplest of the subsystems to budget since, as defined, it is composed entirely of surface flows. The amount of water diverted, less seepage, spillage, and evaporation losses, is the water delivered to the farm-use subsystem. The quantities of these losses are compared to the total flow in the canal system to evaluate the efficiency of the subsystem.

The farm water-use subsystem is the heart of the agricultural enterprise. Other subsystems exist to permit the practice of long term irrigated agriculture here. Since a large number of variables must be measured here with a high degree of accuracy, data are usually collected over a small area and extrapolated to the entire system using land use data. The output from the delivery subsystem, plus effective precipitation, comprises the input to this subsystem. Water applied to the fields is then partitioned into runoff, evapotranspiration, and deep percolation components. Several ratios can be calculated to indicate the efficiency of water management and irrigation system capability with these data. These efficiency measures then serve to indicate likely areas of system design and water management improvement. Since measured salinity concentrations may reflect salt pick up and deposition as well as concentration effects, it is necessary to include a salt storage change term in the salinity budget equation. In less elaborate studies, the magnitude of this term is computed as a residual.

The drainage and removal subsystem is composed of both surface and subsurface flows of water and salt which are treated separately. While surface drainage flows are relatively easy to measure, subsurface flows depend on sensitive, hard-to-measure parameters which must be regarded as approximate. Adjustment of these parameters is often required, based on independent computations of groundwater flow. Salt pick up and deposition are also possible in the groundwater flow regime and this possibility must be examined as in the farm water-use subsystem.

Problems of waterlogging and soil salinization are usually found to occur in conjunction with one another and must be addressed together. Furthermore, they are not usually amenable to simple, single-variable solutions. Successful solutions will almost always be based on a broad social, economic and technical understanding of the problem situation coupled with intense farmer involvement. Externally-imposed solutions are doomed to self-righteous failure.

Over the long run, it must be understood that the individual farmer is the key to productive cultivation. If he understands the reasons for the change being sought and sees the results in terms of increased production for him, the change will come easily. Furthermore, it is only by understanding the basic principals of the plant-soil-water interaction that he is able to make rational water management decisions in the face of changing conditions.

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Appendix A

DETERMINING ACTUAL ET AS A FUNCTION OF CROP AND CROP GROWTH STAGE

An empirical factor, K_{co}, adjusting the PET rate to an actual ET rate was described in Chapter IV. In computing K_{co}, the growing season is divided into two parts separated by the point at which the crop achieves effective cover. The time prior to achieving effective cover is rationalized into percentage of time from planting to effective cover. Following effective cover, the time scale is given simply in days.

A guide for determining this point for some common crops is shown in Table A-1. It should be noted that the times given are only approximate and refer to conditions in the Western United States.

Table A-1. Guide for establishing the date of effective cover. (from Kincaid and Heerman, 1974).

Crop	Effective cover
Small grains	at heading
Beans	bloom or about 50 days after planting
Peas	full bloom or 70 days after planting
Potatoes	about 80 days after planting
Sugarbeets	about 110 days after planting
Corn or sorghum	about 10 days after tasseling on corn and heading for sorghum
Alfalfa	all season except 30 days after growth begins in spring and 20 days after cuttings
Pasture	all season except 30 days after growth begins in the spring

Actual values of K_{co} for both time periods are given in tabular form in Table A-2 below.

Table A-2. Experimental crop coefficients, K_{co}. (from Jensen, 1973).

Crop	Planting to effective cover, percent									
	10	20	30	40	50	60	70	80	90	100
Small grains	0.16	0.18	0.25	0.37	0.51	0.67	0.82	0.94	1.02	1.04
Beans	0.20	0.23	0.30	0.39	0.51	0.63	0.76	0.88	0.98	1.07
Peas	0.20	0.24	0.31	0.40	0.51	0.63	0.75	0.87	0.97	1.05
Potatoes	0.10	0.13	0.20	0.30	0.41	0.53	0.65	0.76	0.85	0.91
Sugar beets	0.10	0.13	0.20	0.30	0.41	0.53	0.65	0.76	0.85	0.91
Corn	0.20	0.23	0.29	0.38	0.49	0.61	0.72	0.82	0.91	0.96
Alfalfa	0.36	0.47	0.58	0.68	0.79	0.90	1.00	1.00	1.00	1.00
Pasture	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
	Days after effective cover									
	10	20	30	40	50	60	70	80	90	100
Small grains	1.04	0.94	0.74	0.49	0.19	0.10	0.10	0.10	0.10	0.10
Beans	1.02	0.96	0.85	0.73	0.59	0.45	0.31	0.19	0.10	0.10
Peas	0.98	1.02	0.99	0.76	0.20	0.10	0.10	0.10	0.10	0.10
Potatoes	0.90	0.85	0.75	0.60	0.38	0.10	0.10	0.10	0.10	0.10
Sugar beets	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Corn	0.99	0.99	0.93	0.82	0.68	0.54	0.40	0.28	0.20	0.17
Alfalfa	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Pasture	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87

Polynomial constants for an equation relating K_{co} to time are shown in Table A-3 below. The equation is of the form

$$K_{co} = A\,t^3 + B\,t^2 + C\,t + D$$

where t is given as a percentage before the achieving of effective ground cover and in days following this time. The equation is discontinuous at this point.

Table A-3. Polynomial constants for the function $K_{co} = f(t)$. (from Kincaid and Heerman, 1974).

Crop	Constant A	B	C	D
	Before effective cover			
Corn	−1.583	2.756	− .4276	0.213
Sugarbeets . .	−1.435	2.382	− .2259	.200
Beans	−1.353	2.562	− .3532	.212
Alfalfa	.0	.0	1.087	.250
Small grain .	−2.893	4.843	−1.140	.233
Peas	−1.321	2.470	− .3067	.211
Potatoes ...	−1.381	2.456	− .3710	.213
Pasture ...	.0	.0	1.508	.25
	After effective cover			
Corn	275×10^{-8}	-4688×10^{-7}	0.01195	0.915
Sugarbeets .	-167×10^{-8}	5×10^{-5}	.0	.899
Beans	165×10^{-8}	-2644×10^{-7}	-112×10^{-6}	1.05
Alfalfa	.0	.0	.025	.5
Small grain .	444×10^{-9}	-7261×10^{-7}	8532×10^{-6}	1.022
Peas	-221×10^{-7}	-9865×10^{-7}	-101×10^{-4}	1.005
Potatoes ...	.0	.0	.0	.90
Pasture ...	.0	.0	.0	.87

Appendix B

MOISTURE HOLDING CAPACITY OF VARIOUS SOILS AND ROOTING DEPTHS OF SELECTED CROPS

The moisture holding capacity of various soils is shown in Table B-1 below.

Table B-1. Moisture holding capacity of various soils. (from Hart, 1975).

Textural classification	Inches of water per foot of soil
Very coarse texture--very coarse sands	0.40 - 0.75
Coarse texture--coarse sands, fine sands, and loamy sands	.75 - 1.25
Moderately coarse texture--sandy loams and fine sandy loams	1.25 - 1.75
Medium texture--very fine sandy loams, loams, and silt loams	1.50 - 2.30
Moderately fine texture--clay loams, silty clay loams, and sandy clay loams	1.75 - 2.50
Fine texture--sandy clays, silty clays, and clays	1.60 - 2.50
Peats and mucks	2.00 - 3.00

The rooting depths of selected crops in deep, well-drained soils is shown in Table B-2 below.

Table B-2. Rooting depths of selected crops. (from Hart, 1975).

Crop	Depth, ft	Crop	Depth, ft
Alfalfa	10 to 15	Grapes	8
Almonds	6 to 9	Ladino clover and grass mix	2
Apricots	6 to 9	Lettuce	1-1/2
Artichokes	4-1/2	Melons	5
Asparagus	10	Milo	6
Beans (dry)	3-1/2	Mustard	3-1/2
Beans (green)	3	Olives	6 to 9
Beans (lima)	4	Onions	1
Beets (sugar)	5 to 6	Parsnips	4
Beets (table)	3	Peas	3-1/2
Broccoli	2	Peaches	6 to 9
Cabbage	2	Pears	6 to 9
Cantaloupes	4 to 6	Prunes	6 to 9
Carrots	3	Peppers	3
Cauliflower	2	Potatoes (Irish)	3
Celery	2*	Potatoes (Sweet)	4 to 6
Chard	3	Pumpkins	6
Cherries	6 to 9	Radishes	1-1/2
Citrus	4 to 6	Spinach	2
Corn (sweet)	3	Squash (summer)	3
Corn (field)	6	Sudan grass	6+
Cotton	4	Tomatoes	6 to 10
Cucumber	3-1/2	Turnips	3
Eggplant	3	Strawberries	3 to 4
Figs	5	Walnuts	12 to 18
Grain and Flax	4	Watermelons	6

*A major portion of the roots of the celery plant are in the first foot.

Appendix C

CROP TOLERANCE TO WATERLOGGING, BORON, AND SALINITY

Table C-1 below shows the relative tolerance of a number of agricultural plants to waterlogging. Because of the variety of factors involved, no exact limits as to the duration of acceptable soil saturation can be set. As a rough guide however, 10 days or less might be acceptable for sensitive crops, 10 to 30 days for semi-tolerant crops, and more than 30 days for tolerant crops. Cool temperatures can lengthen these times considerably.

Table C-1. Relative tolerance of crop plants to waterlogging. (from FAO/UNESCO, 1973).

Sensitive	Semi-tolerant	Tolerant
Alfalfa (*Medicago sativa*)	Apple (*Malus sylvestris*)	Canarygrass, Reed (*Phalaris arundinacea*)
Apricot (*Prunus armeniaca*)	Bromegrass (*Bromus inermis*)	
Barley (*Hordeum vulgare*)	Cotton (*Gossypium hirsutum*)	Clover, alsike (*Trifolium hybridum*)
Bean, green (*Phaseolus vulgaris*)	Fescue, meadow (*Festuca elatoir*)	Clover, White (*Trifolium repens*)
Clover, ladino (*Trifolium repens var.*)	Orchardgrass (*Dactylis glomerata*)	Dallisgrass (*Paspalum dilatatum*)
Clover, strawberry (*Trifolium fragiferum*)	Plum (*Prunus domestica*)	Fescue, tall (*Festuca arundinacea*)
		Pear (*Pyrus communis*)
Clover, sweet (*Melilotus alba*)	Rice, upland (*Oryza sativa*)	
Lettuce (*Lactuca sativa*)	Rye (*Secale cereale*)	Rice, paddy (*Oryza sativa*)
Oats (*Avena sativa*)	Raygrass, perennial (*Lolium perenne*)	Trefoil, big (*Lotus uliginosus*)
Peach (*Prunus persica*)	Sorghum, grain (*Sorghum vulgare*)	
Potato (*Solanum tuberosum*)	Timothy (*Phleum pratense*)	
Tomato (*Lycopersicon esculentum*)	Trefoil, birdsfoot (*Lotus corniculatus*)	
Wheatgrass, crested (*Agropyron cristatum*)		
	Trefoil, narrowleaf (*Lotus tenuis*)	
	Wheat (*Triticum vulgare*)	
	Wheatgrass, slender (*Agropyron trachycaulum*)	

Boron is an essential plant micronutrient almost up to concentrations of 0.5 mg/1 in irrigation water. Water containing more than 4.0 mg/1, however, is generally unsatisfactory for all crops. Concentrations within this range may cause varying degrees of damage to crops. Table C-2 indicates the relative tolerance of plants to boron in applied water. In general, sensitive crops will show slight to moderate injury at boron levels of 0.5 mg/1 to 1.0 mg/1; semitolerant, 1.0 to 2.0 mg/1; and tolerant crops, 2.0 to 4.0 mg/l. In terms of the soil saturation extract, concentrations up to 0.7 mg/l are considered safe.

Table C-2. Relative tolerance of plants to boron. In each group, the plants first named are considered as being more tolerant and the last named more sensitive. (from Richards et al, 1954).

Tolerant	Semitolerant	Sensitive
Athel (*Tamarix aphylla*)	Sunflower (native)	Pecan
Asparagus	Potato	Black walnut
Palm (*Phoenix canariensis*)	Acala cotton	Persian (English) walnut
Date palm (*P. dactylifera*)	Pima cotton	Jerusalem artichoke
Sugar beet	Tomato	Navy bean
Mangel	Sweetpea	American elm
Garden beet	Radish	Plum
Alfalfa	Field pea	Pear
Gladiolus	Ragged Robin rose	Apple
Broadbean	Olive	Grape (Sultanina and Malaga)
Onion	Barley	Kadota fig
Turnip	Wheat	Persimmon
Cabbage	Corn	Cherry
Lettuce	Milo	Peach
Carrot	Oat	Apricot
	Zinnia	Thornless blackberry
	Pumpkin	Orange
	Bell pepper	Avocado
	Sweetpotato	Grapefruit
	Lima bean	Lemon

Figures C-1, C-2, and C-3, shown below, are based on data developed by Bernstein (1964). They show the EC_e values at which yield reductions of 10, 25, and 50 percent might be expected, for field, forage, and vegetable crops respectively. These data are calibrated for EC_e readings taken at 25 degrees Celsius and are correlated with yields at field capacity. If fields dry out excessively between irrigations, instantaneous EC_e values may as much as double those listed with corresponding decreases in yield.

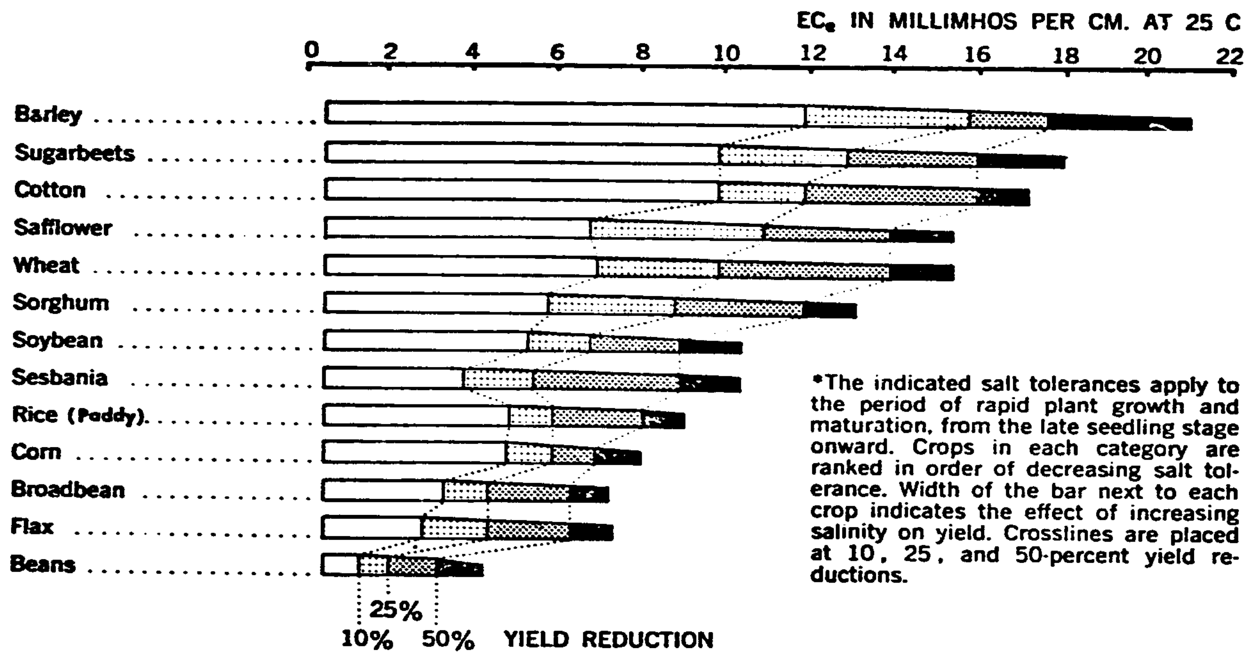

Figure C-1. Salt tolerance of field crops.* (from Richards et al, 1954)

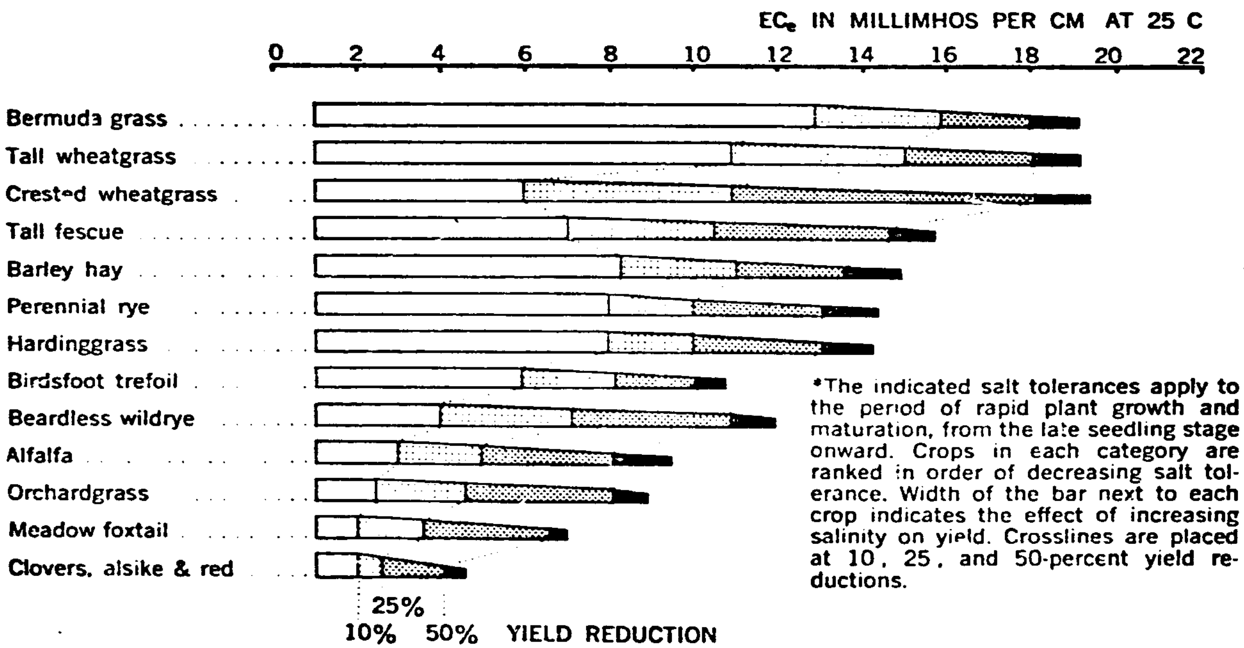

Figure C-2. Salt tolerance of forage crops.* (from Richards et al, 1954).

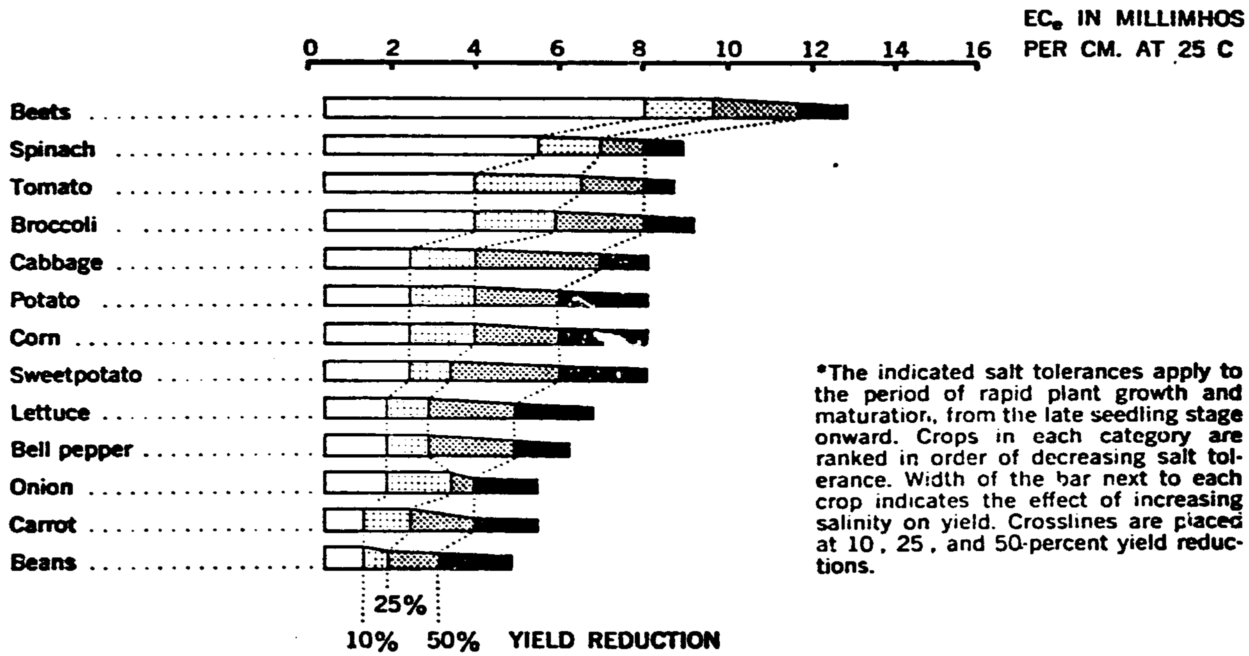

Figure C-3. Salt tolerance of vegetable crops.* (from Richards et al, 1954).