IRRIGATION ENGINEERING

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PREFACE

This paper delineates some aspects of irrigation engineering considered to be vital in the assessment of the potential of irrigation in West Africa. The scope of the paper is described in the introduction (Sec. IC).

The writer gratefully acknowledges the assistance given him by Mr. Bill L. Long, Environmental Affairs Specialist, Office of Science and Technology, AID (Washington, D.C. 20523), in making possible the inclusion of the report, "Techniques for assessing hydrological potentials in developing countries" (Appendix B). Mr. Long emphasizes that the report is in draft form, and any suggestion for strengthening it would be most welcome.

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I. INTRODUCTION

A. ENGINEERING

Engineering is a service profession. The highway designer is effective when he assists others in alleviating the social and economic problems associated with congestion, poor transportation facilities, etc. The mechanical engineer is performing his duties properly when his devices meet the needs and wants of others. He may help to define specific goals of mechanisms, but they are, in the last resort, a reflection of the goals originally set by others. There are two basic concepts which engineers must keep in mind: (1) The engineer must work with non-engineers in arriving at realizable and worthwhile goals and the attainment of them, and (2) Engineering accomplishments are not to be considered as ends in themselves, but merely as means to ends. Failure to recognize this has led to "engineering monuments", examples of which are buildings incompatible with their surroundings, unwanted mechanical contrivances (such as the Edsel car), and some large water resources development projects.

With the above in mind one should recognize engineering activities as being suportive of the overall objectives of an irrigation development program. It should further be recognized that irrigated agriculture, when it occurs, is only one phase in the total development of a nation. Thus it is in competition for available resources--manpower, capital, land and water.

The engineering problems associated with determining the potential for irrigation in an area such as West Africa require the application of present knowledge, and the extension of that knowledge into new situations. This is called applied research, and is a common form of engineering. Whereas basic research can be judged only by a qualified scientist well-versed in that field, applied research can be judged by others as well. Successful applied research results in an immediate, practical answer or solution to a current problem. The steps to be taken in an applied research program are identical to those taken in engineering design. As an aid to the understanding of engineers by non-engineers, the engineering design process is outlined in Appendix C.

The engineer, like other researchers, is plagued with the problem of insufficient data. Either the data is not available at the present time under any circumstances, or it is just too costly to obtain. In these cases the engineer must resort to estimates, <u>not</u> guesses. Woodson (1966) makes the following statement. "Estimation is a projection based upon limited certainties. It is thus distinguished from guessing, which usually is an emotionally-directed speculation." The key to the above statement is the phrase "limited certainties." One seldom has enough information to make a positive decision on the one optimum solution to a problem. However, by careful use of existing data and the accumulation of additional information through research activities, one can usually reduce undertainties to a low enough level that reasonable estimates, and hence reasonable solutions are possible.

Finally, we should discuss the problem of obtaining the "best" solution. Because we are dealing with problems related to irrigation, we shall start with its definition (Cunningham, 1967). "It is the artificial application of water to farmland by canals, ditches, pipes, spraying equipment, flooding, etc., to supply gowing crops with moisture or with additional moisture beyond that furnished by natural means." It would seem then, that a "best" solution to this problem of irrigation would be one that would supply this moisture in the most conservative manner with respect to all the resources used--manpower, water, land and capital. On the other hand, if none of these are limiting, perhaps the "best" solution would be to apply irrigation water in the manner that would give the most crop yield in the irrigated area. Thus, the requirement may not be one of accomplish ing things economically from the resources standpoint, but one of maximizing a specific return. In summary, the objective of all specific irrigation project must be well in mind during all phases of planning, research and execution if a "best" solution is to be obtained.

B. IRRIGATION PROJECTS

The various components of an irrigation project can be catagorized in several ways. A functional breakdown of particular interest to the engineer might be as follows (Vlachos, 1972).

a. Supply
b. Control(storage)
c. Transmission (within the project as a whole, and within farm units of the project)
d. Production (the farming enterprise)
e. Reclamation

Precipitation, in the form of rainfall and snow, is the major source of irrigation water supply within a project area. However, other sources may be of equal or greater importance when precipitation within a basin is inadequate. These might be (desalinized) sea water, water imported from other (irrigated or non-irrigated) areas by surface streams, or ground water if it is the result of interflow from a basin outside the study area.

Control facilities are those which store the water, and they can be roughly divided into surface and underground. The former include lakes, manmade reservoirs and snowpacks. Groundwater reservoirs, resulting from deep percolation of precipitation falling within the project area, may be considered as storage facilities. Sizing and recharge of control facilities is an important aspect of water resources study.

The transmission system carries water through the project area. Natural streams and manmade canals are the most common of these, although closed conduits are also used. Some transmission systems may also act as storage units (ICID,1969). In one scheme water continues to flow from reservoirs during night hours and is stored in the canals, ready for use the next morning. The flow rate from the reservoirs is thus about half that used during the irrigation period. Groundwater aquifers may also transfer water from one area to another. The velocity of movement may be small (due to low permeabilities), but large cross-sectional areas can make flows significant.

The production phase of irrigated agriculture is the farming operation. Under this category are included such items as the consumptive use of crops, water application methods and their evaluation, etc.

The fifth function of an irrigation system is reclamation--of lands so they can be utilized in an irrigation system; of lands that have been used and are now less productive because of problems which have developed and have not yet been solved; and of lands currently irrigated, so that they do not become less productive ("preventive" reclamation). Reclamation includes the removal of excess water or salts and the elimination of scars due to water and wind erosion.

C. SCOPE OF THIS PAPER

The overall study of an irrigation project is the duty of the water resources engineer. He is concerned with the five functions outlined in the previous section, primarily from the overall (meso-scale) approach. His input, along with large-scale planners of other disciplines, is vital if a successful project is to be conceived and executed.

Of equal importance is the planner who looks at the macro- and micro-scale problems. Cantor (1967, pg. 180), a geographer who has analysed irrigation projects throughout the world, makes the following statement.

> "Nor are large irrigation schemes by themselves any guarantee of increased agricultural productivity..... instead of bringing about much needed agricultural expansion (some) such schemes have further favored

> speculation and large landholdings, and in the newly irrigated lands of (one area), farmers have simply cultivated less land better, leaving the rest fallow, thus keeping the same standard of living at considerable expense to the state. A more successful way of extending and improving irrigated agriculture in many areas might be by installing simple, small-scale, water-conserving dams rather than constructing large expensive projects".

This paper therefore deals with some aspects of irrigation engineering which will be most useful to the macro- and micro-scale planner. The writer feels that this not-so-glamorous aspect of irrigation development in West Africa has the potential of large payoffs, with immediate benefits to the farmer, and without seriously jeopardizing any large-scale plans which may be developed simultaneously. Therefore, the subjects chosen are designed to give those people unfamiliar with irrigation engineering some feeling for the production operations--the primary concern of the small-scale planner. An attempt has been made to be specific enough to provide workers with a useful assessment tool.

There are serious gaps in the material that rightfully belong under irrigation engineering of the macro- and micro-scales. Most noticeable of these are discussions on salinity, water quality, and drainage, areas in which others are much more knowledgeable than is the writer. Other areas which should be covered are water measurement, on-farm canal systems, field measurements of irrigation variables, field evaluation of irrigation systems, and conservation practices in humid areas.

II. CONSUMPTIVE USE

All planning for irrigation, and all irrigation scheduling schemes used in irrigation management, require some knowledge of the rate of water use by crops. Such data is therefore of utmost importance in the proper design and management of irrigation systems. This section introduces the subject of consumptive use and methods of determining it.

A. DEFINITIONS

1. Transpiration

Transpiration is the evaporation of water from plant surfaces directly into the atmosphere, or into intercelluar spaces from where it then moves by diffusion into the atmosphere.

2. Evapotranspiration, W_{et}

Evapotranspiration is the sum of transpiration and water evaporation from the soil surrounding the plant. It is commonly expressed in units of depth (mm, in.)--i.e., a volume per unit area.

3. Evapotranspiration Rate, E_t

Evapotranspiration rate is evapotranspiration per unit time (mm day^{-1}, in. day^{-1}, cm $season^{-1}$, etc.).

4. Consumptive Use

Consumptive use is the sum of evapotranspiration plus that water used by the plant for building plant tissue. This latter is less than 1 per cent of that transpired, and thus consumptive use and evapotranspiration are identical for engineering purposes. The term "consumptive use" is common when discussing crop water use, and the term "evapotranspiration" when dealing with energy balance and other climatological investigations.

5. Consumptive Use Rate, CU

Consumptive use rate is the consumptive use per unit time. The terms "consumptive use" and "consumptive use rate" are often used interchangeably, but the meaning is usually obvious.

6. Potential Evapostranspiration, E_{tp}

Potential evapotranspiration is the evapotranspiration by a plant when water is not limiting. Some authors restrict this term to rather specific conditions of crop variety, height, cover, and physiological age. (See Sec. IID.)

7. Evaporation

Evaporation is the change of a liquid to the gaseous state. In order for this to occur there must be a source of energy (586 calories per gram of water at about 20^{o}C), a lower vapor pressure in the air overlying the evaporating surface than at the evaporating surface, and a source of liquid to be evaporated. Evaporation rate is evaporation per unit time.

8. Potential Evaporation

Potential evaporation is the evaporation when water is not limiting. This could occur at a free water surface, as opposed to the case when a matrix is present (a blotter, the soil, etc.). Potential evaporation rate is the potential evaporation per unit time.

B. THE WATER BALANCE CONCEPT

An equation relating the components of the water-plant-soil system (Fig. II B-1) is

$$\Delta W_s = W_i + R_e - W_{et} - W_d$$

where ΔW_s is the change in the water content of the soil in the

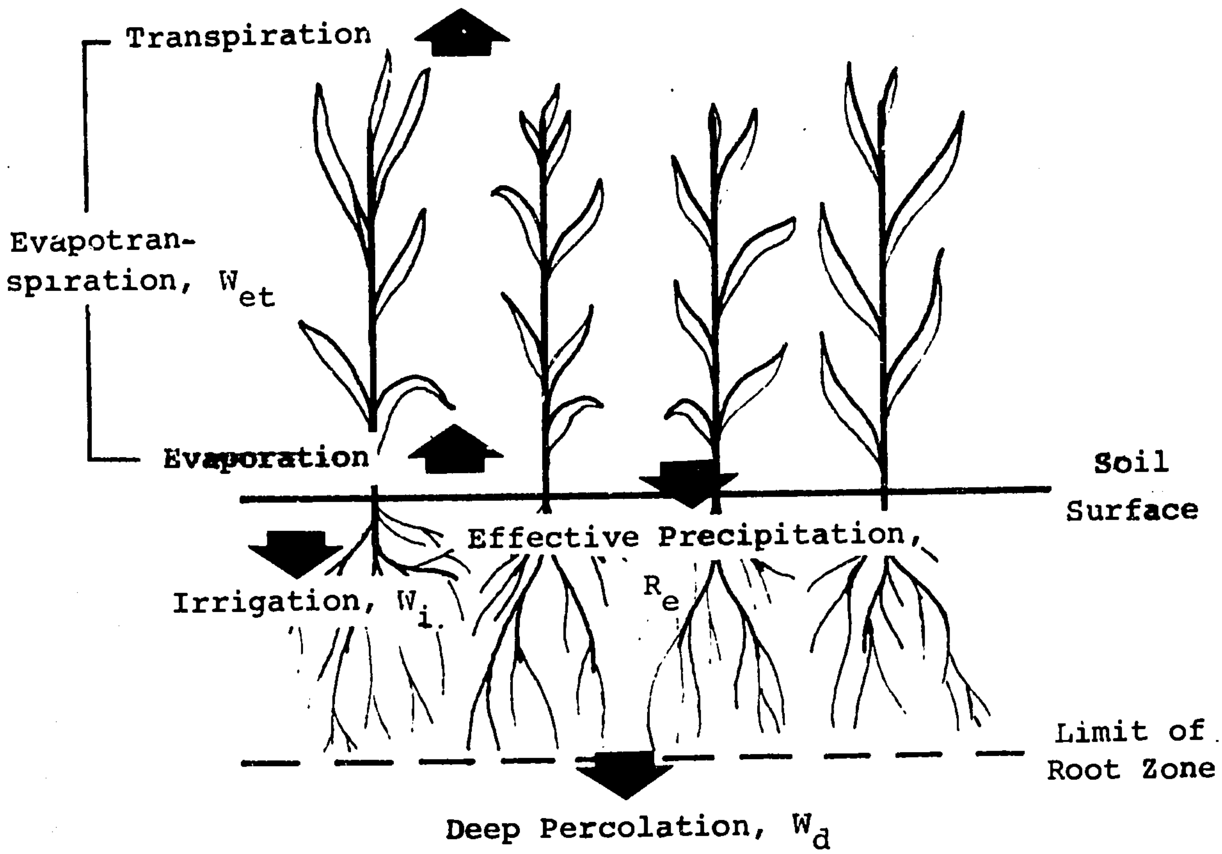

Fig. IIB-1. The field water balance. (Adapted from Hillel, 1971.)

root zone of the plant, W_i is the water added to the soil (i.e. infiltrated into the soil) due to an irrigation, R_e is the effective precipitation (including condensation of dew)--that which enters through the soil surface, W_{et} is the water transpired by the plants or evaporated from the soil, and W_d is the water which drains through the lower boundary of the soil of the plant's root zone (some of which may be beneficially used for the leaching of undesirable or excess salts). Between events of irrigation and precipitation the plant receives its necessary water from the soil water reservoir. The above equation can be solved for long time periods (an entire season), but it is most useful for determining short period changes. If the terms on the right-hand side of the equation are all known, then the depletion of the soil reservoir can be determined. This depletion must be kept within limits; otherwise crop growth will suffer. (See Sec. III of this paper, and other papers of this seminar.) If all terms are known except W_{et}, the water balance can be used for its determination. This is the application of the concept to direct field methods of determining E_t, and to lysimetry.

C. DIRECT MEASUREMENT OF SOIL WATER DEPLETION

The most direct method of determining consumptive use is to grow a crop and, by field measurements, determine all quantities of the equation of Sec. IIA, ΔW_s being determined by soil moisture measurements (gravimetric sampling or neutron devices), and W_i and R_e by direct measurement of water applied (less runoff). Determination of W_d is not so simple and is, in fact, the most common source of error in the method. The usual procedure is to select sites for measurement where R_e is less than that which would cause drainage through the lower boundary of the root zone, and then limit irrigations similarly.

Hillel (1972) has summarized another technique for determining the drainage volume. This method, termed by Watson

(1966) as the "instantaneous profile method" employs the partial differential equation which describes the flow of water in a vertical soil profile. A fairly large plot (about 10 x 10 meters) and extensive soil-water measuring devices--neutron probles and tensiometers--are required. Field determinations of hydraulic conductivity are obtained, and drainage under non-steady conditions can be calculated.

The method outlined above measures directly with consumptive use of the plant under a particular set of growing conditions--climate, soil water availability and the plant's physiological age. Such a measurement is valuable, but in order to completely catalogue the consumptive use of a plant, many hundreds of similar measurements would be needed. Therefore it has become common to determine potential evapotranspiration under a given set of climatic conditions, and apply factors to determine the actual consumptive use of the crop. Microclimatological methods for determining E_{tp} are outlined in Sec. IID and crop coefficients are discussed in Sec. IIE.

D. MICROMETEROLOGICAL METHODS

The use of detailed micrometeorological data to determine E_{tp} has received much attention in the literature. Not only can daily values of E_{tp} be obtained with accuracy, but the measurements also assist in an understanding of the actual mechanisms involved in evapotranspiration. Such detailed investigations require extensive instrumentation and data analysis and are not considered here.

Less detailed climatic measurements, based strongly on solar radiation, also allow prediction of the potential evapotranspiration on a day-to-day basis. Other energy transfers which contribute to E_{tp} are those from the soil to the crop, and those from the air to the crop. Nearly all of this energy is used for evapotranspiration, which requires heat at a rate approximately equal to the heat of vaporization of water (586 cal g^{-1} at 20^{o}C). Thus, E_p (potential evaporation) and E_{tp} are approximately equal, and E_p = CE where C is a constant depending upon the units of E_p and E, and E is the energy made available to the system.

1. Net Solar Energy

Evaporation calculations require the net solar energy, R_n, received by the plant. Net solar energy is the total solar energy, R_s, less that reflected back αR_s , less the outgoing thermal radiation, R_b. Symbolically,

$$R_n = R_s(1 - \alpha)R_s - R_b$$

The quantity R_n can be measured directly with a net radiometer, or the total radiation can be measured with a pyranometer. The albedo, α, or reflectance (of a green crop in full growth and cover, in turgid condition) is between 0.22 and 0.25. R_b must be estimated using empirical equations. One such equation is the following.

$$R_b = a(R_s/R_{so}) + b\ R_{bo}$$

in which R_{so} is the clear-sky radiation (dependent upon latitude and time of year), R_{bo} is the clear-sky outgoing radiation and a and b are empirical constants. R_{bo} can be estimated from the following equation.

$$R_{bo} = (a_1 + b_1\ e_d)11.71 \times 10^{-8}\ T^4$$

where e_d is the saturation vapor pressure (mb) at mean dewpoint and T is the average daily air temperature (^{o}K), and a_1 and b_1 are empirical constants. The necessity of determining the empirical coefficients (a, b, a_1 and b_1) for the conditions under which the equations are to apply can not be over-emphasized. Selected values of these constants are given in Table IID-1.

Table IID-1. Empirical constants for estimating net outgoing thermal radiation, R_b and net outgoing long wave radiation on a clear day, R_{bo}. (Compiled by Jensen, 1972)

Region	(a b)	(a_1 b_1)
Davis, California	(1.35, -0.35)[1]	(0.35, -0.046)[2]
Southern Idaho	(1.22, -0.18)[3]	(0.325, -0.044)[3]
England	(not available)	(0.47, - 0.065)[4]
England	(not available)	(0.44, -0.080)[5]
Australia	(not available)	(0.35, -0.042)[6]
General	(1.2, -0.2)[7]	(0.39, -0.050)[8]
General	(1.0, 0)[9]	

1 W.O. Pruitt. Data provided for analysis by personal communication.

2 Gross, J.R. and F. A. Brooks. 1956. Constants for empirical expressions for downcoming radiation from cloudless skies. Jour. Meteorol. 13(5):482-488.

3 Wright, J.L. and M. E. Jensen. 1972. Peak water requirements for southern Idaho, Proc. Amer. Soc. of Civil Engrs., Jour. of Irrigation and Drainage Div. In press.

4 Monteith, J.L. and G. Szeicz. 1962. Radiation temperature in the heat balance of natural surfaces. Quarterly Jour. Royal Meteorol. Soc. 88:496-507.

5 Penman, H. L. 1948. (See reference list)

6 Fitzpatrick, E. A. and W. R. Stern. 1965. Components of the radiation balance of irrigated plots in a dry monsoonal environment. Jour. Applied Meteorol. 4:469-660.

7 Suggested for arid areas.

8 Budyko, M. I. 1956. The heat balance of the earth's surface. U.S. Dept. Com. Weather Bur. PB 131692. (Translated by N. A. Stepanov, 1958.)

9 Suggested for humid areas, (1.1, -0.1) recommended for semi-humid areas.

2. Soil Heat Flux, G

Heat flux from the soil can enter into the energy balance affecting evapotranspiration. The exchange may be significant over short time periods of a few hours, but it is usually relatively small over a 24-hour period. Short-period measurements are difficult to make, but the average 24- hour exchange can be estimated as follows. Assume that the soil temperature to a depth of 2 m changes approximately with air temperature and that the average volumetric heat capacity of the soil is 0.5 cal $cm^{-3} (^{o}C)^{-1}$

$$G = \frac{\bar{T}_1 - \bar{T}_2}{\Delta t} \quad 100$$

where $\bar{T}_1$ and $\bar{T}_2$ are the average temperatures (^{o}C) for two time periods whose midpoints are Δt days apart.

3. Heat from Air

The air surrounding the plant also exchanges heat with it. The rate of transfer is dependent upon temperature differences, speed of air movement, turbulence in the moving air, and the moisture status of the air and surface. Theoretical equations have been developed for estimating the flux, but the necessary input data are difficult to measure and the use of this technique is therefore unsuited for most CU determinations. Instead, aerodynamic effects are included in the overall semi-empirical potential evapotranspiration equation discussed in the following section.

4. Combination Equation for Estimating E_{tp}

Penman (1948,1956,1963) considered the energy fluxes discussed in the preceeding sections and arrived at a combination equation for estimating potential evapotranspiration. For an extensive short grass cover completely shading the ground, and with water not limiting, the resulting expression is

$$e\,tp = \frac{\Delta}{\Delta+\gamma}(R_n + G) + \frac{\gamma}{\Delta+\gamma}\,15.36(1.0 + 0.0062\ u_2)(e_z^o - e_z)$$

where u_2 is the wind speed at 2 m (km day^{-1}). If the wind speed is measured at another elevation, z , approximate u_2 by setting it equal to $u_z(2/z)^{0.2}$. The terms e_z^o and e_z are, respectively the saturation vapor pressure and the true vapor pressure at the elvation of the wind speed measurement. Values of the ratio $\Delta/(\Delta+\gamma)$ (and hence $\gamma/(\Delta+\gamma) = 1 - \Delta/(\Delta+\gamma)$ are found in Table IID-2. The Penman equation is considered by Jensen (1969) to be the most accurate available for short-term estimates.

Recapitulating, the above equation estimates potential evapotranspiration. The required input data is wind speed, average daily wet and dry bulb temperatures (from which vapor pressures, soil heat flux and the coefficients $\Delta/(\Delta+\gamma)$ and $\gamma/(\Delta+\gamma)$ can be determined), and net radiation (or solar radiation, from which net radiation is determined).

E. CROP COEFFICIENTS

The micrometeorological approach discussed above estimates potential evapotranspiration. Actual evapotranspiration (E_t) is obtained through multiplication of E_{tp} by a crop coefficient, K_c (Jensen, 1969).

$$E_t = K_c E_{tp}$$

Note that K_c is dependent upon the crop and its stage of growth

Table IID-2. Variation of $\Delta/(\Delta+\gamma)$ with elevation and temperature. (After Jensen, 1972)

Temp., ^{o}C	-.67	-1.1	4.4	10	15.6	21.1	26.7	32.2	37.8
Temp., ^{o}F	20	30	40	50	60	70	80	90	100
Elev.,ft.									
0	.296	.377	.461	.534	.620	.687	.745	.794	.833
2,000	.309	.392	.477	.559	.634	.700	.757	.804	.842
4,000	.324	.408	.493	.576	.649	.714	.769	.814	.851
6,000	.339	.425	.500	.592	.665	.728	.781	.824	.859
8,000	.357	.444	.530	.610	.682	.743	.794	.835	.868
10,000	.376	.464	.551	.630	.699	.758	.807	.846	.877

but independent of extra-plant factors contributing to growth--climate and moisture conditions of the soil. The climatic factors are taken care of in E_{tp}. The real problem in using the above equation is that the moisture condition of the soil must not be limiting. If it is, then the predicted value of E_t will be greather than the actual value. The principle redeeming feature of this technique is that the results are conservative from the standpoint of predicting when moisture must be added to the soil. The second redeeming feature is that it makes the determination of E_t (or CU) within practical reach.

Crop coefficients (Figs. IIE-2 through IIE-5) were summarized by Jensen (1969) from a study by Jensen and Haise (1963). Most of the data from which these curves were developed are from arid regions, and the crop coefficients may be somewhat higher in semihumid areas where more frequent precipitation results in higher surface soil moisture content, and thus more evaporation. Other factors which must be considered are the varying degrees of weed growth or cover in orchards and the adequacy of the soil moisture content (as discussed above).

The approach which uses a single crop coefficient curve for a given crop may not be applicable in all cases. Recent investigations in trickle irrigation (Sec. IIIA) have suggested that considerably lower crop coefficients might be suitable for some orchard and vineyard crops as only a fraction of the total ground area need be wetted. Thus, crop coefficients should be related to the irrigation system used. Those given in Figs. IIE-2 through IIE-4 must be considered as being applicable to sprinkler, surface and subsurface systems, and possibly for trickle systems if complete wetting of the surface between rows were practiced. The curve for grapes (Fig. IIE-5) would be considerably altered if trickle irrigation were used. (See Goldberg, _et al._, 1971).

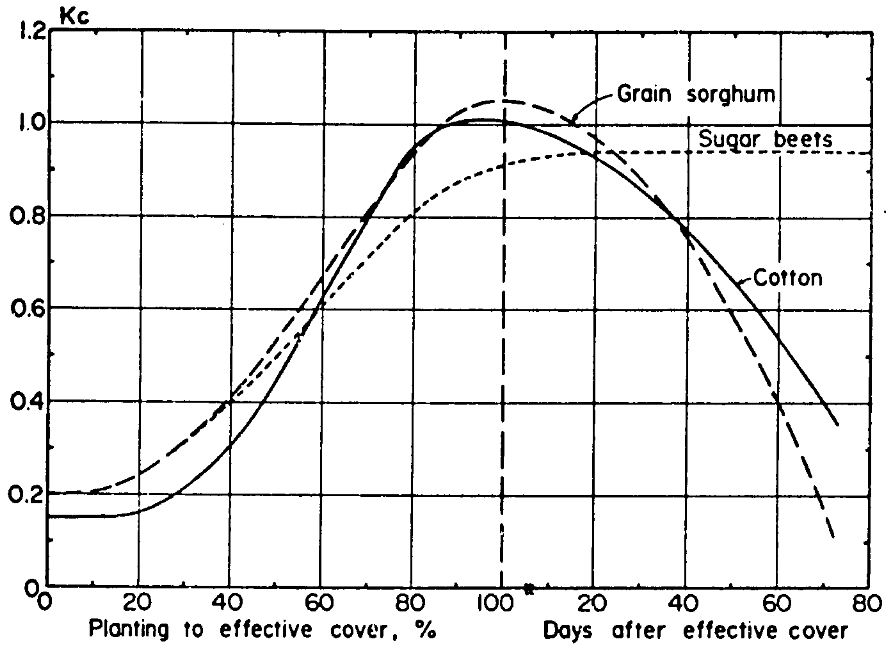

Fig. IIE-2. Crop coefficients for cotton, grain sorghum and sugar beets. (After Jensen, 1969.)

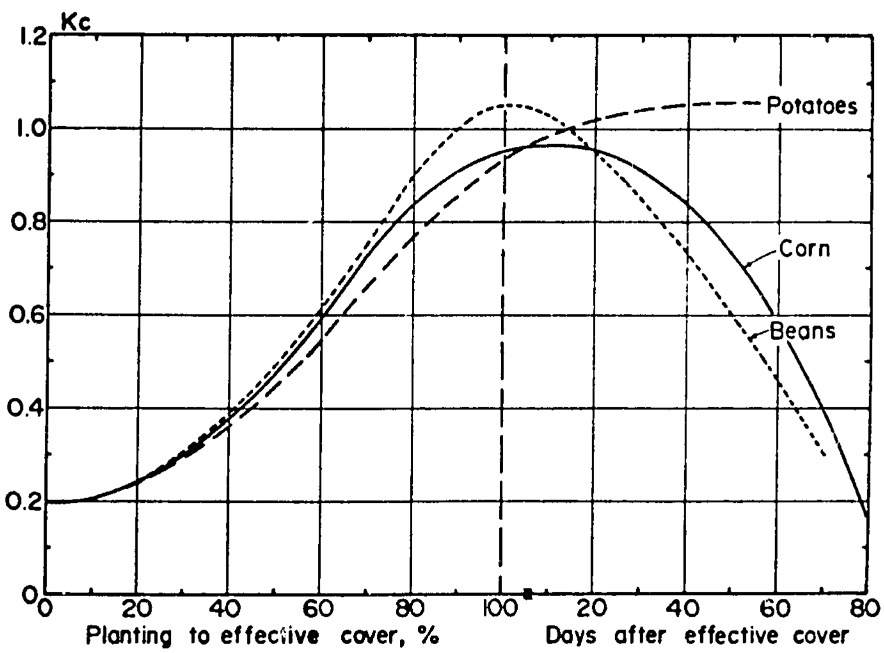

Fig. IIE-3. Crop coefficients for beans, corn, and potatoes. (After Jensen, 1969.)

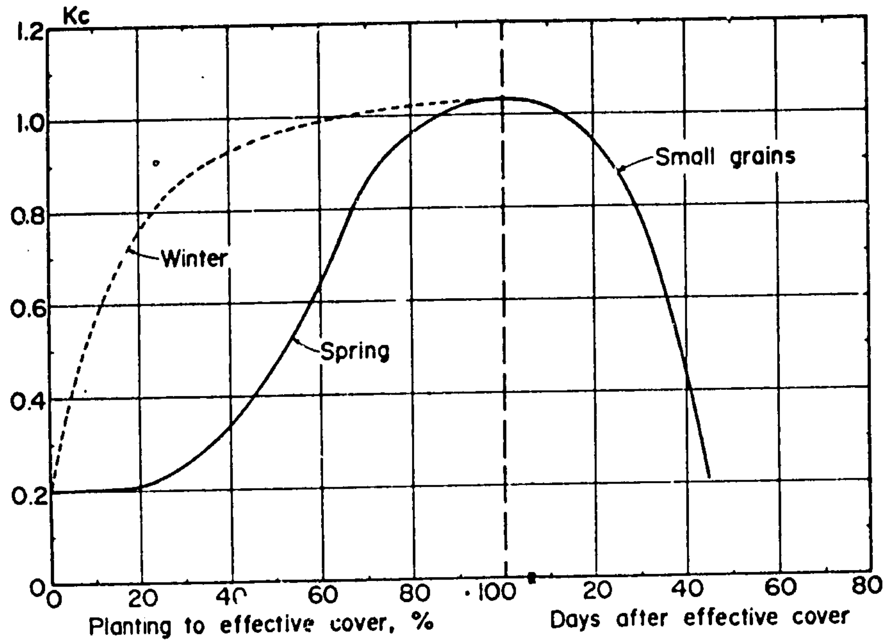

Fig. IIE-4. Crop coefficients for winter and spring small grains. (After Jensen, 1969.)

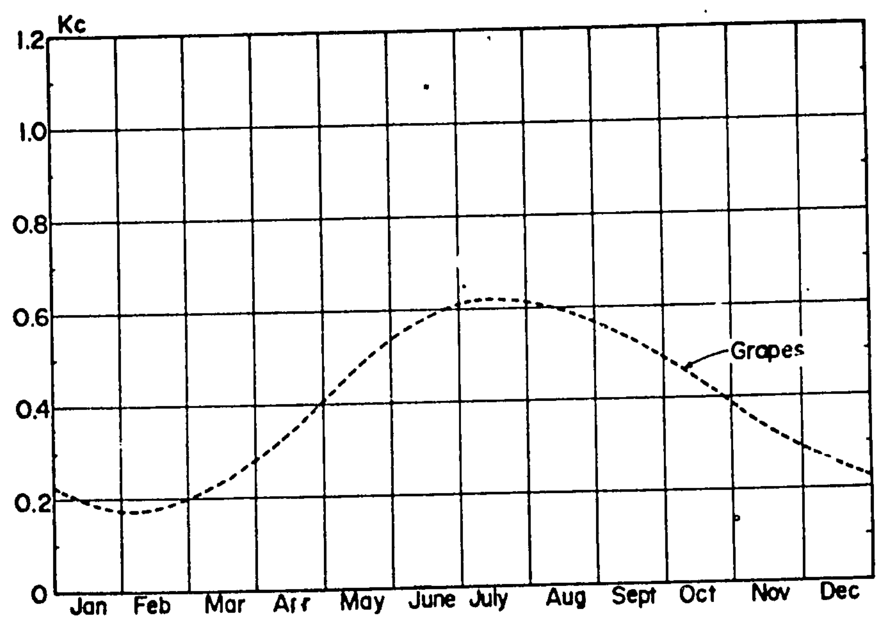

Fig. IIE-5. Crop coefficients for grapes. (After Jensen, 1969.)

F. EMPIRICAL METHODS

One of the most widely used empirical methods was developed for arid areas by Blaney and Criddle (1945,1950,1962) and others (Blaney, et. al., 1952). It is based upon the assumption that the seasonal evapotranspiration is proportional to the sum of the products of mean monthly temperature and the monthly percentage of daylight hours.

$$U = K \sum_{i=1}^{n} t_i p_i / 100$$

where U is the seasonal consumptive use, K is a crop coefficient dependent upon the crop grown, t_i is the average temperature during the ith month, p_i is the percentage of all the daylight hours of the year which occur in the ith month, and n is the number of months in the growing season. Tables of K and p_i have been prepared.

It can not be over-emphasized that the original Blaney-Criddle approach is applicable only (a) for seasonal estimates and (b) for the conditions under which it was developed--those similar to the Western U.S. These limitations have been somewhat overcome by the Soil Conservation Service (USDA-SCS, 1967). The basic procedure has been modified by considering mean temperatures over short durations (on the order of 10 to 14 days) for the 48 states of the continental U.S. and by considering crop coefficients which reflect the influence of crop growth stages on evapotranspiration rates.

The method of Jensen and Haise (Jensen, 1969) is also an empirical one. In a study (from which the crop coefficients of Figs. IIE-2 through IIE-5 were determined--Jensen and Haise, 1963) it was found that

$$E_{tp} = (0.14t-0.37)R_s$$

for the arid and semiarid areas of the U.S. air temperature, t is in ^{o}F and R_s is the solar radiation expressed as evaporation equivalents in mm/day or inches/day. Another form of the estimating equation given by them is

$$Etp = C_t(T-T_x)R_s$$

in which C_t is an air temperature coefficient (constant for a given area), T_x is a constant for a given area, and T is mean air temperature. When accurate evapotranspiration data is available, C_t and T_x can be determined by calibration. Otherwise, C_t can be determined from another empirical formula in which humidity and elevation are factors. Thus, the method can be used to estimate evapotranspiration under humid conditions.

G. LYSIMETRY

Meterological and empirical methods are indirect approaches to determining potential evapotranspiration. They depend on the measurement of a factor other than water use for determining water use. A more direct method is to employ a lysimeter, a device in which a plant community and its soil can be isolated. The water added to it (irrigation and precipitation), and that leaving by drainage can be accurately measured. Some rather complicated weighing lysimeters have been built. These units are expensive and require highly trained personnel to properly operate them, and will not be considered further here. (The interested reader can refer to Pelton, 1961; and Tanner, 1969)

A simple lysimeter can be constructed from a 55-gallon oil drum (Fig. IIG-1). The coarse screen 9 inches above the bottom of the barrel and the 2-inch gravel layer over the screen allows free drainage of the unit. The barrel is installed so that its lip protrudes above the ground surface by 2 inches.

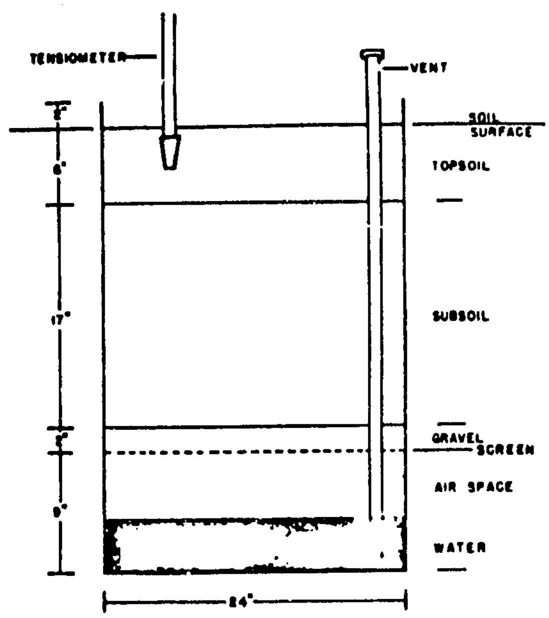

Fig. IIG-1. Simple lysimeter. (After Gilbert and van Bavel, 1954.)

In operation, a crop is grown in the lysimeter, and in a 10-foot diameter area surrounding it. Water is hand sprinkled on the surface of the lysimeter on days when the tensiometer (2-inch depth) reads greater than 100 cm tension (which is considered to be below the level at which transpiration rate is reduced). The depth of the percolate in the bottom of the barrel is measured (to the nearest 0.05 inch) when drainage is essentially complete and field capacity has been reached. This should occur in about 24 to 48 hours, and can be determined by making successive measurements of the percolate volume and noting when it essentially ceases to increase. The amount of water used by the plant, W_{et}, is the sum of irrigation, W_i, and precipitation, R_e (measured by a rain gage nearby) less that which has been percolated, W_d. The term W_x of Sec. IIB is zero if measurements are made at field capacity each time. The evapotranspiration rate is W_{et} divided by the elapsed time.

Moisture is not limiting in the above procedure. If full crop cover has been established, then the measured evapotranspiration is the potential evapotranspiration, E_{tp}. Such lysimetric measurements are the easiest to make because they are independent of the crop's response to soil water tension. They are subject to the same limitations as other lysimeters--mainly that they must have crop conditions similar to those of the crop whose E_{tp} they are estimating.

H. PAN EVAPORATION

Evaporation from open basins of water, called pans, can be used to estimate mean values of E_{tp} for periods of one week to a season. However, it must be remembered that the mass of water within a pan from which evaporation takes place is subject to response lags. Thus pans are not suitable for estimating daily evapotranspiration such as might be utilized in an irrigation scheduling program (Sec. IIIE). Jensen (1969) delineates several precautions to be taken when utilizing pan data.

1. The evaporation rate is not the same for all evaporation pans in a given climatic region with similar site conditions;
2. Site conditions, such as the presence or absence of actively growing grass around the pan, influence the evaporation rate for a given pan;
3. The coefficients recommended are generally more reliable for longer time periods, such as a month or season, than for weekly or 10-day estimates;
4. Evaporation from pans will not reflect the influence of decreasing soil moisture on E_t, a limitation applying also to other estimating procedures.

To these limitations there might also be added the following:

5. The reliability of CU estimates utilizing pans is highly dependent upon the similarity of the fetch conditions surround the pan to those within the field whose consumptive use is being estimated.

Pruitt (1960) has demonstrated the importance of calibration of a particular pan and its immediate environment (Table IIH-1). Note the difference in pan ratios (extreme righthand column of Table IIH-1) for the entire season and the changes in the relative evaporation of different pans during the months of July, August and September. There is actually a reversal in behavior of the pans located on dryland the noncrop areas as opposed to those located on grass sodded weather stations.

Jensen (1969) points out that the crop coefficients discussed for empirical and micrometerological formulations vary. Goldberg, et al. (1967) have demonstrated a practical method for obtaining a relation between water consumption and the evaporation from a pan. They designed an experiment in which two irrigation frequencies, 7 and 10 days, both receiving the same water application, were used. There were four differnt grcss water applications equal to 0.60, 0.75,0.90, and 1.05 times the cumulative evaporation from a pan, beginning when plant cover reached 75%. The optimum treatment was found to be that in which water was applied weekly in amounts equal to 0.90 times the evaporation from a screened class A pan. Ratios greater than 0.90 produced over-irrigation (excessive drainage water but all pan ratios produced about the same total yield. Crop quality decreased considerably when the irrigation interval was extended from 7 days to 10 days. The pan experiments shed light on several aspects of irrigation scheduling. In a summary the authors state that from planting until 5 to 6 weeks of age the consumptive use depends primarily on the moisture of the upper soil layer. The pan ratio was about 0.3. From the beginning of flowering consumptive use increased rapidly until the plants completely covered the ground, reaching a maximum at peak flowering and then decreasing until harvest. The average pan ratio during the period after 50% ground coverage is reached is 0.85 and the optimum irrigation treatment was found to be that in which water was applied weekly in amounts equal to 0.90 times pan evaporation. (Pan ratios are in some ways similar to crop coefficients.)

Where applicable, pans have some advantages over other methods of determining irrigation requirements. They involve the use of a single measurement rather than the several that are necessary in the microclimatological methods. On the other hand they are less suitable for short periods of time than are the other techniques mentioned.

I. SUMMARY OF CONSUMPTIVE USE MEASUREMENTS AND ESTIMATES

Direct measurement of consumptive use by crops is expensive because of the sophisticated equipment which must be used, and because of the variable growing conditions which can occur. Thus, estimating procedures, combined with measurements under restricted conditions, provide the most practical method of determining consumptive use by crops. However, it is extremely important that the chosen estimating method be suitable for the conditions under which it is applied (especially humidity).

Table IIH-1. Monthly and Seasonal Evaporation in Inches and the Ratio of Evaporation From All Pans to Evaporation From the 6-foot Ground Pan. Roza Unit of the Irrigation Experiment Station Near Prosser, Washington, 1955 Season. (After Pruitt, 1960.)

Pan	Diameter of pan (inches)	Depth of pan (inches)	Height of top of pan above ground (inches)	Evaporation in inches						Total May 1 to Nov. 1	Ratio of evap. to 6 ft pan evap.
				May	June	July	Aug.	Sept.	Oct.		
6 ft ground	72	24	3	5.62	7.42	6.20	6.45	3.84	1.76	31.29	1.00
4 ft ground	48	24	3	5.74	7.74	6.36	6.76	4.29	1.93	32.82	1.05
2 ft ground	24	24	3	6.02	8.21	6.80	7.44	4.72	2.20	35.39	1.13
4 ft USWB	48	10	16	7.48	10.46	8.41	8.79	5.17	2.26	42.57	1.36
2 ft surface	24	24	24	6.64	10.09	7.87	8.43	5.17	2.35	40.55	1.30
2 ft elevated	24	24	42	7.55	11.69	9.08	9.81	6.22	2.75	47.10	1.51
3 ft ground°	36	24	3	7.06	10.95	9.22	9.84	5.95	2.49	45.51	1.45
2 ft surface°	24	24	24	--	--	10.15	11.13	6.68	2.76	--	1.68

°These pans were located in a large (5- to 6-acre) dryland, noncropped area about 600 ft. north of the regular weather station. The other six pans were located on a grass-sodded weather station in the cropped area.

III. IRRIGATION SYSTEMS

A. WATER APPLICATION METHODS

There are four basic methods of applying water to land--surface, sprinkler, subsurface and trickle. Each, depending on field conditions, has advantages and disadvantages. The paragraphs which follow describe these methods. Appendix A lists some criteria for selection of systems.

1. Surface

Surface methods apply water directly to the ground surface. Water flows down the prevailing slope, infiltrating into the soil as it goes. It is characteristic of such systems that water is in contact with soil longer at some points (usually near the point of application) than at others. This, due to the nature of the soil's water intake function, results in non-uniform distribution of water over the field (Sec. IIID). However, properly designed systems can have water distributions which are quite acceptable. In fact much over half the area irrigated in the U.S. is by surface methods. Table IIIA-1 lists the most common types of surface systems, and their ranges of applicability.

"Level" systems are those on land which has little slope. Level border systems are those in which low parallel levees, 15 to 100 feet apart, guide the water down the field. They operate best if the cross-slope (that at 90 degrees to the direction of irrigation) is zero, but it can be greater than this (Marr,1958). It is common to make levees quite low when the borders are used for sown, drilled or sodded crops in order that farm machinery can easily pass over them. Low levees also make it possible for the water to sub across them, and thus a crop can be grown there, reducing the area for weed growth.

Table IIIA-1. FACTORS AFFECTING THE SELECTION OF SURFACE IRRIGATION SYSTEMS. After Turner and Anderson, 1971.

Type of System	Maximum Slope: Humid Areas: Non-Sod Crops	Maximum Slope: Humid Areas: Sod Crops	Maximum Slope: Arid Areas: Non-Sod Crops	Maximum Slope: Arid Areas: Sod Crops	Water Application Rate of Intake Family*: Min.	Water Application Rate of Intake Family*: Max.	Shape of Field	Adaptable to: Row Crops (Row or Bedded)	Adaptable to: Sown, Drilled, or Sodded Crops	Adaptable to: Weed Control in Rice	Adaptable to: Orchards and Vineyards	Labor Required	Approximate Cost**
	(percent)				(inches per hour)							(hours per acre per irrigation)	(dollars per acre
Level:													
Level Border	Nearly Level				0.1	2.0	Any shape			Yes		0.10 - 0.5	100 - 250
Contour Levee	0.1				0.1	0.5		Yes	Yes		Yes	0.05 - 0.5	50 - 150
Level Furrow	Nearly level				0.1	2.0	Rows should be of equal length			No		0.20 - 0.7	100 - 250
Graded:													
Graded Border	0.5	2.0	2.0	4.0	0.3	2.0	Rectangular	No				0.20 - 1.0	100 - 300
Contour Ditch	NA	4.0	4.0	15.0	0.1	3.0	Any shape					1.00 - 2.0	25 - 50
Graded Furrow	0.5	NA	3.0	NA	0.1	3.0	Rows should be of equal length	Yes	Yes	No	Yes	0.40 - 1.2	100 - 300
Corrugation	NA	NA	4.0	8.0	0.1	1.5	Rectangular	No				0.40 - 1.2	50 - 100
Contour Furrow	Cross slope 3.0		Cross slope 6.0		0.1	2.0	Rows should be of equal length	Yes	No			0.50 - 1.5	75 - 150

*Intake family is a grouping of soil by the Soil Conservation Service. It is based on the ability of the soil to take in the required amount of water during the time it takes to irrigate.

**Does not include the cost of water supply, pump, power unit, and mainline.

Level furrow systems utilize small channels to carry the water down the field. Water subs across the banks between the furrows (due to capillarity) and so essentially the entire field is wetted at the surface in a good irrigation. Furrow spacing is usually the same as the crop spacing, although for some vegetables, furrows are spaced every two rows. The vegetables are then grown on beds. In the case of orchard crops, there may be several furrows between each row of trees, and then a space (down the tree row) where there are no furrows. Both level borders and level furrows usually require the land to be prepared. Land forming equipment may move as much earth as 800 $yard^3$ $acre^{-1}$ (1500 m^3h^{-1}).

Contour levee (also called contour check) systems are similar to borders in that a very wide channel conveys the water down the irrigation slope. In California, where they are used on rice, there is often little land leveling--only minor irregularities are removed. The system receives its name from the fact that the leves are on contours (points of equal elevation). Thus, in contrast to level borders in which the water courses are straight, the channels conveying the water are curved, following the general lay of the land.

The basin system is another surface application method often used on very flat lands. Rectangular areas, with 0.2-ft maximum elevation difference within their boundaries, are surrounded by levees. When available irrigation heads (water flow rates) are high these basins can be rapidly filled with water, resulting in a highly uniform irrigation.

"Graded" systems are those in which the land slope is considerably greater than in level systems. In fact, except for slope in the direction of irrigation, graded and level borders and graded and level furrows are identical.

The contour ditch system is used extensively for low value crops--such as forage or irrigated pastures--on marginal soils and rolling topography. It requires little or no land preparation, outside of a ditch to convey water (nearly) along the contour. A dam or check structure in the ditch causes the water surface to rise and as it does so, water overflows into the field. There are usually no guides (channels or levees) in the direction of the irrigation slope to direct the flow and the result is that water often is very non-uniformly distributed.

Contour furrow systems also require little alteration to the topography. The furrows are made nearly on contour and may be of varying distances apart. For this reason it is often necessary to install short furrows that do not extend the full length of the field. These irrigate areas not reached by the full length furrows. The short furrows cause management difficulties and require additional labor over that required in flat land (level) furrow systems. Furrows must be substantial to provide for adequate drainage in the event of high-intensity storms. Otherwise water will break through the banks and cause extensive damage (Marr, 1967). It is usually necessary to provide drainage-ways at the downstream end of the furrows.

Corrugation systems are those employing very small channels, similar to furrows but not nearly so large in cross section. Although some authors suggest that they be made on contours, this can cause some difficulty if the cross slope of the land is at all significant for they will be unable to carry runoff from storms. On the other hand, if they are aligned directly down a slope, any one corrugation can accumulate water from an area no greater than that equal to twice the area between two corrugations. Thus, the "watershed" feeding a corrugation is limited, and it will adequately contain flows and prevent erosion. In rolling lands this means that the corrugations are not uniformly spaced down a field. Corrugations can also be used in conjunction with contour levees, or borders.

2. Sprinklers

"A sprinkler system is a network of tubing or pipes with sprinkler heads or nozzles attached for spraying water over the land surface" (Pair, 1969). The distinction between such systems and surface ones is immediately obvious--the method by which water is spread. It is common to limit the application rate by sprinklers to some level below that which the soil can infiltrate. In this way, all water goes directly into the ground and does not spread laterally over the soil surface. However, it may indeed spread laterally beneath the surface (Hart, 1972).

Many sprinkler systems were developed in an attempt to save labor. Others were designed primarily to save water. Most are more costly initially, and require more power, than do surface systems. Manufacturers have been quite innovative in developing a miriad of systems.

Fry and Gray (1971) have divided systems into five categories. Fully Portable systems have portable mainlines, submains, laterals and pumping plants and are designed to be moved from field to field or to different pump sites in the same field. A semiportable system is similar to a fully portable one except that the location of the water source and pumping plant are fixed. A semipermanent system has portable lateral lines, permanent mainlines and submaines, and a stationary water source and pumping plant. The mainlines and submaines are usually buried, with risers or valves located at convenient intervals. A solid-set system has enough portable laterals (positioned in the field early in the season and remaining until the last irrigation before maturation of the crop) to eliminate the need for being moved during the season. The mains and submains may be either buried or portable. Fully permanent systems consist of permanent mains, submains and laterals, and a stationary water source and pumping plant. Mains submains and laterals are all buried, and sprinklers are permanently located on each riser.

Fully portable and semiportable systems have the advantage of being easily moved from field to field, or even from farm to farm. They are ideally suited to cases where only supplemental irrigation is needed, for they can cover a large area at little initial cost.

On the other hand, semi-permanent, solid-set, and fully permanent systems are designed to be used on a single field, at least throughout a season. Fully permanent systems are most often used in turf and nursery applications.

Turner and Anderson (1971) chose a classification system based upon the nature of the sprinkling unit designed to distribute the water (Table IIIA-2). All classes outlined by Fry and Gray can be included in the Turner and Anderson system. The following discussion of system characteristics will follow that outlined in the table.

Hand-moved portable and solid set systems have sprinklers spaced on laterals at equal intervals ranging from 30 ft. (9m) to 60 ft. (18m), depending primarily upon wind conditions. A lateral is operated for a fixed length of time (the set time) and then moved 40 ft. (12m) to 80 ft. (24m). (A common method of designating spacing is "30 x 50 feet", indicating that the spacing of sprinkler in a direction perpendicular to the prevailing wind direction is 30 ft, and that parallel to the wind is 50ft.) Set times of 7, 11, and 23 hours allow the sprinkler moving task to be conveniently combined with other farming operations. Solid-set systems have sprinkler and lateral spacings similar to portable ones. The sprinklers are usually turned on and off automatically, by time clocks or moisture-sensing devices. When operated by clocks, the set times are often some interval that is not integrally divisible into 24 hours. In this way advantage can be taken of diurnal variations in winds, which assists in obtaining uniform water distribution from the sprinklers.

Tractor-moved (skid-mounted and wheel-mounted) and self-moved (side-wheel-roll and side-move) have spacings and set times similar to those of hand-moved systems. The increased first cost over portable systems--about double--is offset by their reduced labor requirements.

The self-propelled systems are characterized by extremely low labor requirements. The center-pivot system consists of a single lateral, usually 1320 feet long, which pivots about a

Table IIIA-2. FACTORS AFFECTING THE SELECTION OF SPRINKLER IRRIGATION SYSTEMS. After Turner and Anderson, 1971.

Type of System	Maximum Slope	Water Application Rate Min.	Water Application Rate Max.	Shape of Field	Field Surface Conditions	Max. Height of Crop	Labor Required	Size of Single System	Approx. Cost*	Adaptable To: Cooling and Frost Protect.	Adaptable To: Pesticide Application	Adaptable To: Fertilizer Application	Adaptable To: Liquid Animal Waste Distribution
	(percent)	(inches per hour)				(feet)	(hrs per acre per irrigation)	(acres)	(dollars per acre)				
MULTI-SPRINKLER													
Hand-moved:													
Portable set	20	.10	2.0	Rectangular	No limit		0.50 - 1.50	1- 40	50-200	No			Not Recom.
Solid set	No limit	.05	2.0	Any shape			0.20 - 0.50	1 or more	400-900	Yes			
Tractor-moved:					Smooth enough for safe tractor operation	No limit							
Skid-mounted	5 - 10	.10	2.0				0.20 - 0.40	20- 40	100-300				
Wheel-mounted	5 - 10	.10	2.0				0.20 - 0.40	20- 40	100-300				
Self-moved:				Rectangular									
Side-wheel-roll	5 - 10	.10	2.0		Reasonably smooth	4	0.10 - 0.30	20- 80	100-300				
Side-move	5 - 10	.10	2.0			4 - 6	0.10 - 0.30	20- 80	125-300				
Self-propelled:					Clear of obstructions, path for towers								Yes
Center-pivot	5 - 15	.20	1.0	Circular		8 - 10	0.05 - 0.15	40-160	125-250				
Side-move	5 - 15	.20	1.0	Square or Rectangular		8 - 10	0.05 - 0.15	80-160	125-250	No	Yes	Yes	
SINGLE-SPRINKLER													
Hand-moved	20	.25	2.0	Any shape	No limit		0.50 - 1.50	20- 40	50-200				Not Recom.
Tractor-moved:					Safe operation of tractor								
Skid-mounted	5 - 15	.25	2.0				0.20 - 0.40	20- 40	100-300				
Wheel-mounted	5 - 15	.25	2.0			No limit	0.20 - 0.40	20- 40	100-300				
Self-propelled	No limit	.25	1.0	Rectangular	Lane for winch and hose		0.10 - 0.30	40-100	120-250				
BOOM-SPRINKLER													
Tractor-moved	5	.25	1.0	Any shape	Safe operation of tractor	8 - 10	0.20 - 0.50	20- 40	200-300				Yes
Self-propelled	5	.25	1.0	Rectangular	Lane for boom and hose	8 - 10	0.10 - 0.50	40-100	200-300				
PERMANENT													
Manual or Automatic	No limit	.05	2.0	Any shape	No limit	No limit	0.05 - 0.10	1 or more	400-1000	Yes			

*Does not include the cost of water supply, pump, power unit and mainline.

single point in the center of a square field. The lateral is supported by wheel-or skid-mounted towers which are individually driven by electrical, oil, or water power. A feedback control mechanism maintains alignment of this lateral. Such a unit, once started into operation, needs only occasional maintenance. One of its limitations is that it applies water at high rates (up to 1 inch per hour) at the distal end of the lateral, and is therefore suited only to soils where such high rates can be readily absorbed. Traction problems can occur because the ground over which the towers travel is always freshly irrigated. Side-move systems have a single lateral, usually 1320 feet long, which travels laterally across the field. Some times pipes perpendicular to the lateral, with 1 or 2 sprinklers on each, drag behind the lateral. The tractor-moved systems have a single line of sprinklers which is towed into place by a tractor hooked to one end. Both of the potential problems of the center-pivot--high application rates and travel over wet ground--can be circumvented with the self-propelled side-move and tractor-move systems.

Single-sprinkler systems are characterized by large sprinklers, some discharging hundreds-of-gallons per minute, in contrast to most of the multi-sprinkler systems which commonly have sprinkler discharges in the range of 5 to 20 gallons per minute. Application rates may be high or low depending upon design. Self-propelled single sprinklers are usually moved by winching a firmly-anchored cable, and so unstable soils are not a problem. Steep slopes may cause significant distortion of the sprinkler application pattern and may result in low uniformities.

Boom sprinklers have a single rotating pipe, up to 250 ft. (76 m) long, with large sprinklers on the ends and smaller ones between them. The reaction to the water leaving the sprinklers rotates the boom. These massive sprinklers are unsuited to rough terrain because high inertial forces develop when they are moved. Well-graded roadways can help to alleviate this problem.

The three self-propelled systems mentioned have one thing in common--the potential for extremely uniform distribution of water. This is so because of the nature of water application. Consider the process of painting an area. The brush is swept over the surface, laying down a uniform coating (self-propelled systems). Consider another method of "painting" in which a brush with a circular end is pressed down on the surface, then lifted, moved to another area, and again pressed down (systems not self-propelled). It is obvious that the latter method would result in a less uniform application than the other. The analogy applies to the two types of sprinkler systems.

3. Subirrigation

There are two general systems of subirrigation--natural and artificial. The former takes advantage of natural conditions at the site, and may provide a very efficient and economical irrigation system. The other requires the installation of rather large amounts of equipment and has not proven as economically successful. Subirrigation has appeal for several reasons. No water is applied directly to the soil surface, so surface structure breakdown (crusting and plating with surface systems, puddling with sprinkler ones) does not occur, the infiltration capacity of the soil is maintanined, and the surface readily absorbs natural precipitation, adding to the available water and preventing erosion due to runoff. In some cases no water reaches the soil surface, resulting in less evaporation and higher soil temperatures than with either sprinkler or surface irrigation. These advantages may result in increased yield per unit land area, or per unit volume of water (Harrison, et al., 1970), and per unit of applied fertilizer (Davis and Belson, 1970). With some artificial systems all equipment is buried and there is no interference with farming operations, another advantage. As will be seen in the following paragraphs subirrigation requires rather specialized conditions if it is to be successful.

Zimmerman (1966) gives the following "natural and organizational conditions" as being required for successful natural subirrigation.

1. A soil profile consisting of:
   a. medium to very light textured top soil,
   b. stable subsoil with high permeability rating permitting rapid water movement through it,
   c. impermeable substratum or free water table at a depth of 5 to 9 feet below surface level, or
   d. peat soils allowing fast lateral moisture movement.
2. A very flat and meticulously even field surface.
3. Abundant water supply of excellent quality and very low salinity.
4. A centrally managed irrigation organization if a large area is to be irrigated by this method.

In the continuous flow natural subirrigation system ditches 1000 to 2000 ft. (300 to 600 m) apart and 3 to 4 ft. (90 to 120 m) deep are continuously flodded to a specified level. This allows water to seep into the porous subsoil where it rises to the surface by capillarity. The system is applicable to peat soils and very deep sandy loam soils. The intermittent flow natural subsurface irrigation system consists of a network of channels (Sacramento-San Joaquin delta of California, USA). Land should be level or have a maximum grade of 2 ft/100 ft. toward main drains, which are spaced 100 to 300 feet apart. Water is introduced rapidly into the ditches, so that the water table rises to such level that capillarity can carry it to the surface. Immediately thereafter check gates are opened and the water is allowed to drain from the ditches. If this is not rapidly accomplished, soils will become waterlogged and roots will suffer from lack of oxygen. Thus, operating conditions are extremely critical.

Artificial irrigation, which utilizes underground pipelines of considerable extent, or other devices, does not have the natural soil and topographic conditions to assist it. Thus, the distributors must be very closely spaced, and the system is generally expensive. In addition, because water is unevenly distributed throughout the pofile, plant roots grow toward and into the water distributors, plugging them. New distributors, developed primarily for trickle irrigation, have shown promise and their use may considerably extend the application of subirrigation.

Because of the limited applicability of natural subirrigation, and the developmental state of the new equipment and techniques for artificial subirrigation, these systems will not be considered in detail in future discussions.

4. Trickle Irrigation

A relatively recent development in water application methods is trickle, or drip, irrigation. Developed in Israel, the principle is to apply water to the soil surface very slowly, and only to areas from which it can flow to a plant's root system. For orchards it is necessary to consider only 25 to 50 per cent of the total possible root zone volume. Water is delivered to the system at low pressures (often less than 15 psi) and discharges through small outlets discharging 1 or 2 gpm. Water high in salts can be used under some conditions, but it must be relatively free of suspended solids, passing a 100-mesh screen (Kenworth, 1972 and Goldberg et al., 1971--see below).

There is ample evidence in the literature that trickle irrigation has applicability in many instances. Goldberg et al. (1971) irrigated grapes with a trickle system, at intervals of approximately 1, 7, 15 and 30 days. Their results (Fig. IIIA-1) showed that the more frequent intervals resulted in higher moisture contents, a greater portion of the time, within the root zone. All treatments received the same total amount of irrigation. Because the experiments were performed over two years (and thus yields were markedly effected by factors other than water management), yields were expressed as ratios to that of the 15-day interval yield. The results (Fig. IIIA-2) show the increased

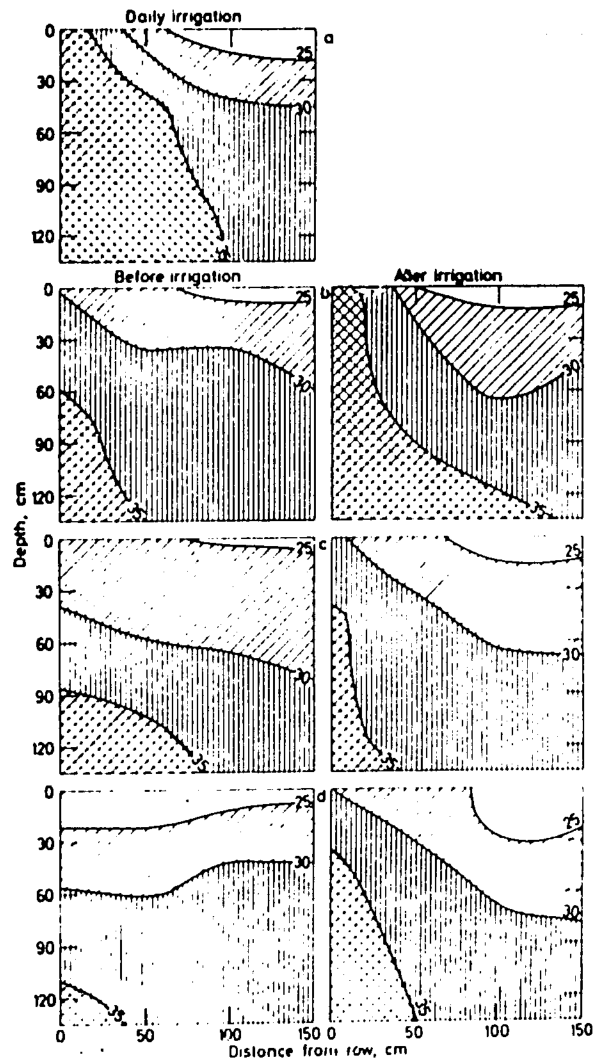

Fig. IIIA-1. Soil moisture profiles: (a) Daily irrigation, (b) 7.5-day irrigation interval, (c) 15-day irrigation interval, (d) 30-day irrigation interval. Contour line numbers are in volumetric moisture percentage. (After Goldberg, et al., 1971)

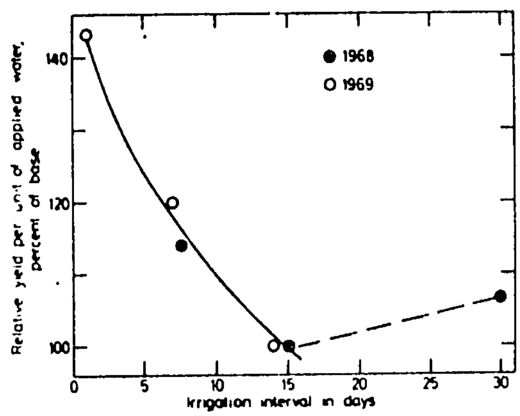

Fig. IIIA-2. Relative water use efficiency for grape production. Owing to extraneous variations in the overall level of productivity in different seasons, results were calculated relative to the 15-day or 14-day treatment in 1968 and 1969, respectively. (After Goldberg et al., 1971)

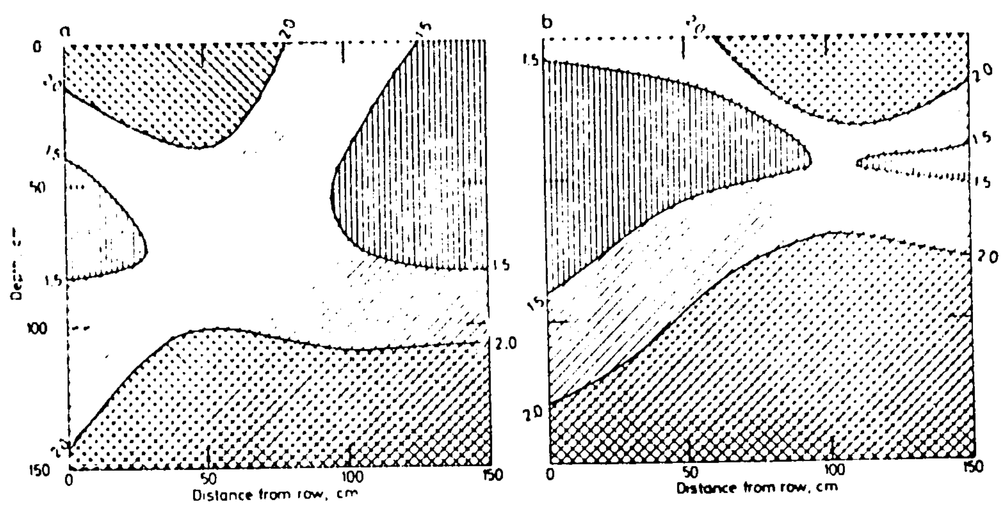

Fig. IIIA-3. Salinity in the soil profile: (a) 7.5-day interval, (b) 30-day irrigation interval. Contour line numbers are conductivities of saturation extract in mmho/cm.

water utilization, as reflected in increased yield, at the more frequent intervals. Trickle systems are admirably suited to light, frequent irrigations.

Another facet of the above investigations evaluated the effect of trickle irrigation on soil salinity (Fig. IIIA-3). The authors state that "the characteristic profile has an isolated pocket of accumulated salts adjoining to part of the (soil) surface and a second, deep level of accumulation, with an onion-shaped leached zone between them, situated beneath the row". The authors conclude that "the possible long term extent of salination resulting from the inherent limitations in the leaching pattern of tricklers is a cause of some concern", especially in arid zones where the upper soil layers may be insufficiently leached by rains.

B. SYSTEM DESIGN

1. Field Sizes and Shapes

All mechanized and to a lesser extent nonmechanized farming operations are effected by field size and shape. Miles (1972) indicates that farming costs on a per acre basis are twice as high for triangular 10-acre fields as for rectangular 40-acre ones. Small 1-and 2-acre surface-irrigated plots in Pakistan are noted for low irrigation efficiencies. Although this may be partly due to field practices it is also a result of large conveyance losses which occur when water is delivered to the small fields.

Sizes of fields may eliminate some otherwise potentially useful irrigation methods. As an example, borders are often 500 to 1,000 feet (125 to 300 meters) long. Furrows may be a kilometer in length under ideal conditions. Some sprinkler systems require fields of over 50 hectares to be economically feasible. The center-pivot system previously discussed is one of these. The initital cost of the distribution equipment for these and side-roll systems are shown in Fig. IIIB-1.

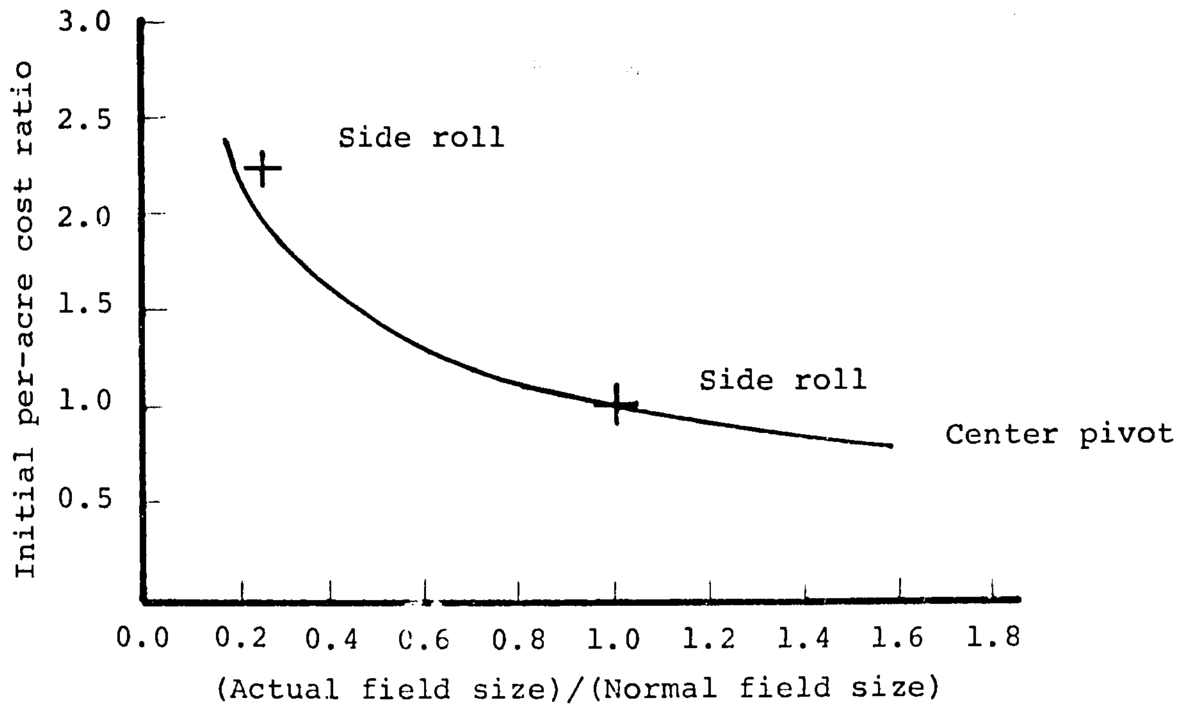

Fig. IIIB-1. Cost of distribution equipment.
(Exclusive of mainline, pumps, etc.)

The normal size field for a center-pivot system is 160 acres (square) and that for a side-roll is 40 acres (square). When field sizes are halved the initial cost of these units go up about 50% and when field sizes are reduced to a quarter of the normal size the initial equipment cost doubles.

The above discussion illustrates the need for field size and shape considerations during the initial planning stages of an irrigation enterprise. Although institutional constraints may dictate otherwise in areas that are already under irrigation, in areas to be newly developed it may be possible to limit the minimum size of farms.

2. System Capacity

Of concern to the system planner and designer is the quantity of water which must be made available over the season for crop growth, and the rate at which it must be supplied. Crop requirements for water and means for determining them have been discussed in Sec. II. From measurements and calculations outlined the daily use can be determined. The sum of daily uses, for the entire growing season, gives the total water which must be made available.

The rate at which water must be made available is a function of the peak use rate of the plant and the size of the reservoir from which the plants can withdraw water. This rate is called the system capacity (USDA-SCS,1968).

$$Q = \frac{453Ad}{FH}$$

where Q is the rate of delivery of irrigation water during the time it is delivered (gpm), A is the area irrigated (acres), d is the gross depth of application (inches), F is the number of days over which the application is applied, and H is the time of applying the water (hours/day).

Application of the above equation to a simple case of corn irrigation will serve to demonstrate its usefulness. Keller (1962) states that the average consumptive use rate during the peak use period of 14 days, around July 30, is 0.335 in/day (Nebraska). This is a total depth of 0.335 x 14 = 4.7 inches. If the readily available water reservoir in the plant's root zone is also 4.7 inches, then this amount must be applied every 14 days. Assume the water application ratio (Sec. IIID) is 0.80, then the gross depth to be applied is 4.7/0.80 or 5.9 inches. A typical sprinkling system might be installed on a 40-acre square field such that 60-foot lateral spacings are used, requiring a total of 22 sets (1320 divided by 60). A reasonable schedule would be 2 sets per day, of 11 hours each (allowing 1 hour for moving). The system capacity would be

$$Q = \frac{453 \times 40 \times 5.9}{11 \times 22}$$

$$= 442 \text{ gpm}$$

Assume now that the soil water reservoir is larger than 4.7 inches, so that some water is available from the soil reservoir to assist over the peak-use period of 14 days. Using a 42-day total period (3 irrigations) an average CU of 0.300 in/day, then d = 0.300 x 42/0.80 = 15.8 in.

$$Q = \frac{453 \times 40 \times 15.8}{11 \times 22 \times 3}$$

$$= 395 \text{ gpm}$$

The system capacity need be but 90% of that originally calculated, with possible savings in equipment costs.

In the case of multiple cropping systems, the system capacity for each crop must be found. There may be several critical periods, where one or more crops have a peak use, and the maximum system capacity must be determined. The example of Table IIIB-1 demonstrates the calculation of system capacity for the case where several crops are grown.

The above methods of computing system capacities are adequate when dealing with arid lands--those in which precipitation cannot be counted on during the irrigation season. However, in the case of humid or sub-humid areas, where a considerable portion of the applied water comes from rainfall, a system so determined would be over-designed and thus more expensive than necessary. A more refined technique should be used.

Godwin, et al. (1971) developed a computer model for determining system capacities in humid regions, utilizing 20-year records of precipitation and pan evaporation. The root zone was assumed to increase as the crop got older, and corresponding to it, the soil water reservoir. E_t was estimated from pan evaporation, crop growth state and soil moisture content. The irrigated area was divided into sections, which were irrigated sequentially with a specified application of water, during a given irrigation period. A sequence of irrigations commenced when the soil moisture was calculated to be at 60% capacity. Depletion was determined using the water balance equation of Sec. IIB. As the irrigation sequence continued, each sector in turn was irrigated if its soil moisture content was at less than 20% of its total capacity, the number of days for which this occurred was tallied, and added to the total tally of days for all similarly depleted sectors. The number of sector-days below 20% of capacity, divided by the total number of sectors, gave a "failure index". The total number of failures (years for which failure index was greater than or equal to 1) for the 20-year period of the study was divided by 20 to give the probability of failure. The same calculation procedure was repeated for other application amounts, and for three different soils (a fine sand and two fine sandy loams). Plotted results (Fig. IIIB-2) for the fine sand and one fine sandy loam) allow the pumping rate (net daily application rate) to be determined for any given probability of failure.

Table IIIB-1. Computing capacity requirements for a crop rotation (After USDA-SCS, 1968)

Given:

Design area of 90 acres with crop acreages as follows:
10 acres Irish potatoes, last irrigation May 31.
2.6 inch application lasts 12 days in May (peak period).
30 acres corn, last irrigation August 20.
2.9 inch application lasts 12 days in May.
3.4 inch application lasts 12 days in July (peak period).
50 acres alfalfa, irrigated through frost-free period.
3.6 inch application lasts 12 days in May.
4.3 inch application lasts 12 days in July (peak period).
Irrigation period is 10 days in 12 day irrigation interval.
System to be operated 16 hours per day.

Calculation:

Capacity requirements for <u>May:</u>

$$Q = \frac{453Ad}{FH}$$

(All three crops are being irrigated)

Irish potatoes $Q = \frac{453 \times 10 \times 2.6}{10 \times 16}$ = 74 gallons per minute

Corn $Q = \frac{453 \times 30 \times 2.9}{10 \times 16}$ = 246 gallons per minute

Alfalfa $Q = \frac{453 \times 50 \times 3.6}{10 \times 16}$ = 510 gallons per minute

Total for May = 830 gallons per minute

Capacity requirements for <u>July:</u>

$$Q = \frac{453Ad}{FH}$$

(Potatoes have been harvested, corn and alfalfa using moisture at peak rate.)

Corn $Q = \frac{453 \times 30 \times 3.4}{10 \times 16}$ = 289 gallons per minute

Alfalfa $Q = \frac{453 \times 50 \times 4.3}{10 \times 16}$ = 609 gallons per minute

Total for July = 898 gallons per minute

Although only two of the three crops are being irrigated, the maximum-capacity requirement of the system is in July.

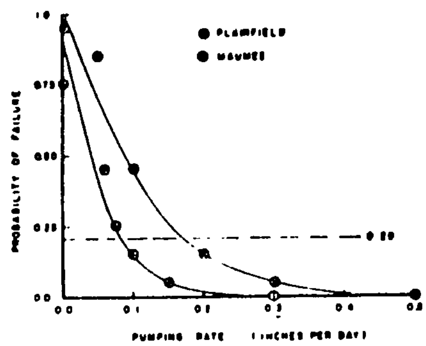

Fig. IIIB-2. Probability of failure vs. pumping rate. (After Godwin, et al., 1971)

The second evaluation procedure used by Godwin et al. determined the number of stress days suffered by each sector of cropped area. A stress day is a day in which the crop has lost turgor (Dale and Shaw, 1965). By establishing an acceptable number of stress days, an alternate design criteria was established.

Another approach to accounting for both the expected variation in E_t and precipitation is to use extreme value analysis (Gumbel, 1954). Jensen and King (1962) and Grag et al. (1966) have used this approach. Stegman and Shah (1971) have shown that such extreme value analysis techniques will give a more conservative design than will a suitable system simulation scheme.

3. Principles of Surface Irrigation

Most analytical studies of surface irrigation have addressed the situation wherein water flows over a land surface having uniform slope in the direction of irrigation and no side slope. The soil surface initially has no water on it and is permeable. Irrigation is accomplished by a surface stream introduced at the upper end of the field and advancing in shallow sheet flow down the surface as is common in border irrigations. While most studies describe only the advance of the stream the problem in general also includes the buildup of impounded surface storage, depletion of that storage and final recession of water from the surface. The general phenomenon, therefore, represents a case of unsteady nonuniform flow over a porous bed, and is similar to other cases of overland flow. Solution variables usually desired include rates of advace and recession, infiltration opportunity times, depth of water infiltrated and some measure of uniformity of application. Also frequently sought are the depths and average velocities of surface water at points along the run.

As irrigation water flows into a field and progresses down its length an ever-decreasing portion of the total volume applied flows above ground while the remainder infiltrates into the soil and composes the subsurface storage. Any rational approach to prediction of surface irrigation flows must equate the total volume of water discharged at the head ditch to the sum of surface storage and subsurface storage. Moreover, this volume balance should obtain at every instant of time subsequent to the initial turning of water onto the land. In addition to the mass continuity requirement just described the flow of water is also subject to the requirements of energy and momentum conservation. Either of these, when properly applied, will result in equations which when solved in conjunction with mass continuity yield a solution to the problem. The particular solution obtained is, of course, dependent upon the boundary conditions (flow into the border, length of border, etc.).

Unfortunately, solutions of the problem described above are difficult to obtain. One usually considers an upstream boundary condition of constant inflow. The downstream flow boundary, during advance, is moving. The shape of the water surface at that point is difficult to determine and most solutions (Kruger and Bassett, 1965) have resulted from arbitrary assumptions regarding tip geometry. Further, the solutions so far obtained have been primarily through the use of finite-difference techniques. These are in general too expensive and complicated to be considered practical ones for design purposes. A committee made up of members of the eleven western states of the U.S. has been working on the hydraulics of surface irrigation for over 10 years. Recently there have been some significant advances in the analysis of the problem.

For the simple case of border irrigation the advance of water is a function of the inflow, the slope of the border, its hydraulic roughness and the infiltration of water into the soil. In all solutions to date it has been assumed that the inflow rate is constant (q_o), the surface slope is constant (S_o), the roughness factor is constant (Manning's n or Sayre and Albertson's (1961) χ), and the infiltration function is a

2-parameter family of the following form:

$$z = Kt^a,$$

where z is the total depth of water infiltrated (volume per unit area) in time t, and K and a are constants. Strelkoff (1972) has shown that these five parameters can be reduced to three nondimensional ones by an appropriate choices of non-dimensionaliziang constants. Attempts are now being made to develop nondimensional advance curves which are functions of these three parameters only. In particular it turns out that under certain conditions only one or two of the parameters are important. Thus it seems possible that in the not too distant future a practical analytical solution to the advance phase of border irrigation will be available.

The next phase of irrigation occurs after the advancing tip reaches the end of the border. Water begins to run off the lower end, or to be stored behind a dam. At about this time the inflow is either reduced or shut off completely. Eventually the water recedes from the soil surface, due to infiltration and flow down the border. The period over which this occurs is known as recession, and the three factors just mentioned--time of shutoff, field length, and downstream boundary condition--become important. To date there has been no generalized solution to the recession and storage phases of the border irrigation problem, although Bassett (1965,1972) has solved some specific cases.

Water flow in furrows is even more complicated than in borders. Additional problems arise because of the shape of the furrow. Two factors are important. In borders the flow gometry is essentially that of a wide channel and thus the hydraulic radius is equal only to the depth. However, with furrows the flow cross section can have a very complicated shape. Except for the idealized situation of a triangular-shaped furrow, the hydraulic radius and the cross-sectional area, both of which are factors in the general flow equations, are complicated functions of depth. Of even more significance is the effect of any cross section, other than that of a wide channel, on the infiltration function. It is reasonable to assume that infiltration into most agricultural soils is a function of the intake opportunity time--the total time for which water has been on the surface (Sec. IID). In border irrigation infiltration is essentially one-dimensional--vertically downward into the ground. With furrows, however, infiltration has both vertical and horizontal components. As the water level in the furrows rises and falls the wetted area varies and infiltration is no longer a single-valued function of intake opportunity time. Although it is theoretically possible to handle such conditions with the finite-difference models already developed, this has not yet been done.

A few other items of precautionary nature should also be noted. The irrigation continuum is a dynamic system changing with time, both during an irrigation and throughout the irrigation season. The infiltration functions for any given irrigation will depend upon not only the soil but also on the moisture content at the time the irrigation takes place and upon the past history of wetting and drying. The roughness in an irrigation system is also time-dependent. Roth (1971) presented data indicating extreme variation in roughness during irrigation. The work he reports is only for bare soils and roughnes during a single irrigation varied from 0.28 to 0.42 (Manning's n). This is due in part to the breakup of large clods as they are wet by the advancing water. The variation in roughness is further complicated when vegetative elements are present. If roughness elements are rigid and relatively unaffected by the flow of water past them, one sort of model is applicable. If they are flexiable and bend as water passes by them another model is necessary. If they are closely spaced wave interference must be considered. Current analytical solutions to surface irrigation consider only one parameter to describe roughness, rather than the several which may be necessary.

Most surface irrigation systems are designed on the basis of empirical relations that have been developed through practice. The soil conservation service (USDA-SCS, 1969,1972) has developed design criteria for contour levee and border irrigation, but their procedures are too comprehensive and complicated to present here. Marr (1958) has discussed border irrigation as practiced in the state of California, U.S. His recommendations for strip sizes and inflow rates for alfalfa and pasture are presented in Tables IIIB-2 and IIIB-3.

Marr (1958) also discusses the design of levees used in border irrigation. He recommends that they be low and have relatively flat side slopes. This allows the water in the border to sub through and makes it easy for harvesting equipment to cross them. If this were not the case the levees could be subject to considerable weed growth, contaminating the field and taking area out of production. Such borders can tolerate little cross slope, and the elevation difference between two adjacent borders must be small. More substantial levees are used for paddy rice. They must be capable of withstanding the wave action developed in the large basins of water that are present.

Marr (1967) has also discussed furrow irrigation in some detail. His recommendations for furrow lengths are based upon basic water intake rates (Sec. IIID) and the probable soil texture (Table IIIB-4). Long lengths of run are possible on the carefully graded fields in the large central valley of California. The U.S. Bureau of Reclamation (USBR,1951) has also made recommendations for furrows or corrugation lengths. A comparison of its values (Table IIIB-5) with those of Marr show that there is considerable agreement. (The Bureau of Reclamation values are for areas other than California.)

Table IIIB-2. Tentative Standards for Estimating Unit Flow of Water and Length of Strip Check for Border Irrigated Alfalfa. (After Marr, 1958.)

Soil profile	Slope	Flow per foot width of strip check		Average depth of water applied*	Strip check		Suggested basis for design
					Width	Length	
	ft. per 100 ft.	g.p.m.	c.f.s.	inches	feet	feet	
SAND	.2- .4	50–70	.11-.16	4	40–100	200–300	Very rapid spread of water, minimum length of strip check and small average depth of water application
60-inch permeable	.4- .6	45–50	.10-.11	4	30–40	200–300	
subsoil	.6-1.0	25–40	.06–.09	4	20–30	200–300	
SANDY LOAM	.2- .4	25–35	.06–.08	5–6	40–100	300–600	Fairly rapid spread of water, short length of strip check and medium average depth of water application
60-inch permeable	.4- .6	20–30	.04-.07	5–6	20–40	300–600	
subsoil	.6–1.0	10–20	.02-.04	5–6	20	300	
CLAY LOAM	.2- .4	15-20	.03-.04	6-7	40–100	600–1000	Fairly slow spread of water, long strip checks and heavy water application
60-inch permeable	.4- .6	10-15	.02-.03	6-7	20–40	300–600	
subsoil	.6-1.0	5-10	.01-.02	6–7	20	300	
CLAY 60-inch + permeable subsoil	.2- .3	10–20	.02-.04	7–8	40–100	1200 +	Slow spread of water, long strip checks, maximum depth of water applied
CLAY ADOBE	.2- .3	2-10	.004–.02	7–8	40–100	1200 +	

* Depends on the available water-holding capacity of the soil. Usually 1-inch depth of water will wet sandy soil 12 inches or more deep; loam soil, 6 to 10 inches deep; and clay soil, 4 to 5 inches deep.

Table IIIB-3. Tentative Standards for Estimating Unit Flow of Water and Length of Strip Check for Border Irrigated Pasture. (After Marr, 1958.)

Soil profile	Slope	Flow per foot width of strip check		Average depth of water applied	Strip check		Suggested basis for design
					Width	Length	
	ft. per 100 ft	g.p.m.	c.f.s.	inches	feet	feet	
CLAY LOAM	0.15–0.6	25–35	.06–.08	2–4	15–60	300–600	Fairly rapid spread of water, short lengths of strip checks
24-inch + over per-	.6 –1.5	20–30	.04–.07	2–4	15–20	300–600	
meable subsoil	1.5 –4.0	10–20	.02–.04	2–4	15–20	300	
CLAY	0.15–0.6	15–20	.03–.04	4–6	15–60	600–1000	Slow spread of water, long strip checks
24-inch + over per-	0.6 –1.5	10–15	.02–.03	4–6	15–20	600–1000	
meable subsoil	1.5 –4.0	5–10	.01–.02	4–6	15–20	600–1000	
LOAM 6- to 18-inch over hardpan	1.0 –4.0	5–20	.01–.04	1–2	15–20	300–1000	Steep slope, narrow strip checks, depth of water application restricted by substratum

Table III B-4. Recommended Furrow Lengths for Initial Layouts on Slight Slopes. (After Marr, 1967.)

Basic WIR inches per hour	Probable soil texture	Maximum furrow length
		feet
High: 1 to 3-------------	Sandy, Clay, Sand Clay Loam	660
Medium High: $\frac{1}{2}$ to 1-----	Loam, Silt Loam	1,320
Medium Low: $\frac{1}{2}$ to $\frac{1}{4}$-----	Clay, Clay Loam, Silty Clay Loam	2,640
Low: $\frac{1}{4}$ or less----------	Clay	2,640

Table IIIB-5. Lengths of Run for Furrows and Corrugations. (After USBR, 1951.)

Length of Furrows or Corrugations in Ft.

Slope in %	Loamy Sand and Coarse Sandy Loams	Sandy Loams	Silt Loams	Clay Loams
0-2	250-400	300-660	660-1320	880-1320
2-5	200-300	200-300	300-660	400-880
5-8	150-200	150-250	200-300	250-400
8-15	100-150	100-200	100-200	200-300

C. FARM DISTRIBUTION SYSTEMS, HEADLAND FACILITIES AND WATER MEASUREMENT

The function of on-farm water distribution systems and headland facilities is to convey water to its place of need. The distribution system delivers water to a given field and the headland facility transfers it from the distribution system to the furrow, garden, sprinkler lateral, etc. The two types of conveyance systems--open and closed conduits--each have applicability according to conditions. Initial, operating and maintenance costs will vary for each system according to several criteria.

- Energy state of water delivered to and needed in the distribution system
- Flow rate
- Land topography
- Soil infiltration and erosiveness characteristics
- Convenience factors--acc ssibility of fields, weed seed control, maintenance, operation
- Availability of materials and construction equipment

Only a complete engineering and economic study can dictate the particular system to choose. However some general guidelines are possible.

1. Farm Distribution systems

Sprinkler and trickle irrigation methods require pressures above atmospheric--sprinklers from 20 to 150 psi (1.3 to 10 atm) depending on the particular system, and trickle systems from 15 to 45 psi (1 to 3 atm). Thus, pressure energy available at the point water is delivered to the farm should be conserved for such systems to avoid additional pumping costs at the field edge. In addition, if pressure is not available or must be dissipated in transmission, it is sometimes desireable to provide it at a control point where electrical power is available. Electric motors are more trouble-free and require less maintenance than do internal combustion engines.

Many types of closed conduit are available for such applications. Among those most popular now in the Western U.S. are PVC (poly-vinyl chloride) plastic, reinforced concrete, and asbestos-cement (all usually buried) and aluminum (usually left on the ground surface). Plastic often has the lowest initial material and installation cost but may not be applicable if there are sharp stones in the soil. Thermal expansion accompanying temperature changes can result in abrasive action, which weakens the pipe. If not properly backfilled when installed it can become severely distorted, accompanied by a reduction in flow capacity. Concrete pipe is heavy and requires machinery at installation. Asbestos-cement pipe is midway between plastic and concrete in weight, and is relatively easily installed. Most pipe made from the above materials have slip-type rubber-gasket joints and are easily assembled. Aluminum pipe is available in several pressure ratings. Coupler configurations vary widely with different manufacturers. The principle factor to be considered is pressure rating. If the couplers are not adequate in high pressure applications there will be continual problems of failures.

Surface systems require only enough energy at the field edge to overcome minor head losses and topographic irregularities. For this reason most head available at the point of farm delivery can be dissipated in the transmission system and need not be conserved. Either open channels or low-pressure conduits are possible. All will dissipate energy according to a chezy-type equation (for steady uniform flow).

$$Q = CAR^{\frac{1}{2}}S^{\frac{1}{2}}$$

where Q is the flow rate, A is the cross-sectional area, R is the hydraulic radius, S is the rate of energy loss (due to surface roughness) and C is a factor dependent upon relative roughness and viscosity effects. When topography is suitable, open channels can provide economical conveyance. However, the control of water in them can be more difficult than in a closed conduit. If soils are erosive, or if their infiltration rates are excessive, the channels may need to be treated or lined. Bentonite can be used to seal leaks in some soils, but the most common lining material is concrete. It is relatively permanent (although it often develops cracks) but expensive. Plastic, such as polyethylene, PVC or butyl rubber (listed in order of increasing permanence) are also used. These must be protected from damage by animals--domestic or wild--and plant growth.

Open channels require control structures to divert the water into other open channels or closed conduits. Control structures usually include a check structure (small dam) to build up head within the channel, and a gate or overflow device. Care must be taken in their design and operation so that bank overflow will not occur in any portion of the transmission system

Most of the above problems are overcome with the use of low-head pipe systems. These can be of concrete (non-reinforced), plastic or asbestos-cement. They have the advantage of providing good water control, and of being underground to prevent interference with farming operations. They are somewhat more difficult to repair than open channel systems when failures occur. Adequate provision must be made to control head to within the working limits of the pipe (usually 10 to 15 feet) through the use of overflow weirs or automatic float valves.

2. Headland facilities

Headland facilities receive water from the farm distribution system and deliver it to the field application system. The headland facility of sprinkler systems is mainline pipe, with valves for controlling water delivery to laterals. Mainlines which are frequently moved should have self-draining gaskets and couplers which can be easily assembled or disassembled by grasping a pipe section at its midpoint. In high pressure systems (greater than 80 psi) quick-couplers may not be feasible because they are less reliable under the high forces that are developed. Mainlines infrequently moved should have non-draining gaskets.

Surface irrigation headland facilities are varied in type and depend to a large extent on the type of system they supply and the topography. As an example, border systems are often fed from a ditch (lined or unlined) by syphon tubes. One or several may be used depending on required flow (up to 10 cfs per border) and tube diameter (3/4 in. (2 cm) to 1 ft (30 cm)) and irrigation head (4 in (10 cm) to 1 ft (30 cm)). They may be moved from field to field, and so they are relatively low in first cost. Another outlet facility often used in unlined ditches is the spile--a short tube installed in the bank, through which water flows into the border. They are not too practical with concrete lined ditches as they must be installed at construction time at considerable extra expense. Once installed they are not easily adjusted if found to be out of alignment. Small open cuts are also popular in open earthen ditches. Water control is difficult, however, and the cuts must be stabilized to prevent erosion of the ditch banks. In all open channel systems check structures raise the water level, causing flow through the outlets.

Most furrow systems are characterized by small flows (usually less than 10 gpm) into each channel. Thus, each outlet setting requires labor for control of a considerably smaller flow than with borders. Syphon tubes, spiles, and open cuts are common outlet devices. Spiles are often preset so that when the water level raises in the supply ditch, a large group will discharge simultaneously. If supply ditches are on too high a grade, it is sometimes convenient to provide a forebay--a level basin fed by the ditch--in which the spiles are installed. Forebays are not practical, however, where soil infiltration rates are high. In this case open ditches are usually lined and the forebay would to some extent negate the advantage of the lined ditch.

Several unique headland facilities have been developed for use on Hawaiian Sugar Cane. Some of the soils of the area are highly permeable, with basic intake rates in excess of 0.5 in. hr^{-1} (1.2 mm hr^{-1}). Thus, flows into furrows often exceed 75 gpm. In place of ditches, concrete or aluminum flumes are used, especially in steeper lands. Outlets of plastic and metal deliver water to the furrows. When not distributing water to individual furrows the flumes can act as conveyance channels. On steep slopes, aluminum flumes are closed to make non-pressurized pipe with the seam being on the upper side. Open channel flow occurs within such a pipe. This equipment and the irrigation systems with which it is used, are discussed by Humbert (1968) and, to a lesser extent, by Israelsen and Hansen (1962).

The use of multipel outlets and other equipment designed to reduce labor costs has been discussed extensively in the literature (Haise and Kruse, 1969; Humphery, 1969; Garton, 1966; Sweeten et al., 1969; Sweeten et al., 1970; Hart and Borrelli, 1972).

D. EVALUATION OF IRRIGATION SYSTEMS

The irrigation designer attempts to choose that system which will make the best use of those resources -- manpower, capital, land and water -- allocated to the production function. Inappropriate methods must be eliminated early in the study, and this can often be accomplished by determining how efficiently each system uses water. The extension irrigationist, in his attempt to assist farmers, must evaluate water use so he can compare different systems and farms. The following paragraphs give a basis for each evaluation.

In the past descriptors such as those to be defined have been labeled efficiencies, but in a recent action of a regional committee studying the hydraulics of surface irrigation (WRCC-6, 1972) it was decided to use the term "ratio", and that term will be adopted here.

1. Quantity Definitions

In the following definitions all quantities are in terms of volume per unit area, a surface depth of water.

a. Plant System

The _plant system_ is that combination of factors which determines the amount of beneficially used water (see below). Included are the plant itself, the soil it grows in, the subsoil underlying it and the environment surrounding the plant.

b. Irrigation Interval

The _irrigation interval_ is the elapsed time (usually expressed in days) between the starting of two successive irrigations.

c. Beneficially Used Water or Useful Water

Beneficially used water is the total amount of water (usually expressed as a surface depth) used by the plant system during an irrigation interval. The major part of useful water is commonly consumptive use. Other portions of it include water for leaching and temperature control.

We can write the following equation.

$$w_u = CU + LR$$

in which w_u is the useful water, CU is that water required for consumptive use and LR is the leaching requirement. Although water for heat and frost control is beneficially used, it is not considered in this discussion.

It is possible to extend the beneficial use concept to a period other than the irrigation interval. The following definition applies to seasonal use.

d. Seasonal Beneficially Used Water or Seasonal Useful Water

Seasonal beneficially used water is the total amount of water used on the plant system during an irrigation season (W_u).

Although the beneficially used water appears to be a measure of the amount of water desired by the plant system, the actual use can be limited by the water made available during an irrigation period.

e. Available Water

Available water is the total water made available to the plant system by an irrigation.

The major portion of the available water is usually that stored in the root zone of the soil, and later used by the plant. It is equal to the quantity expected to be in the root zone soil at the end of the current irrigation and drainage period minus the amount that will be in the root zone soil at the end of the current irrigation interval. In addition, the water consumptively used during the irrigation and drainage period is available to the plant. If the irrigation takes place over a long period of time, the consumptive use during this period is also water made available to the plant.

$$w_a \leq (T_i + T_d)\ cu + RW + LR ,$$

in which w_a is the available water, T_i and T_d are the times for irrigation and drainage (of irrigation water), respectively, cu is the consumptive use per unit time, and RW is the water which can be stored in the root zone. Because RW and LR are not always satisfied by an irrigation, the "less than or equal to" symbol is used. The special requirements of heat and frost control water are again ignored.

f. Seasonal Available Water

Seasonal available water is the total water made available to the plant by all irrigations during a season (W_a) .

g. Requirement or Rated Depth

The requirement is the maximum value of w_a possible, that is

$$r = (T_i + T_d)\ cu + RW + LR.$$

2. Ratio Parameters for Evaluating Irrigation Systems

a. Water Application Ratio, R_a

$$R_a = w_u/w_d$$

where w_u is the volume of water used by the plant-water system during an irrigation interval or that made available for use and w_d is the amount delivered to the field during an irrigation. The water delivered is that which enters the irrigation system at the field boundary and goes into the furrows, borders, sprinklers, etc., less that which is collected as runoff for reuse. In the U.S. the practice of intentionally putting on excess water at the head of a field and collecting the runoff for reapplication to the same or other fields is being increasingly practiced. Such procedures improve the uniformity of application on surface systems. Water application ratios vary greatly with systems and local conditions. The following values were found in the Upper Colorado River Comprehensive Framework Study

(UCRCFS, 1971).

System	R_a
Level border	0.50 to 0.80
Graded border	0.60 to 0.75
Furrow	0.45 to 0.70
Contour ditch	0.40 to 0.60
Corrugation	0.45 to 0.70
Sprinkler	0.65 to 0.75

The above measurements did not consider the reapplication of runoff water.

If w_d is quite small, R_a can be unity, signifying a good irrigation. In such a case a measure of how much of the requirement was met would be more indicative of the quality of the irrigation.

b. Water Requirement Ratio, R_r

$$R_r = w_u/r \ .$$

This ratio indicates that fraction of the water requirement actually met by an irrigation and is a measure of the adequacy of the irrigation. As with R_a , R_r can be made unity (again, a good irrigation being implied) by applying an excess of water. In this case R_a would be a better indicator of the quality of the irrigation.

c. Production Ratio

$$R_p = \text{(crop yield)/(water delivered)}$$

This ratio is only applicable to a field (or farm) after all irrigations have been completed and crop yield has been determined. It is extremely sensitive to management practices, such as fertilizer application and, especially, irrigation timing. Data of Schneider *et al*. (1969) amply demonstrate this. Their experiment consisted of irrigating wheat at various stages of growth. Treatments from dry (depending only on rainfall for moisture) to every combination of irrigations during early spring growth, early spring to late boot, heading to flower, and early grain development were applied. Thus, the variations in yield for a given amount of water are due to the timing of water application (and experimental error, soils, etc.). The production ratios for the experiment ranged from 0.79 bu/ac-in. to 2.15 bu/ac-in., with the highest ratios attained when there was irrigation during the heading to flower period and either the early spring growth period or the early spring to late boot period. The ratio is valuable for evaluating water management strategies when water is limiting.

d. Other Ratio Parameters

Expressions similar to those already defined can be developed for analysing facets of an irrigation project. The water delivered by a reservoir, divided by that which enters it, measures how well the reservoir performs its function of storing water. The water beneficially used by all crops in a project, divided by the water diverted to the system measures overall project performance.

3. Distribution Parameters for Evaluating Irrigation Systems

The ratio parameters described above deal only with total volumes. They do not consider that irrigation systems distribute water nonuniformly over a field. Thus, additional parameters have been developed to describe such nonuniformity. The importance of these measures first came to light in the evaluation of sprinkler irrigation systems but they may also be used in evaluating other methods of irrigation.

a. Christiansen's (1942) Uniformity Coefficient, UCC

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

where the summation term is the sum of the absolute deviations of individual observations of water depth (X_i) from the average depth of water applied, $\bar{x}$, and n is the number of observations. The fractional term is thus the mean deviation, expressed as a fraction of the average application. One method of determining the observations, X_i, is to space cans uniformly throughout the area to be sprinkled, operate the sprinkler system, and then measure the depth of water in each can.

b. HSPA* Uniformity Coefficient, UCH

$$UCH = 1 - \sqrt{\frac{2}{\pi}}\ \frac{s}{\bar{x}}$$

where s is the standard deviation of the observations and the other terms are as defined previously. UCH and UCC are equal if the observations are Gaussianly distributed, as is the case in many practical sprinkler irrigation installations (Hart, 1961; Senigwonse, *et al.*, 1970). When an irrigation results in a Gaussian distribution of the applied water approximately 80 percent of the area irrigated will have an application equal to or greater than UCH $\bar{x}$.

c. USDA Pattern Efficiency, PEU

$$PEU = 1 - \frac{\sum_{i=1}^{n^*} X_i^*}{n^*\bar{x}}$$

where $\sum X_i^*$ is the sum of the 25 percent of the observations having the lowest values, n^* is the number of observations used in computing $\sum X_i^*$ and $\bar{x}$ is the average of all observations in the pattern. This parameter is very easy to calculate, and for this reason alone is useful. Again, if the water is Gaussianly distributed, there is a specific relationship between this parameter and the uniformity coefficients discussed above.

d. Other Parameters

Several other parameters have been discussed in the literature. The purpose of their introduction has been to define parameters which will more nearly describe the distribution of irrigation systems than do those already in existence. It can be shown that each parameter is

*Hawaiian Sugar Planters' Association

capable of describing only a portion of a distribution function and if it is necessary to completely describe a general distribution as many parameters are needed as there are values within the distribution. For most small portable and solid set sprinkler systems, the values are Gaussianly distributed and so the standard deviation and mean completely describe the water application. Both skewness and kurtosis have also been investigated but were not found of value in describing small sprinkler systems (Senigwongse, et al., 1970).

The scale of distribution measurements may be important. some investigators (Kenworthy, 1972) in dealing with trickle irrigation have indicated that only a fraction of an orchard floor, or a tree's root system, need be irrigated. This brings an entirely new concept into distribution measurements and their interpretation. Perhaps such systems should be analyzed by first looking at the distribution between trees and then looking at the distribution for a single tree with respect to the water and the root zone. Dr. Kemper's paper mentions the practice of irrigating every other furrow and placing nitrogen in the alternate furrows. Thus a measurement of water uniformity on the scale of every furrow would be quite low, while the uniformity of the entire field, measured on a different scale, could be high. There is also lateral movement of water through the soil and so a measurement of water as applied to the soil surface may not adequately describe the true distribution of water within the root zone (Hart, 1972).

On the other hand, the importance of uniformity can not be overemphasized. Chang, et al., (1963) have shown that the relationship between water and sugar cane yield in Hawaii can be approximated by the following:

$$Y/Y_p = -\ 0.61 + 2.70S - 1.09S^2;\ S \geq 0.73$$

where Y is the yield of a field, Y_p is the potential yield for that field if water is not limiting, and S is the ratio of the amount of effective water applied to the field (by irrigation and rainfall) to the total water evaporated from a standard U.S. Weather Bureau pan, both for one complete crop. The evaporated water is an estimate of the amount of water needed by the crop for maximum yield and is based on past records of field yields, climatic conditions, and soil factors. It is intuitively obvious that extremes in irrigation practices (such as a long draught period that might cause death to the plant) will make the equation invalid, even though the minimum seasonal value of S (0.73) is not reached. However, the equation does give some insight to the importance of distribution. If the expression for UCH is manipulated and combined with the above equation one obtains an equation of the following form:

$$Y_T = b_0 + b_1\bar{x} + b_2 s^2$$

where Y_T is the total yield on a field that has had a nonuniform distribution of water, $\bar{x}$ is the average application of water on the field and s^2 is the standard deviation of the applied water. The coefficients b_0, b_1, and b_2 are constants which take into consideration the potential yield of the field and other factors in the previous equations. Such a relationship gives some insight into the effect of water distribution on yield. However, it is important to realize that this analysis has dealt only with the spacial distribution of water and not the temporal ones discussed by Dr. Kemper.

4. Measurements for Evaluating Irrigation Systems

Paragraphs 2 and 3 of this section explained parameters used for evaluating irrigation systems. This paragraph is devoted to an explanation of the measurements necessary for determining those parameters.

a. Soil Water Content

Consider a sample of soil which has been removed from a field. Its mass is M_w . After drying in an oven (24 hours at 110°C) it has a new mass M_d . The sample, before drying, had a fractional water content P_m .

$$P_m = (M_w - M_d)/M_d \ .$$

The water content can also be discussed on the basis of the volume of water present. The sample volume (whether wet or dry) is V . (If the soil is high in clay the volume may change significantly with water content.) The water removed by drying is V_w . Therefore, the water content of the sample before drying, θ , is

$$\theta = V_w/V \ .$$

It is difficult to directly determine θ so it is usually computed from P_m and the bulk density, B_d , of the soil. B_d is defined as the ratio of the mass of the dry soil to the volume of the dry soil.

$$B_d = M_d/V$$

By manipulation of the above three equations it is found that

$$\theta = A_s P_m$$

in which A_s is the apparent specific gravity of the soil.

$$A_s = B_d/\rho \ ,$$

where ρ is the density of water.

Note that any consistent set of units can be used in the above computations. It is common, however, to use the cgs system.

Terminology in the literature is confusing for the above rather simple concepts. One usually speaks of "weighing" rather than "balancing", and so P_m is often called the water (or moisture) content by weight. In addition, many authors choose to multiply the right-hand sides of the first two equations by 100, expressing water contents as percentages. Such a procedure is both unnecessary and undesirable as it may cause difficulty in later calculations.

b. Water Content as a Surface Depth

A common method of designating the water needs of crops is to that they need x "inches (millimeters) of water per day". This expression is really an expression of volume of water per unit area of cropland, per unit time. Thus,

$$CU = [L]^3 [T]^{-1} [L]^{-2}$$

in which CU is the consumptive use (water required by the crop) and [L] and [T] denote units of length and time, respectively.

Similarly, the water content of the soil can be expressed in terms of surface depth. Consider a vertical prismatic column of soil of length L , cross-sectional area A and volumetric water content θ . Then

$$\forall_w = \theta A L$$

and D , the water content expressed as a surface depth (with units of $[L]^3 \ [L]^{-2}$) is

$$D = \forall_w / A$$

or

$$D = \theta L \ .$$

If the moisture content of the soil is not uniform in the vertical direction then the above equation can be extended as follows.

$$D = \sum_{i=1}^{n} \theta_i L_i$$

where i refers to one of the n stratum into which the column is divided.

c. <u>Water Removal by Plants</u>

If a soil is throughly irrigated, and plants are allowed to grow in it, they will reduce the amount of water in the soil (and thus θ). As this occurs the work required to remove each succeeding small increment of water from the soil increases. When this work is due only to surface tension effects accompanying air entry, and to the effects of soil particle repulsion, they are referred to as matric or capillary ones, ar conveniently measured as a pressure (the soil water tension, p). A sample of soil placed on a porous membrane, when subjected to pressure, will give up its water (Hagan et al., 1967), resulting in a desorption curve similar to one of those of Fig. IIID-1. Due to hysteresis, such a curve is dependent on the past history of wetting of the sample.

Plants utilize water stored in the filling of this reservoir is the function of the irrigation system. The upper limit of the reservoir is known as field capacity (FC). It is the amount of water remaining in the soil after gravity drainage has essentially ceased. We say "essentially" because gravity acts continuously on a soil matrix and continues to remove water over a long period of time. However, there is a rapid reduction in the rate of water removal after a few (1 to 4) days, and the water content at this point determines the field capacity. It is often considered to be the water content at 1/3 atmosphere of tension.

The lower limit of the water content of the soil reservoir is called the permanent wilting point (PWP) and is that water content of the soil at which plants will wilt, and fail to recover, unless additional water is added. The water content at PWP is commonly taken to be that of 15 atmospheres tension. The PWP and FC for two soils are given in Fig. IIID-2.

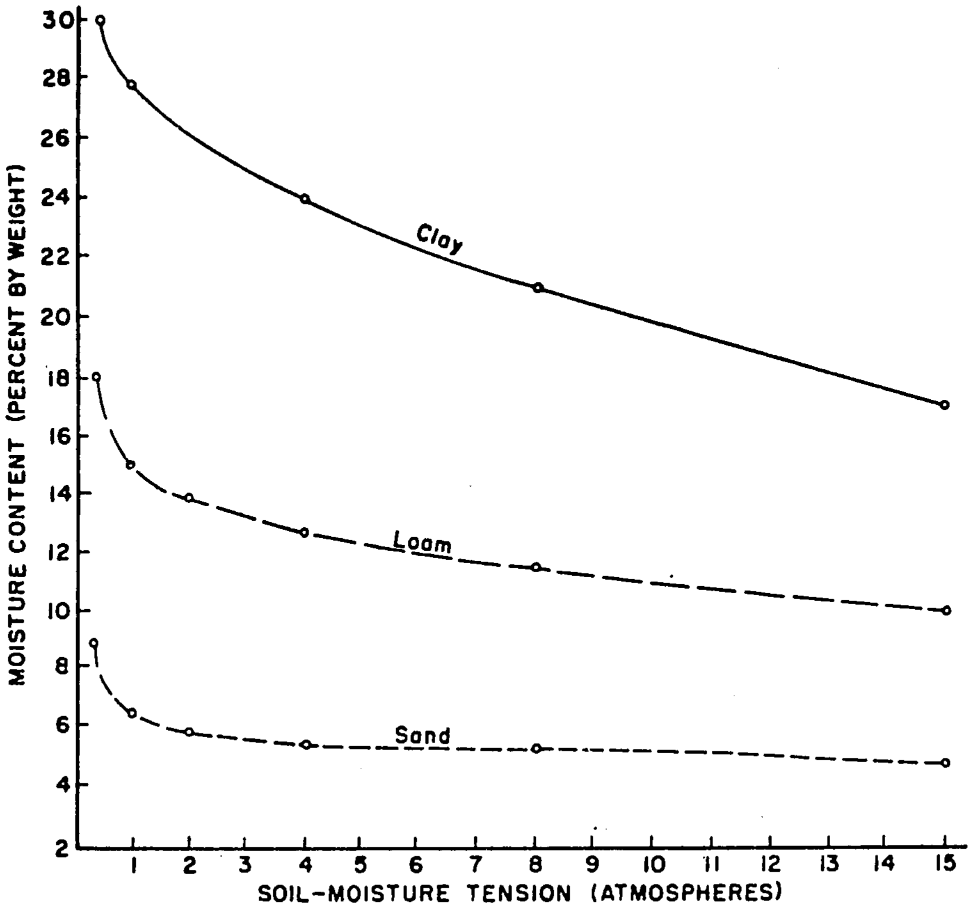

Fig. IIID-1. Moisture characteristic curves (After Thorne and Raney, 1956. As presented in USDA-SCS, 1965.)

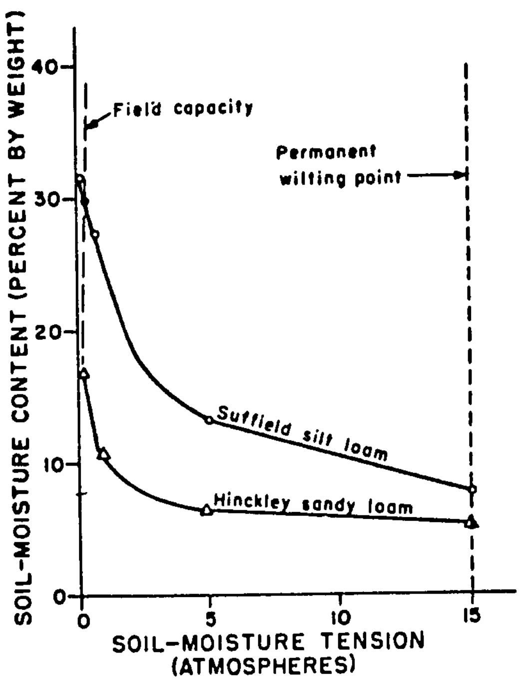

Fig. IIID-2. Relation between soil-moisture content and soil-moisture tension in a sandy loam and a silt loam. (After USDA, 1964.)

The total available moisture, TAM, is that between FC and PWP .

$$TAM = FC - PWP .$$

However, it is not common to withhold irrigation until PWP is reached, because this would require plants to expend a large amount of energy to remove water from the soil with a consequent uneconomical yield reduction. Rather, only a fraction -- 0.25 to 0.75 -- of the TAM is extracted between irrigations. The readily available water, RAM, is

$$RAM = f(FC - PWP)$$

where f is the fraction to be extracted between irrigations. RAM , TAM , FC and PWP are commonly expressed on a volume basis. The effect of f on the yield of some crops at Logan, Utah is summarized in Table IIID-1. It is clear that the choice of f will depend upon crop, economics and possibly other considerations (such as soil). A value of 0.5 is often used when additional information is not available.

The plant can remove water from that portion of the soil in which its roots grow. Thus, for a homogeneous soil the reservoir of readily available water, S_r (expressed as a surface depth) is

$$S_r = f(FC - PWP)L .$$

For a non-homogeneous soil of n horizons,

$$S_r = \sum_{i=1}^{n} f_i(FC_i - PWP_i)L_i$$

where the subscript i refers to the ith horizon.

The total available moisture in a soil varies roughly according to textural classification because of the relationship between texture and soil particle size, void size and clay content (Table IIID-2).

Table IIID-1. Effect of soil moisture level on the yield of some crops at Logan, Utah (1949 to 1955). (After Keller, 1962)

Moisture Extracted Before Irrigation $f = \frac{RAM}{TAM}$	Average Crop Yields				
	Potatoes (7 yrs.) Bu/ac.	Canning Peas (4 yrs.) Lbs/ac.	Sugar Beets (1 yr.) T/ac.	Barley (3 yrs.) Bu/ac	Alfalfa (1 yr.) T/ac.
0.05 to 0.10	504	3460	20.2	75	5.6
0.25 to 0.35	476	3300	20.2	70	5.8
0.50 to 0.65	390	2770	19.5	69	5.7
0.75 to 0.80	289	2010	18.2	75	5.9

Table IIID-2. Total available moisture of a Hinckley sand (Adapted from USDA SCS, 1964).

Horizon	Depth in.	Bulk Dens. cc/gm	PWP frac., P_w	FC frac., P_w	TAM frac.	TAM in. in horiz.
A_p	0-8	1.15	0.137	0.211	0.083	1.18
B_{21}	8-14	1.25	0.169	0.225	0.087	1.04
B_{22}	14-20	1.23	0.132	0.170	0.051	0.88
C	20-26	1.39	0.076	0.098	0.030	0.57
D	26-32	1.47	0.055	0.060	0.014	0.41
					Total	4.08

A final source of water directly obtained from the irrigation system must also be accounted for -- that made available during the irrigation and drainage periods. During the time water is on the field the crop is transpiring at its normal rate. In some surface systems this time may be as much as 5 percent of the total irrigation interval, and thus at no expense to the soil water reservoir there is additional water made available to the plant. Likewise, during the drainage period -- i.e. until FC is reached -- there is use of water by the plant. Again, this may extend over a considerable time period and up to 10 percent of the total water made available to the plant may be from such a source.

d. Infiltration

Infiltration of water into soil is a time-dependent phenomenon. A "well-behaved" soil is one that has a monotonically decreasing intake rate which is rapid when the soil is dry and slow when it is wet. Even such well-behaved soils will have different infiltration functions under different moisture conditions. Consider the case of a soil that has been dried out through the extraction of moisture by plants. Assume that the entire profile of four feet has been reduced to 20 percent of the total available moisture. If the soil surface is flooded, water will enter the soil according to a measureable intake rate function. On the other hand, if the soil had only been reduced to 50 percent of its total available moisture capacity the intake function would be different. In general, the rate at a given time after flooding would be less for the wetter soil. Consider the further complication of a soil which has not been uniformly depleted of its moisture. Such a condition often exists at the time of an irrigation. Thus, one cannot determine a general infiltration function which will always apply to a given field or soil. For engineering design purposes an attempt is made to determine the infiltration function of a soil while in its expected moisture condition just prior to an irrigation.

Most infiltration functions are developed by fitting empirical data to a functional form. Only three of these will be discussed here. The first is the Kostiakov-Lewis equation,

$$z = Kt^{a} ,$$

in which z is the amount of water that has been infiltrated into the soil (expressed as a surface depth) in time t and K and a are constants. The usual units for z are in the United States or cm in other countries, and the usual time is min. For these units, the corresponding units of K would be in. min^{-a} (cm min^{-a}); a is dimensionless. Differentiating both sides with respect to time yields

$$i = Kat^{a-1} ,$$

in which i is the infiltration rate. For the well-behaved soils discussed earlier

$$0 < a < 1 .$$

If $a = 0$, it implies that all infiltration takes place at the instant water is applied to the soil. This approximates the case of clay soils with large surface cracks. Water rushes into the cracks which then swell and prevent significant additional water entry. On the other hand, if a equals 1, it would imply that infiltration rate is constant with time. This might occur in a nearly-saturated soil. In actual practice a usually ranges between 0.2 and 0.6.

Values of K range between 0 and 2 (in.min^{-a}) for many soils in the Western U.S. It would be helpful in determining infiltration equations if it were possible to obtain a relationship between a and K. Unfortunately this has not yet been possible, although low values of K are associated with high values of a, and vice versa.

The Kostiakov-Lewis equation has been extensively used and reported in the literature. Several reasons account for this. In some of the analytical solutions to the advance of water in surface irrigation it has been found that the Kostiakov-Lewis equation gives simple solutions to the analytical techniques employed. It is also possible to find the constants K and a by plotting data on log-log paper.

The Soil Conservation Service (USDA-SCS, 1967) classifies soils according to intake families. The designations -- 0.1, 0.3, etc. -- are equal to the approximate basic intake rates of these soils. The basic intake rate is that nearly-constant rate which occurs after a long period of infiltration. Families are divided by lines which have the following functional form

$$z = Kt^{a} + c \ .$$

Intake families are presented in Fig. IIID-3.

Another infiltration function of interest is that presented by Philip (1957)

$$z = St^{1/2} + At \ .$$

In the above, S and A are constants and the other symbols are as indicated previously. Differentiation yields an infiltration rate equation.

$$i = \frac{1}{2} St^{-1/2} + A \ .$$

The importance of the Philip relationship, aside from the fact that it often matches empirical data, is that it was developed from physical principles. A diffusion-type equation has long been postulated to represent water movement through soils under certain conditions. That partial

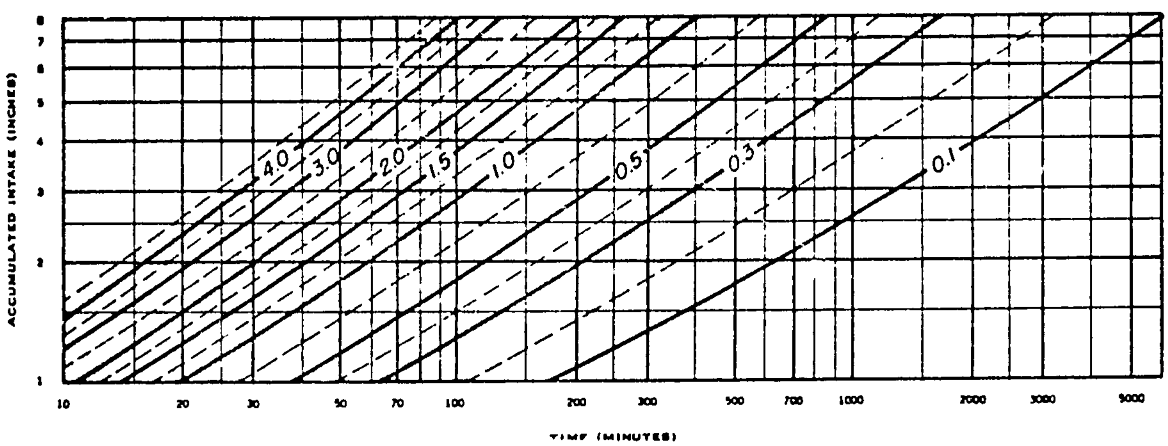

Fig. IIID-3. Intake families for surface-irrigation design. (After USDA-SCS, 1964.)

differential equation (which combines Darcy's law and mass continuity), when solved by certain approximate methods, and under rather restrictive boundary and initial conditions, yields the above infiltration equation. The solution method and the determination of the constants S and A are beyond the scope of this paper. However, S and A can also be found by empirical means (Nielsen, Biggar and Davidson, 1962; Davidson, Nielson, and Biggar, 1963). At small times, when capillary forces are large, the first term of the rate equation predominates. At large times, when gravitational forces are large, the second term predominates, although the theoretical development of the equation does not apply to very large times.

The previous discussion has considered infiltration as a single-valued function of intake opportunity time. This assumption is closely approximated by surface irrigation systems not utilizing furrows or corrugations. Once water is applied to the horizontal soil surface it remains there until the total amount has entered the soil. This entry is essentially in a vertical direction, through a wetted area which remains constant during the application time. With furrows, however, the complicated cross sectional geometry causes additional problems. As the water level rises and falls in the furrow the wetted perimeter increases and decreases. Thus, although the rather simple functional relationships discussed above do not in anyway describe this change in wetted area, they are used nevertheless for describing the infiltration into furrows.

f. Field Measurement of Soil Water and Infiltration

Techniques for measuring the items discussed above are not included here because of space limitations. Procedures for determining the moisture content of soils are discussed in Hagan et al., 1967 and Black et al., 1965. Criddle et al., (1956) give detailed instructions and examples for making field measurements of infiltration for border and furrow irrigation. Additional information is available in the literature (Bondourant, 1957; Shull, 1960; Tovey and Pair, 1966).

g. Determination of Ratio and Distribution Parameters Under Surface Irrigation

The advance, storage and recession phases of surface irrigation were discussed in Sec. IIIB. If the advance and recession down a border or furrow are plotted (Fig. IIID-4), and the infiltration function for the soil at the time of the irrigation is known, the distribution of water throughout the soil can be determined. The distance between the advance and recession curves is the time at which water remains on the soil. Thus, in the example of Fig. IIID-4, the water is on the soil approximately 220 minutes at the 300-foot point. This results in an infiltrated depth of about 3.9 inches. From such computed depths the entire depth vs. distance profile can be plotted, and the distribution parameters computed. In order to compute the ratio parameters it is necessary to know also the requirement. This value can be plotted as a horizontal (dashed) line on the depth-infiltrated graph (Fig. IIID-4(b)), dividing the infiltrated water into that which contributes to the requirement, and thus made available to the plant system, and that which is lost as deep seepage. The inflow rate multiplied by the time to shutoff gives the total water applied.

Field measurements to determine advance and recession curves for borders and furrows are discussed in detail, with examples, by Criddle *et al.*, (1956). Methods of testing sprinklers and analysing these data are discussed in ASAE (1972) and Criddle *et al.*, (1956).

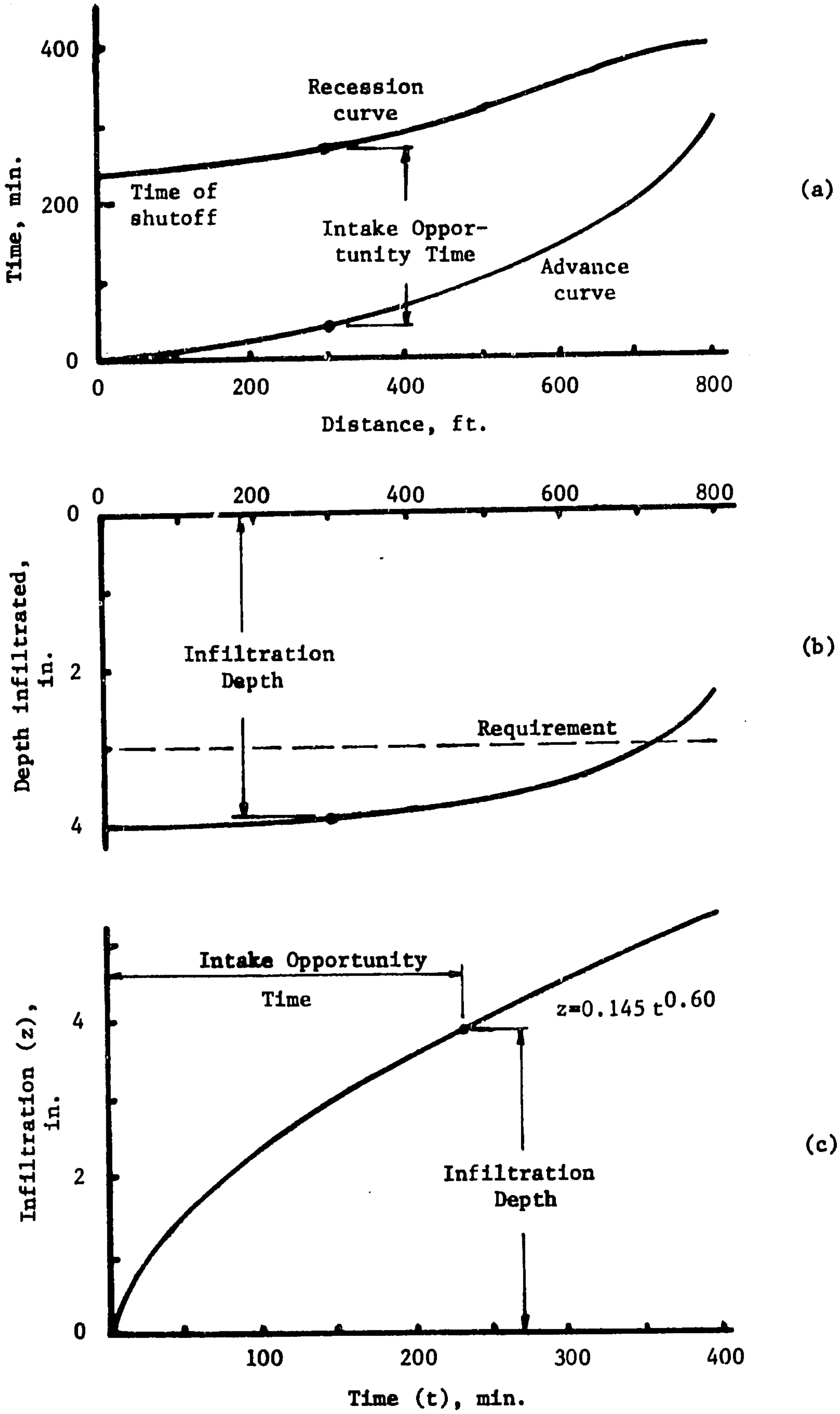

Fig. IIID-4. (a) Advance and recession of water in surface irrigation, (b) Depth infiltrated, (c) infiltration function.

E. IRRIGATION MANAGEMENT

Only a properly managed irrigation system will allow the maximum return to be realized on the resources invested in the irrigation system. Irrigation management in the broad sense includes the agronomic aspects outlined by Dr. Kemper and others at this seminar. It also includes consideration of possible salinity problems due to poor quality water and saline soils. The overall decisions of how to allocate a scarce water supply between several demands requires special techniques of optimization. The irrigation technician can make his greatest contribution to efficient use of water on the farm by assisting in the attainment of high values of the ratio and distribution parameters discussed in Sec. III D. An important facet of any such program is the efficient scheduling of irrigation water, both in time and amount.

1. Scheduling Irrigations Using Climatic Data

Jensen (1972a) estimates that in 1971, 50,000 hectares within the continental United States would be under irrigation scheduling. The cost of such scheduling services range from $4 to $10 per hectare, the lower cost for the larger acreages. The services being offered by private companies as well as some government agencies (such as the U.S. Bureau of Reclamation).

Consider the following equation:

$$D = \sum_{i=1}^{n} (E_t - R_e - I + W)_i ,$$

where D = the soil water depletion in n days and the subscript i refers to the ith day. The remaining terms in the equation are as defined previously and are daily volumes expressed as surface depths. E_t is determined by one of the methods described in the section on consumptive use. All computations are carried out by computers. Immediately after a thorough irrigation, D = 0 (the soil w ter depletion is zero). The date of the next irrigation is predicted by the following relationship:

$$N = \frac{D_o - D}{\overline{E}_t}$$

where N is the number of days until the next irrigation, D_o is the allowable soil water depletion at the time an irrigation must take place, and $\overline{E}_t$ is the current mean rate of E_t. The magnitude of D_o will vary with each crop and with its physiological growth stage. When water is limiting D_o may also depend upon that available for irrigation. Finally, it may depend upon the irrigation practice to be used.

The total water to be applied the next irrigation, W_i, is determined by dividing D_o by the obtainable water application ratio for the irrigation system. If additional water is needed for the leaching of salts this can be incorporated in W_i. Thus the irrigator can be told at any time what his expected date of irrigation will be and the amount that he should apply. The calculations are made each day and the irrigator is informed of the changed status twice a week when shallow-rooted crops are involved or when evapotranspiration rates are high. Weekly updating suffices for field crops.

The successful operation of an irrigation scheduling program depends upon the use of accurate data. Of particular concern is input from the farmer. He must tell the irrigation schedulers when he irrigates and how much water he puts on. This is the only way that the water balance equation can be utilized effectively and it is the crux of the entire system. It has been found necessary, especially as the program is introduced, to have technicians visit the farmer frequently to inform him what is going on and also to determine what the farmer is doing. At the same time the technician may take soil moisture samples to check the application of the irrigation scheduling computer program.

The basic input data for the system includes the regional constants for the evapotranspiration equation (height of wind measurements) and the crop and soil system data for each field (farm name, crop name, crop code number, field identification, planting date, estimated effective cover date, estimated harvest date, estimated water application ratio for the system being used, maximum amount of soil water depletion allowed for each crop).

Current meteorological data required in each region are the daily minimum and maximum air temperatures, daily solar radiation, daily dew point temperature, and total daily wind run for each day since the last computation day.

Current field data consists of the date of the last irrigation, the allowable soil water depletion at the present stage of growth, and rainfall and irrigation amount and date of occurrence.

The output from the computer program can be modified to fit any particular requirements. One form of the output is given in Fig. IIIE-1.

2. <u>Adaptation of Meteorological Schedulings to Humid and Sub-Humid Areas</u>

The method described in the previous paragraphs was developed primarily for scheduling in arid areas. However, it is applicable to scheduling in humid and sub-humid areas and developments of the method under such conditions are described by Heerman and Jensen (1970) and Jensen (1972a). One refinement that has been made in the program is to estimate more accurately the expected rate of evapotranspiration for the days until the next irrigation. This is done by assuming a normal distribution of potential evapotranspiration rates (E_{tp}). Thus the number of days until the next irrigation can be estimated more accurately provided the normal distribution concept is a valid one. This is shown to be so, under some conditions at least, and should be verified for any area in which it is to be used.

The second major program modification necessary for high rainfall areas is the inclusion of precipitation probabilities. Incomplete gamma functions have been used to estimate the

REGION:BURLEY-TWIN FALLS

FARM:JOHN DOE EXAMPLE DATE OF COMPUTATION:JULY 28, 1969

		SOIL MOISTURE DEPLETION			IRRIGATIONS:LAST,NEXT & AMOUNT					
CROP-FLD	COEF	TO DATE	OPTIMUM	RATE	LAST	RAIN=0		W RAIN		CM
W WHEAT	0.10	3.5	15	0.1	JUL 10	NONE	0	NONE	0	0
BEANS	1.01	1.8	5	.7	JUL 26	AUG	3	AUG	3	9
PEAS	0.10	11.0	11	.1	JUL 07	AUG	3	AUG	3	17
POTATOES	0.90	3.0	5	.6	JUL 24	AUG	1	AUG	1	7
SUG BEETS	0.90	3.7	8	.6	JUL 23	AUG	4	AUG	4	12
CORN	0.93	2.5	8	.6	JUL 25	AUG	5	AUG	5	12
ALFALFA	0.67*	12.3	18	.4	JUL 11	AUG	9	AUG	9	27
PASTURE	0.87	0.0	8	.6	JUL 28	AUG	10	AUG	10	12

PROBABLY RAIN NEXT TWO WEEKS = 0.1 CM

FORECAST:PARTLY CLOUDY & WARM

*The low coefficient for alfalfa reflects the effects of a recent cutting.

Fig. IIIE-1. Computer output sheet for irrigation scheduling. (After Jensen, 1972.)

probability of receiving at least a given amount of rainfall in a one-, two-, or three-week period at many stations in Colorado. Rainfall probabilities are utilized as follows. First, the date of the next irrigation is determined assuming no rainfall. Next, for a given probability of rainfall (say 50%) the amount of rain that is expected during the previously computed period (before the next irrigation) is determined. This alters the calculated amount of water in the soil, so a new irrigation date which is further in the future than the originally computed one is determined. From this new irrigation date a new rainfall amount can be determined and the procedure is continued until successive iterations make no significant alteration in the predicted irrigation date.

The final alteration of the program might include consideration of irrigation systems which can efficiently apply water at frequent intervals and in small amounts. Such systems, when used in humid areas, could be scheduled to always leave an amount of water storage capacity in the soil such that rainfall occurrences could be stored in the soil reservoir and not go into runoff or deep seepage. All of the methods so far discussed have either been incorporated in a computer program or are in the process of being incorporated.

3. Other Scheduling Methods

There are technical irrigation services offered by private organizations which will predict for a farmer when his next irrigation should take place. Their calculations use micrometeorological approaches or direct measurements of the soil, either gravimetric sampling or some device to indirectly sense the moisture condition of the soil. The most popular among these are tensiometers and resistance blocks. Their readings are correlated with the amount of moisture tension. From previously determined consumptive use of knowledge the date of the next irrigation can be predicted. Such methods require large amounts of labor and frequent sampling within the field, as opposed to the micro-meteorological methods which require relatively little labor and infrequent field sampling.

Another method which is used in southern Idaho by the Bureau of Reclamation and an irrigation district consists of generalized forecasts of irrigation needs for common crops in the major soils in the area. These are based on local or regional experimental data and are frequently used in areas needing only infrequent supplemental irrigations. Although the approach is economical it generally requires farm managers to interpret the forecast and monitor their own fields to verify their predictions.

IV DATA COLLECTION

A successfully designed irrigation system, whether for a farm or an entire continent, requires an input of data. Information on current agricultural practices, both irrigated and unirrigated, will help to direct future development. An inventory of the resources available for development is also a necessary input. Some aspects of these subjects are discussed in the following paragraphs.

A. CURRENTLY CROPPED LAND

The categorization and tabulation scheme outlined below relies heavily on the Upper Colorado Region Comprehensive Framework Study (UCRCFS, 1971).

1. Currently Irrigated Land

Irrigated land may be conveniently categorized according to the adequacy of its water supply (Table IV A-1). The first category would include all land which receives an adequate water supply every year. The second category would be that which receives only a partial supply in some years, but receives at least some water every year. The third category would be land that is idle in an average year because there would be no water available for it. Cropped areas may also be broken into hydrologic subregions (Green River, Upper Main Stem, and San Juan-Colorado) and into political subregions (the states of Wyoming, Utah, Colorado, Arizona and New Mexico) Fig. IV A-1. In some cases the source of the irrigation water for each of the political or hydrologic subregions might be tabulated. In the case of the UCRCFS 99% of the area was irrigated with surface waters and the remaining from ground water. The table shows that development of additional water supplies would contribute to increased agricultural production, as only 58% of the total irrigated land has received an adequate water supply in all years.

Existing cropping patterns indicate the base upon which the current agricultural economy is based (Table IV A-2). In

Table IVA-1. Irrigated areas in the Upper Colorado Region in the year 1965. (From UCRCFS, 1971.)

(Unit--1,000 acres)

Hydrologic Subregion and State	Irrigated cropland: Full supply land	Irrigated cropland: Short supply land	Irrigated cropland: Total	Idle land1/	Total
Green River					
Colorado	69.2	44.9	114.1	3.3	117.4
Utah	162.2	101.9	264.1	19.7	283.8
Wyoming	130.5	151.5	282.0	29.1	311.1
Subtotal	361.9	298.3	660.2	52.1	712.3
Upper Main Stem					
Colorado	418.4	157.2	575.6	34.3	609.9
Utah	3.5	4.8	8.3	.2	8.5
Subtotal	421.9	162.0	583.9	34.5	618.4
San Juan-Colorado					
Colorado	107.7	60.6	168.3	18.4	186.7
Utah	16.6	18.6	35.2	5.1	40.3
New Mexico	38.5	6.3	44.8	8.1	52.9
Arizona	1.2	3.5	4.7	6.2	10.9
Subtotal	164.0	89.0	253.0	37.8	290.8
Region					
Wyoming	130.5	151.5	282.0	29.1	311.1
Utah	182.3	125.3	307.6	25.0	332.6
Colorado	595.3	262.7	858.0	56.0	914.0
Arizona	1.2	3.5	4.7	6.2	10.9
New Mexico	38.5	6.3	44.8	8.1	52.9
Total	947.8	549.3	1,497.1	124.4	1,621.5

1/ Idle land is tabulated separately as it is land which is not irrigated in an average year.

As indicated in Table 1, 712,300 acres or 44 percent of the total irrigated land is in the Green River Subregion, of which 80 percent is in

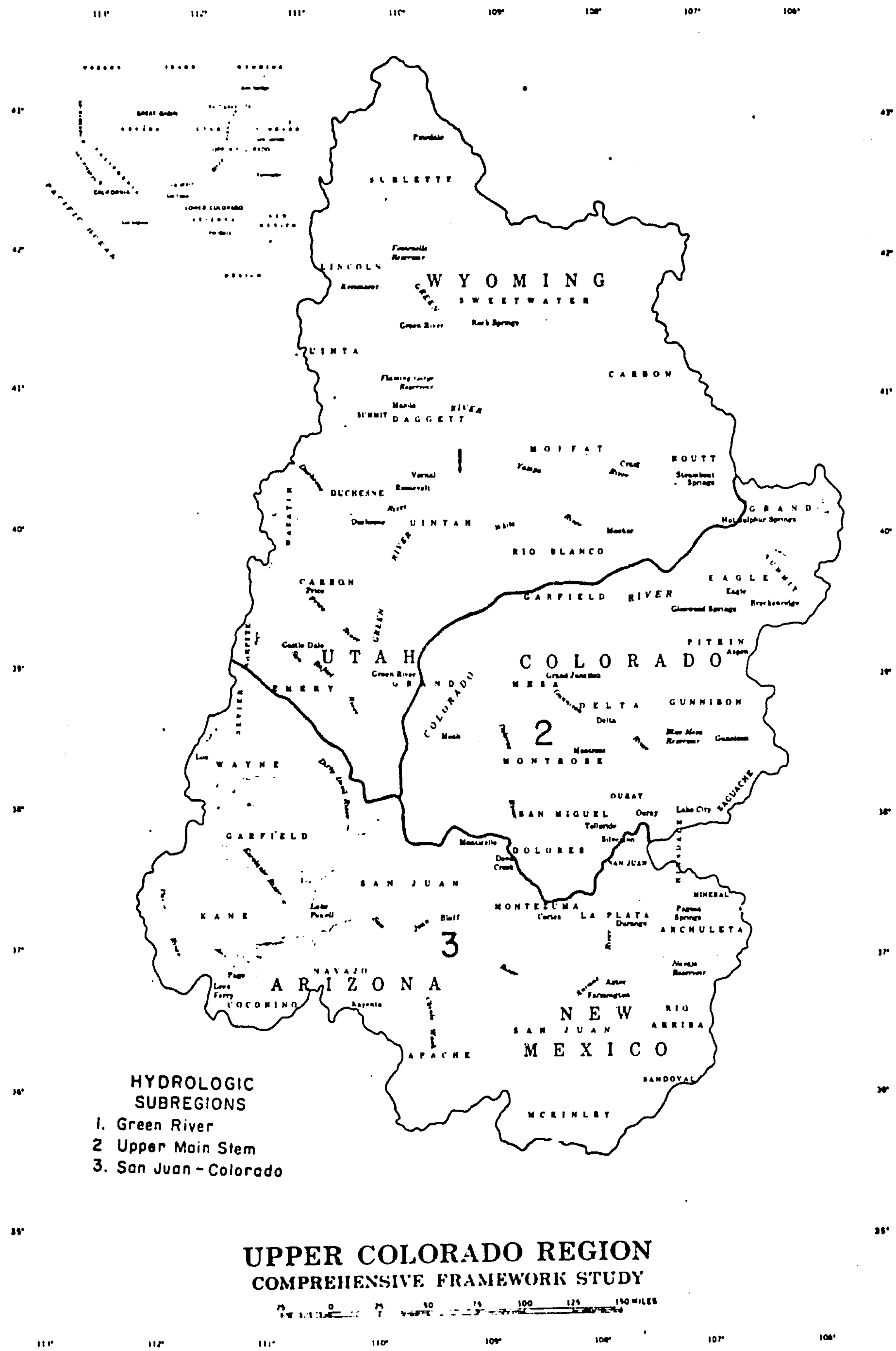

Fig. IVA-1. Map of Upper Colorado Region. (Note: Length of Nigeria at 10° N. Latitude is approximately 670 miles.)

the Upper Colorado Region over 80% of the irrigated region is in alfalfa, grass hay and pasture production and complements livestock grazing lands. Much of the small grain production is also used to support cattle operations within the basin. Less than 10% of the total area is in the high cash crops of fruits and vegetables. Those states growing such crops--Arizona, Colorado, New Mexico and Utah--have a long enough growing season to make such crops profitable.

Accumulation of the above data is a problem. In the United States much of the data is tabulated in the U.S. census of Agriculture, which is compiled at irregular intervals. However, in other countries such records may not be available and actual determinations may be difficult and expensive to obtain. Some data might be obtained from tax records of political subdivisions, or from visits to individual communities and villages. Remote sensing techniques, such as photographs from high flying aircraft, may also prove useful (Appendix B).

Irrigated lands should be located on a large-scale map (Fig. IVA-2) along with ancilliary features such as villages and the transportation and communications network. As can be seen from the Upper Colorado Region study, agricultural development often parallels water courses.

Table IVA-2. Crop distribution on irrigated lands of the Upper Colorado Region in the year 1965. (From UCRCFS, 1971.)

(Unit--1,000 acres)

Principal crops	Arizona	Colorado	New Mexico	Utah	Wyoming	Total
Grass hay and pasture	0.4	571.4	15.2	186.3	245.5	1,018.8
Alfalfa	.4	167.7	17.3	83.4	29.5	298.3
Small grain		47.6	2.1	25.4	7.0	82.1
Other crops	3.9	71.3	10.2	12.5		97.9
Total cropland	4.7	858.0	44.8	307.6	282.0	1,497.1
Idle	6.2	56.0	8.1	25.0	29.1	124.4
Total irrigated	10.9	914.0	52.9	332.6	311.1	1,621.5

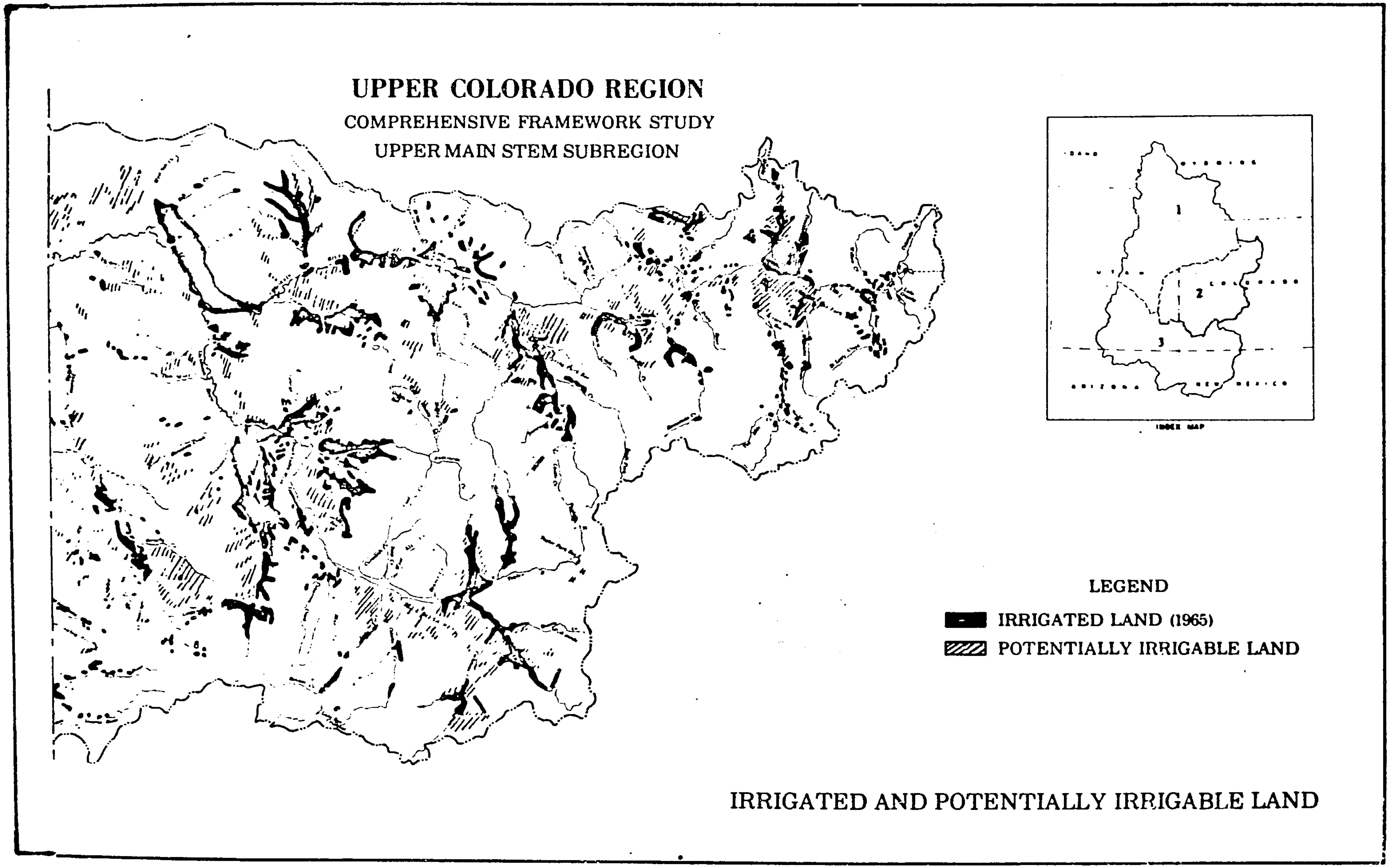

Fig. IVA-2. Potential and currently irrigated areas.

Areas currently dry land farmed should be indicated on the same map. When additional irrigation water is developed these may be irrigable as well. However, some problems encountered in dry land agriculture can be intensified when such lands are put under irrigation. Highly erosive soils, if not properly managed, can be extensively damaged. Some diseases (fungus or root rot) may increase with irrigation.

The final source of information from existing systems we wish to maintain is the cataloging of problems reported by operators, supervisors, designers and planners. The International Commission on Irrigation and Drainage has reviewed the current status of irrigation in many countries of the world (ICID, 1968); data on nineteen states and countries of Africa is summarized here (Table IVA-3). The problems they reported were grouped into six general categories, some of which are outside the basic realm of engineering, but are included here for completeness

Personnel
Lack of basic data
Capital availability
Resources
Normatives
Existing facilities

Personnel problems were centered almost exclusively around the training of people to do specific jobs. Some countries indicated a lack of personnel trained in the planning phases of irrigation and drainage projects. Others indicated a lack of technical personnel, those who could be utilized in the field or in the office. Eight countries indicated that farmers were inadequately trained in irrigation or in the cultivation of the new crops that would be grown under irrigation. It is clear that the reporters felt that people within a country, when properly prepared, could adequately perform the needed work.

Countries indicating a need of additional basic data were referring to a lack of one or more of the following types: hydrologic, climatic, soil moisture, soil infiltration, agronomic, ground water, or topographic. Also included are

TABLE IV A-3 Problems existing in Irrigation & Drainage on the African Continent.*

COUNTRY	Problem** 1	2	3	4	5	6
Botswana	X	X	X		X	
Ethiopia	X	X	X		X	
Ghana	X		X		X	
Kenya	X				X	
Malawi	X	X	X	X	X	
Morocco	X	X	X		X	
Nigeria - N.E.	X	X	X		X	
Nigeria - N.W.	X	X	X		X	
Rhodesia				X	X	
Senegal	X	X			X	
Sierra Leone	X	X		X		
South Africa (Union of)				X		X
Sudan						X
Swaziland			X	X		
Tanzania		X	X			
Tunisia	X			X		X
Uganda	X				X	
United Arab Rep.				X	X	X
Zambia	X	X		X		
Number of countries with problem	13	10	9	8	12	4

* Developed from data in ICID, 1968.

**1) Personnel; 2) Lack of basic data; 3) Capital availability; 4) Resources; 5) Normatives; 6) Existing facilities. See text for further discussion.

countries which indicated a lack of research facilities which would allow them to obtain such data. Most countries indicating the need for data were those which have not already developed extensive irrigation schemes.

Capital limitations include not only the mere accessibility of funds for a given project, but also other peripheral considerations. As an example, communication and transportation facilities were cited as a necessary adjunct to the development of irrigation. The lack of construction equipment was another specific cited. Health hazards--malaria and shistosomiasis--were included in this category because adequate capital for research and action should make such diseases controllable. Finally the lack of demand within the country for additional food products was cited. It is probable, however, that some countries, if properly located along transportation routes, could sell as an export their increased food production. Others could develop markets from within if increased buying power could be developed.

A lack of resources necessary for the development of irrigation was listed by some contributors. However, all of the countries mentioned are potentially irrigable, having adequate arable land and water supplies for some agricultural industry. Thus, the lack of resources or the poor quality of some resources are primarily circumventable or correctable items. They included rainfall distribution, surface storage sites, perennial stream locations, salt-affected soils, poor drainage conditions, and highly erosive soils.

Normatives are those items related to law and certain social problems. Specific examples cited within the publication are the lack of canal and drainage legislation, current land tenure policies, and farms of sizes too small to be efficiently irrigated. The last item was the most important, 13 contributors indicating that average farm sizes were less than ten acres (4 hectares).

Existing facilities refer to conditions in those countries that already have rather extensive experience in irrigation and drainage and have encountered difficulties with their current systems. These difficulties, of course, would be found anywhere in the world, but several were specifically cited. Canals lose water through seepage or evaporation and are subject to silting and weeds. Reservoirs, especially in some of the hotter and drier climates, are great sources of loss due to evaporation. Improvement in on-farm water management is a rich source of increased efficiencies of water use.

B. RESOURCE INVENTORY

Planning for irrigation systems requires a detailed inventory of all available resources, as indicated in the previous section. From the engineering standpoint, land and water are the main factors. However, the development must be integrated with economic, institutional, legal and other constraints. The proximity of communication and transportation facilities is expecially important when the more sophisticated methods of irrigation are considered, for they sometimes require complex equipment requiring maintenance by trained personnel. These advanced systems, because of their high initial cost, are often used on lands growing products of high economic value, and which must be shipped to a ready market.

1. Hydrologic Investigations

A recent publication by AID (1972) outlines in detail techniques for assessing hydrological potentials in developing nations. Items covered include streamflow, erosion and sediment transport, water movement in unsaturated soils, and ground water. This article is reproduced in its entirety as Appendix B of this paper, and will not be discussed further here.

Some hydrologic data is essential for analyzing the available water resources of an area. When one considers the planning of water resource projects or irrigation schemes one of the greatest handicaps seems to be the lack of good long-term hydrologic data. This implies that the collection of sufficient hydrologic records must precede the design of projects. Otherwise, the design could be greatly in error, resulting in failure of structures because of unforeseen events or oversizing, which unwisely uses limited economic resources.

When hydrologic data is collected one of the biggest problems seems to be the storing of this data in a place and form that it can be accessible to the maximum number of users at the least cost. This indicates that early thought should be given to the management of data storage and retrieval systems.

Following the design and construction phases of a project, the need still exists for the collection of hydrologic records. The form might possibly be different from that used in the planning phase, or include new items for use in administering the project and developing optimal operational policies. Often this latter data need requires information on the current status of the system--e.g., reservoir stages and canal flows. To provide this information it is necessary to capture the data and make it available to the water administrator in a useable form. As water use is increased, the competition between users will require more administrative decisions, with a resultant greater need for the proper data.

To illustrate some of these hydrologic data problems we will refer to current work now underway in the State of Colorado, USA*. Colorado is located in a semiarid region and has experienced a great increase in the demand for water for irrigation, domestic, municipal and recreational uses. The need exists to evaluate new projects designed to meet increased water demands and to administer the current uses so that minimum water waste will occur and multiple uses will be coordinated. Colorado and other Federal agencies have been collecting hydrologic data for nearly 100 years; however, it

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*Information on the Colorado State Water Data Bank is presented through the courtesy of Professor Robert Longenbaugh, Colorado State University.

was only in July 1972 that a decision was made to develop a State Water Data Bank as a centralized location for storing the many records on over 10,000 canals and 20,000 wells. This State Water Data Bank is to be prepared with the aid of a large computer and should provide data retrieval capability that will service both the planning and administrative staffs. A schematic of the different subsets in the data bank is presented in Figure IV B-1. The data stored in each subset includes the following:

a. Dams
Identification number, name, height, length, crest width, spillway width, spillway capacity, freeboard, type of dam, design engineer, outlet type, outlet capacity, stream managed, water rights.

b. Reservoirs
Identification number, owner (name and address), use, capacity, drainage area, outlet type and capacity, reservoir area, file number of adjudication, date approved, elevation, stream name, amount stored and date (may be several entries).

c. Ditches
Identification number, ditch dimensions, water source, water rights, acreage irrigated, diversion records, wells under ditch.

d. Water quality
Station number, water source, elevation, physical data, chemical data, biological data, bacteriology data.

e. Climatic data
Precipitation amount, maximum and minimum temperature, snowmelt, snowdepth, wind movement, evaporation, estimated precipitation, location. (Additionally, relative humidity or wet-bulb temperature would be desirable, but such is generally not available from U.S. Weather Bureau records.)

f. Water rights
Owner (name and address), stream name, water source, serial number, amount of appropriation, appropriation

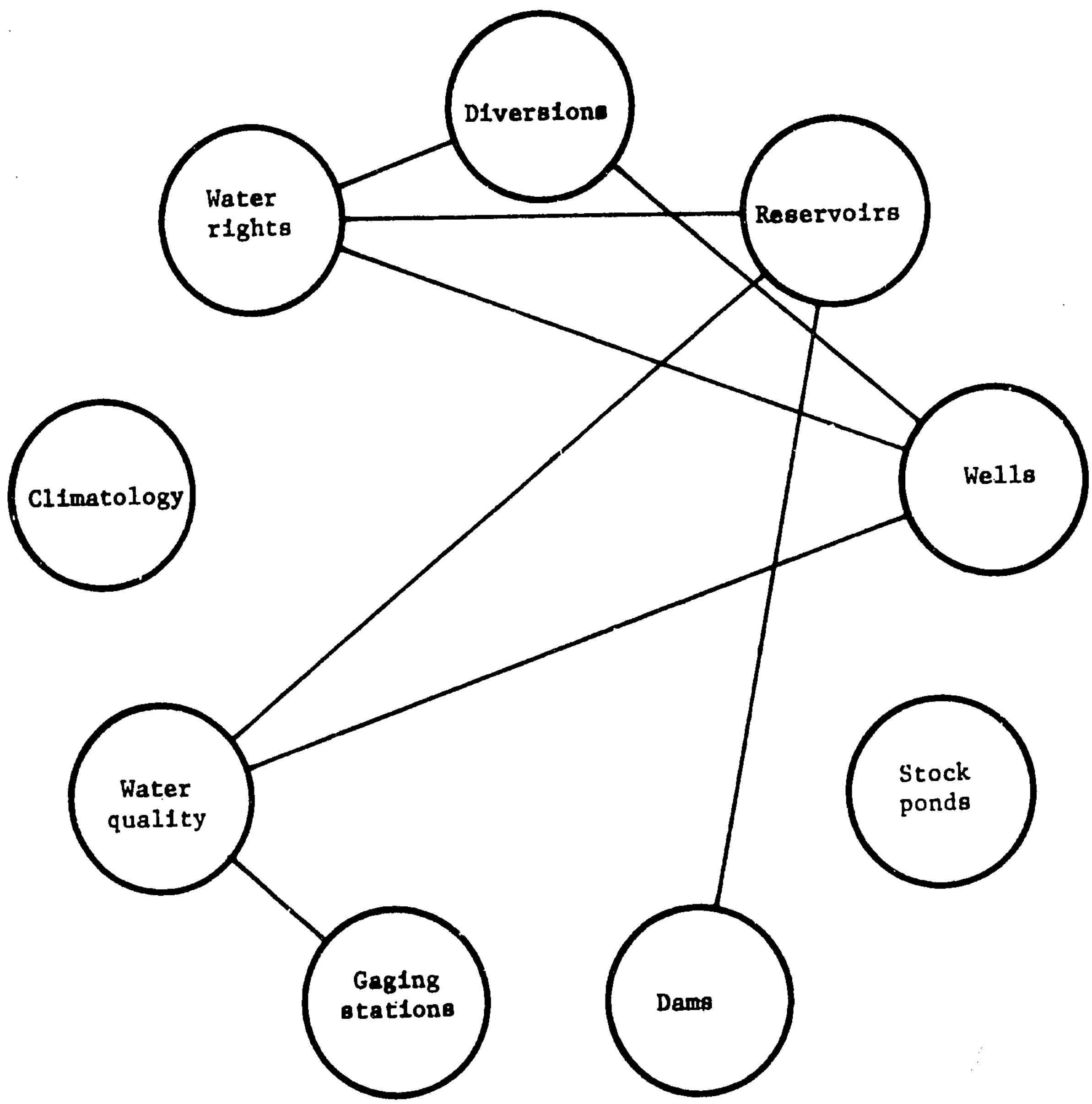

Fig. IVB-1. Data segments in the Colorado State Water Data Bank. Connecting lines represent need for cross referencing between respective data sheets.

date, adjudication date, previous adjudication date, working date, civil action number, use of water, structure.

g. Stock ponds
Identification number, owner (name and address), drainage area, storage capacity, surface area, height of dam, outlet (type and size), date approved.

h. Wells
Permit number, owner (name and address), use, yield, depth, management, district, location (coordinates), drainage basin, application date, water level at drilling date, M.P. elevation, area irrigated (size), annual appropriation, gravel pack data (size, internal), power source, prime mover size, casing data, yearly pumping rates, water level measurements, well test data.

The bank will allow determination of water transfers such as often occur in complicated and efficient water allocation schemes. Competing demands of agriculture, industry, municipalities and recreation can be considered when such data is rapidly accessible.

The State Water Data Bank for Colorado will require the use of a large digital computing facility for storage and access. Although not too many developing nations have nearly the complex problem (as yet) as does Colorado, nevertheless the concept should be employed at an early stage of development. This will save considerable expense and time when the need of rapid access arises in the future, and will serve planners efficiently in the present.

A key to successful data accumulation is a system which requires minimum hand processing of data. Perhaps the most efficient way of gathering data from field installations is to use digital tape recorders. However, this is usually impractical because of the expense of initial installations and the problems of maintenance. When measurement intervals are large (frequencies of days or fractions of a day, to weeks) hand recording may be entirely adequate, provided data is accumulated and accurately recorded and transcribed. New optical scanning techniques have made such programs feasible. They employ printed forms, designed for a specific job (Fig. IVB-2). The user marks readings directly on a sheet which is then sent to the computer center for processing. (A carbon copy is produced for retention in the local office.) At the processing center the sheets are scanned optically by machine and the data is stored (on magnetic tape, discs, etc.), ready for immediate access.

The use of such a system, even by those organizations not planning data processing for the immediate future, will provide two prime benefits. First, it will require the system of data taking to be according to a well thought-out plan from the outset. This will assist in assuring that all pertinent data are accumulated, and in a manner which is uniform and orderly. Second, it will put the data in such a form that it can easily be transferred in the future to an automated data retrieval system, with a minimum of additional data handling (and its associated errors).

2. Soils and Land Data

The Upper Colorado Region study used two different systems for classifying land and soil (Tables IVB-1 and IVB-2). The main differences between the systems is that the soil classification ignores on-farm land development of brush, tree, and stone removal, land leveling, and drainage, and the economic factors affecting feasibility of irrigation development (size and shape of tracts or the distribution pattern of lands). The result of land classification in the Upper Colorado Region is given in Table IVB-3. Land and soil classifications should be performed only by well-trained personnel.

The above gross classification schemes are adequate for planning irrigation systems on a large scale, but further refinement is needed when designing individual farm units. Each field or section of a field must be considered individually. Nutrient status must be determined so that proper fertilization,

Fig. IVB-2.

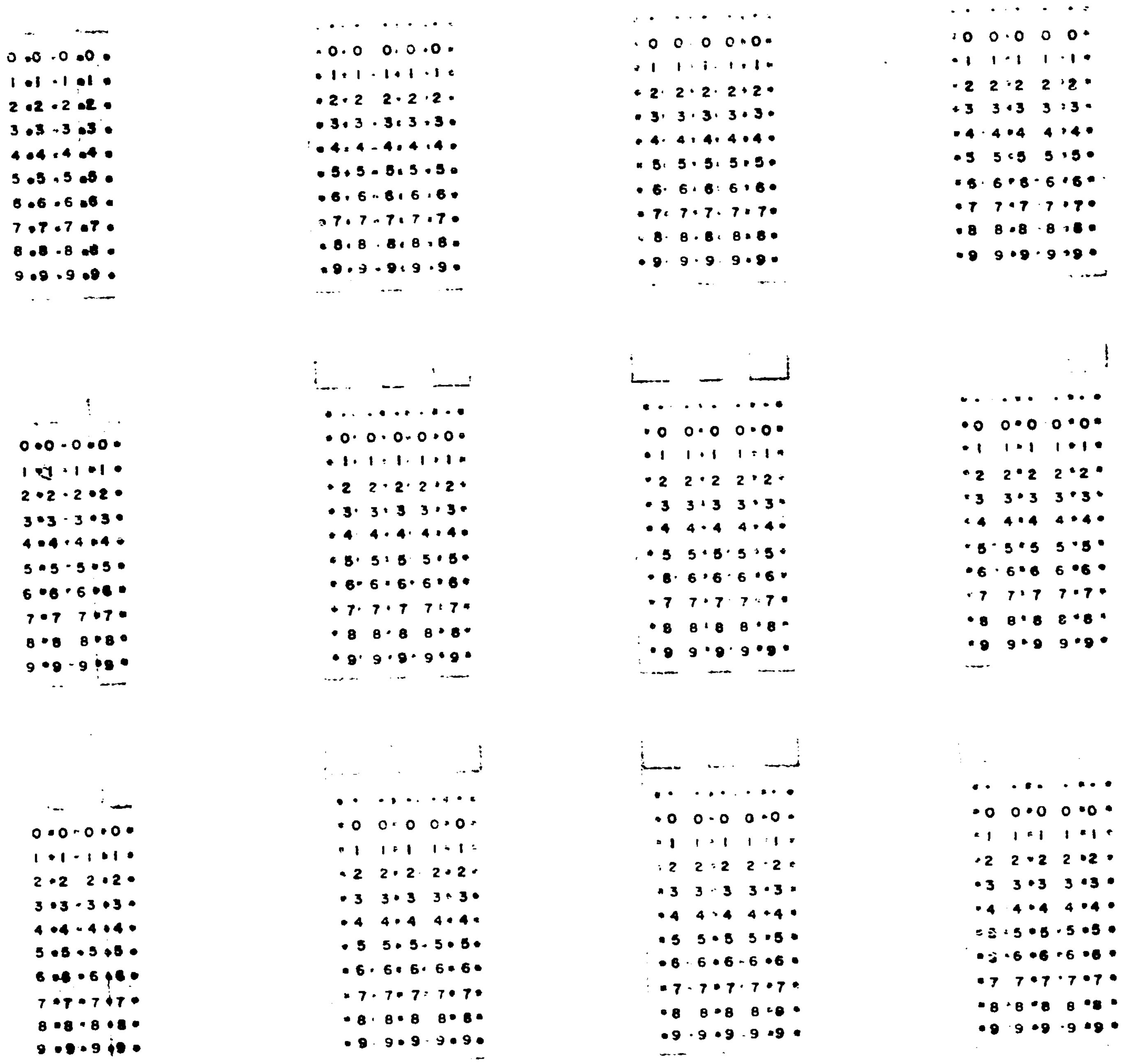

Fig. IVB-2.

Table IVB-1. Land Classification Specifications for Irrigation Land Classes[1/].

Land characteristics	Irrigation land classes				
	Class 1	Class 2	Class 3	Class 4	Class 6
Soils					
Texture (surface 12 inches)2/	Loamy very fine sand to clay loam	Loamy sand to clay	Medium sand to clay	Medium sand to clay	All other lands not meeting criteria for irrigability
Available water-holding capacity to 48 inches3/	6.0"	4.5"	3.0"	2.5"	
Effective depth (inches)4/	40	30	20	10	
Salinity ($EC_e \times 10^3$ at equilibrium with irrigation water)	4	8	12	16	
Sodic conditions5/					
Percent area affected	5	15	25	35	
Severity of problem6/	Slight	Moderate	Moderate	Moderate	
Permeability (in place--inches/hour)	0.2-5.0	0.05-5.0	0.05-10.0	No limit	
Permissible coarse fragments (percent by volume)					
Gravel	15	35	55	70	
Cobbles	5	10	7/15	7/35	
Rock outcrops (distance apart in feet)	200	100	50	30	
Soil erosion8/					
Topography (or land development items)9/					
Stone for removal (cubic yards per acre)	10	25	50	70	
Slope (percent)					
Moderately to severely erodible	2	5	10	20	
Slightly erodible	4	10	20	25	
Surface leveling or tree removal (amount of cover)	Light	Medium	Medium heavy	Medium heavy	
Irrigation method10/					
Drainage					
Soil wetness					
Depth to water table during growing season with or without drainage					
Loam or finer	60"	40"	20"	10"	
Sandy	50"	30"	20"	10"	
Surface drainage	Good	Good	Restricted	Good	
Depth to drainage barrier in feet	7	6	5	1.5	
Air drainage11/	No problem	Minor	Restricted	Restricted	

1/ Specifications are representative of conditions after land is developed for irrigation. Each individual factor represents a minimum requirement, and unless all other factors are near optimum two or more interacting deficiencies may result in land being placed in lower class or designated class 6--nonarable.

2/ Finer textures may be required than those indicated for each class in areas subject to critical hot spells or wind; coarser textures permissible for specific crop and climatic conditions.

3/ In areas of very warm growing season 3 inches may be required for class 4 and in cold areas as little as 5 inches may be permitted for class 1.

4/ Depth of 60 inches or more required for class 1 where deep-rooted crops are important in crop pattern.

5/ More extensive and severe sodic problems may be tolerated in areas of wide crop adaptability.

6/ Severity of problem: Slight--ESP less than 15 percent or less than 25 percent if dominated by nonswelling clays, moderate--ESP less than 20 percent or less than 30 percent if clay minerals favorable, severe--ESP less than 30 percent; with certain soil minerals may range above 50 percent as measured by usual techniques.

7/ May range above 50 percent in subsoil for certain crops if surface soil favorable.

8/ Soil erosion--for all classes: severely eroded soils will be downgraded one class. Less severely eroded soils may be downgraded one class, depending on other conditions.

9/ Special crop and management practices may justify exceeding the limits for stone removal or slope in class 4; irregularity of slope may necessitate downgrading of class unless deficiency is compensated for by possibility of sprinkler irrigation.

10/ Irrigation method--lands unsuited to gravity irrigation where land grading would permanently reduce soil fertility below irrigable limits or exceed permissible costs, or field pattern too complex, may be considered for sprinkler irrigation. Land must meet other requirements for irrigability. Designated by "S," as for example, class 3S.

11/ Air drainage a consideration mainly in areas adapted to fruit or to early or late vegetables.

Table IVB-2. Criteria for Irrigation Soil Classes, Upper Colorado Region.

Soil Property	Irrigation Soil Class A	B	C	D
Depth in inches to:				
Gravel, cobbles and stones	40	30	20	10
Fractured bedrock or hardpan	40	30	20	10
Texture, surface 12 inches	loamy very fine sand to clay loam	loamy sand to clay	medium sand to clay	medium sand to clay
Available water holding capacity to 48 inches (inches)	6	4.5	3	2.5
Soil permeability - inches per hour	0.2-5.0	0.05-5.0	0.05-10.0	no limit
Coarse fragments (percent by volume):				
Gravel	15	35	55	70
Cobbles and stones	5	10	15	35
Rock outcrops (distance apart in feet)	200	100	50	30
Salinity (Electrical Conductivity X 10^3)	4	8	12	16
Alkali (percent of area affected)	5	15	25	35
Severity of problem	slight	moderate	moderate	moderate
Slope:				
Moderately to severely erodible soils	2 percent	5 percent	10 percent	20 percent
Slightly erodible soils	4 percent	10 percent	20 percent	25 percent
Depth to water table during growing season: (inches)				
Clay soils	60	40	20	10
Sandy or stratified soils	50	30	20	10
Frequency of overflow in years	None	rate 1 in 10	occasional 2 in 10	frequent 5 in 10
Soil erosion status	Severely eroded soil phases will be reduced one class: eroded soil phases may be reduced one class depending on soil profile characteristics.			

Note: Range of soil properties established so that the most limiting property becomes the determinant in classification. Nonirrigation Soil Class E is outside the limits established for A, B, C, and D.

Table IVB-3. Summary of Potentially Irrigable Land in the Upper Colorado Region in the Year 1965. (From UCRCFS, 1971).

(Unit--1,000 acres)

Hydrologic Subregion and State	Potentially irrigable land					Nonirrigable
	Class 1	Class 2	Class 3	Class 4	Total	Class 6
Green River						
Wyoming	70.1	282.8	176.8	175.9	705.6	12,348.1
Utah	50.8	237.7	158.4	82.9	529.8	10,070.2
Colorado	46.3	392.4	260.8	177.2	876.7	5,758.5
Subtotal	167.2	912.9	596.0	436.0	2,112.1	28,176.8
Upper Main Stem						
Colorado	47.0	400.7	320.8	174.2	942.7	12,575.3
Utah	11.4	102.2	56.7	56.7	227.0	2,337.1
Subtotal	58.4	502.9	377.5	230.9	1,169.7	14,912.4
San Juan-Colorado						
Arizona	40.6	221.4	251.0	148.6	661.6	3,749.0
Colorado	12.3	115.7	75.3	42.1	245.4	3,269.1
New Mexico	70.3	773.8	1,034.8	589.7	2,468.6	3,696.2
Utah	26.4	174.2	140.5	60.1	401.2	9,749.7
Subtotal	149.6	1,285.1	1,501.6	840.5	3,776.8	20,464.0
Region by States						
Wyoming	70.1	282.8	176.8	175.9	705.6	12,348.1
Utah	88.6	514.1	355.6	199.7	1,158.0	22,157.0
Colorado	105.6	908.8	656.9	393.5	2,064.8	21,602.9
Arizona	40.6	221.4	251.0	148.6	661.6	3,749.0
New Mexico	70.3	773.8	1,034.8	589.7	2,468.6	3,696.2
Total	375.2	2,700.9	2,475.1	1,507.4	7,058.6	63,553.2

an integral part of proper water management, can be planned and executed.

Although general slopes are included in land classification studies, only with topographic maps can realistic planning be done. Large-scale maps assist in the location of reservoir sites, canals, etc. Small-scale ones are necessary in the design of irrigation systems. A topographic map of scale 1" = 100 ft is usually adequate. Marr (1965) gives recommendations for contour intervals (Table IVB-4). An example of a finished contour map, suitable for design purposes, is shown in Fig. IVB-3.

In areas where a water table is near the surface its location can be indicated on the surface contour map. Although ground surface contours are relatively unchanged (unless intentional excavation or unintentional erosion occurs), ground water levels will fluctuate with precipitation, irrigation, etc.

Table IVB-4. Recommended Contour Intervals

Average land slope ft/ft	Contour interval ft
0.00 to 0.01	0.2 to 0.5
0.01 to 0.02	0.5 to 1.0
0.02 to 0.05	1.0 to 2.0
0.05 to 0.10	2.0 to 5.0

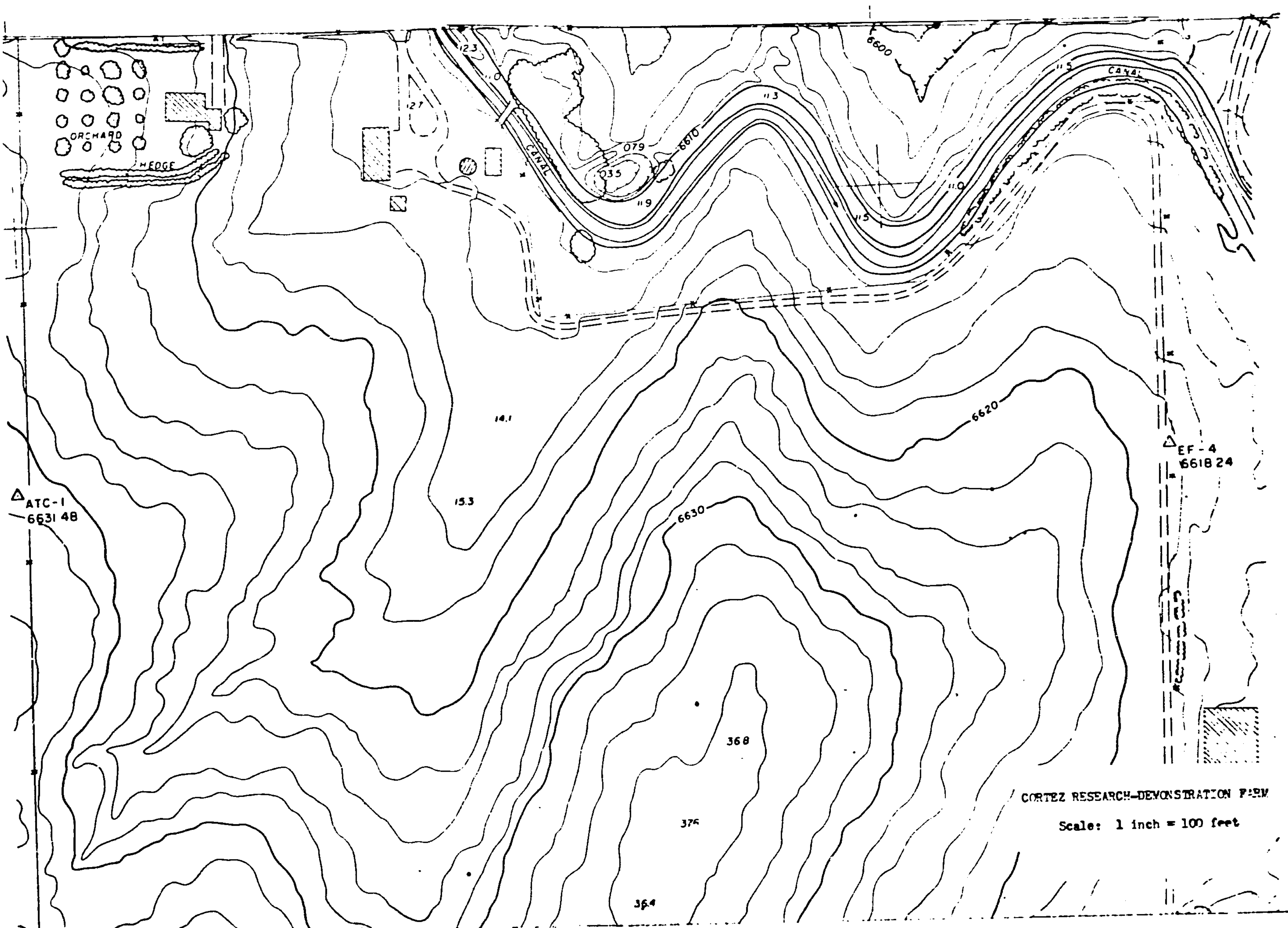

Fig. IVB-3. Contour map suitable for irrigation systems design purposes.
(Actual map at scale of 1" = 100 ft.)

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APPENDIX A

CHOICE OF AN IRRIGATION SYSTEM

The various methods of irrigation -- surface, sprinkler, subsurface or trickle -- and variations of them are discussed in the text (Sec. III). Selection considerations have been suggested by many authors (Marr, 1965; Marr, 1967; Turner and Anderson, 1971; USDA-SCS, 1967; USDA-SCS, 1968) and the attention of the readers to such information is encouraged. The outline which follows was adapted from articles by Finkel and Nir (1960) and Hamilton and Schrunk (1953). At the time of the writing of those articles the method of trickle irrigation had not been invented. As indicated earlier, it is still in its infancy. However, an attempt has been made to indicate where this system fits in with others when this was possible. Subsurface systems were also ignored by the authors. They have been covered in the text and are not discussed further here.

Two things should be kept in mind when selecting a system. First, it must be workable within physical (and other) constraints. Second, it is often possible to make a trade-off, in small amounts, of land, water, labor and capital to arrive at the optimum system (Moore, 1964).

I Water Supply

A. Source

1. Elevation
   a. Small static head above field -- Probably use surface or trickle
   b. Large static head above field -- Probably use sprinkler, but could use any other.
   c. Lightly to moderately below field, bring up with pumps -- May use any system.
   d. Greatly below field (such as deep wells) -- Select system to make maximum use of water pumped.
2. Distance from irrigated field.
   a. Short distance -- Choice open
   b. Long distances -- May be able to replace a long winding canal with a shorter pipe line, thus may consider retaining pressure and irrigating by sprinkling.

B. Size

1. Discharge
   a. Low (less than 1 cfs) -- Border checks out because of small widths, but short furrows might work. Inefficient labor wise, and perhaps other farm operations. Sprinklers or trickle possible.
   b. Medium (1 to 4 cfs) -- Can handle furrows, borders, basins, sprinklers, trickle.
   c. Large (greater than 4 cfs) -- Advantages in large borders, but others possible.
   d. Note -- May use storage to increase a continuous small flow to a large one during working hours.
2. Total quantity
   a. Limited water -- Dictates most efficient use of water, which <u>may</u> be through sprinklers or trickle.
   b. Quantity vs. discharge -- When combination is such that have limited qty <u>and</u> discharge, sprinkler may be dictated. However, if limited qty with <u>large</u> discharge, flooding may be the answer.

C. Quality

1. Sediment -- Presence of sediments, silt, algae, or other suspended matter may preclude the use of <u>small</u> sprinklers. May limit choice of measuring devices for surface systems.
2. Sewage and Organic matter -- Health hazard requires choice of crop and method of irrigating so fruit (or vegetable) is not contaminated directly.
3. Quality -- Must avoid concentration of salts, which usually means no irrigation by furrows exclusively. May be able to use flooding, large or small sprinklers, trickle.

D. Cost
   1. Limited land -- Must look at water cost in relation to maximum yield per acre of available land.
   2. Limited water -- Must look at water cost in relation to maximum yield per unit of water available.

II Topography
   A. Slope
      1. Degree
         a. Mild slopes -- Suitable for virtually any type of irrigation system. Land forming feasible.
         b. Moderate slopes -- Furrow irrigation, border checks laid down the slopes, and sprinkling. Land forming may be feasible.
         c. Steep slopes -- Usually suitable only for sprinkling, one of its great advantages. Large guns a problem. May be made suitable for surface by terracing, at some expense. Trickle a possibility.
      2. Uniformity
         a. Highly uniform -- Can use any system, including border, which is the most sensitive to slopes.
         b. Slightly non-uniform -- Furrow irrigation can be adapted to some slope variation. Intentionally put in some cases, sprinklers and trickle acceptable.
         c. Greatly non-uniform -- Usually applicable to sprinklers only, but even this may cause some difficulty in unequal pressures. Also, usual practice of laying sprinkler lines parallel to cultivation may be bothersome. Trickle irrigation possible.

   B. Drainage
      1. Water Table
         a. Level land -- Rising water table due to overirrigation could cause salinity or reduced aeration.
         b. Alluvial fan -- May receive underground drainage from other area.
      2. Public health -- Breeding place for mosquitos, fly larvae (if polluted).

   C. Field configuration
      1. Size
         a. Large -- May be suitable to any type of irrigation, because border effects usually not important.

b. Small -- If runs not long enough, consider sprinklers. But choose systems which are designed with small margin losses. Effect on cultural, harvest operations.

2. Shape
   a. Regular (rectangular) -- Generally applicable to any type.
   b. Irregular -- Usually difficult to design efficient systems, especially if water supply is a problem. Consider sprinklers, or combination of sprinkler and surface, realizing that any system will probably be more expensive to purchase, install, operate, and maintain.

D. Erosion
   1. Existing -- Extensive gullies and rills may dictate sprinklers. If can fill (as might wish to bring more land into cultivation) then consider surface as well. Possibility of trickle.
   2. Potential -- If erosive, lay furrows out accurately to small gradients. For borders, use contour type. Sprinklers may be dictated but may also have to take care of erosion hazard. Trickle applicable.

III Climate
A. Wind
   1. High (greater than 15 mph) -- May preclude use of sprinklers because of low uniformity, and borders and basins because of wave action, flow retardance. Consider wind breaks. Furrows not usually effected by winds.
   2. Medium (between 5 and 15 mph) -- May be able to find satisfactory sprinkler system if consider operating schedule. Other systems usually acceptable.
   3. Low (less than 5 mph) -- Any system.

B. Temperature and Humidity
   1. Sprinkler system -- Imply high "evaporation losses" for sprinklers. May not be all loss--cooling, other crops nearby.
   2. Surface system -- Relatively unaffected by high temperature plus low humidity. Borders usually lose less than 2%.

C. Frost
   1. Sprinkler systems properly controlled give some protection.
   2. Surface systems -- Can also help, but require large flows (border), hard to apply at night, may be detrimental to crop.

D. Rainy areas.
   1. Supplemental systems -- Recommend light portable sprinklers, with low initial per acre investment. Keep application low in case have rain immediately following irrigation.
   2. Non-supplemental -- Rain not during normal irrigation period. Design as arid land.

IV Soils
   A. Capacity for Available Moisture -- Factors which tend toward a larger capacity for moisture favor flooding methods, and factors tending toward lower capacities favor sprinkling and trickle.
      1. Depth -- Shallow soils over bedrock, hardpan, gravel, permanent water table or other obstructive layer have lower total capacity for available moisture.
      2. Textures
         a. Open sandy soils -- Low capacity for available moisture (0.4 to 1.25 in/ft)
         b. Very heavy clays -- Low capacity for available moisture.
         c. Loams, silt loams, some clays -- Moderate capacity for available moisture-- Use any system (1.25 to 2.5 in/ft)
         d. Soils with very high capacity for available water -- (2.5 to 3.0 in/ft). Try to use flooding.
      3. Volume weight -- Not too variable in itself, but reflects some of the above characteristics.

   B. Infiltration rate
      1. Irrigation design factor
         a. Low intake soils (0.5 inch per hour) -- Favor border checks and furrows with long lengths of run, thus making them favorable for large fields (few ditches).
         b. Intermediate intake soils (0.5 to 3.0 inches per hour) -- Suitable for any method.
         c. High intake soils (greater than 3.0 inches per hour) -- Usually not suitable for surface irrigation.
      2. Accumulative effect of irrigation method or infiltration.
         a. Flooding deep silt loam growing alfalfa decreased infiltration to 1/6th original in two years.
         b. Sprinkling similar plot did not reduce infiltration very much in same period.
         c. Furrows -- Movement of plate-like clay particles may cause sealing.

3. Surface Crusting
   a. Loessal soils -- Particularly subject to crusting under sprinklers.
   b. Sprinkling -- Use fine spray (especially until crop cover) to prevent crusting.
   c. Flooding -- Differential separation of soil particles.
   d. Furrow method -- Least likely to cause crusting.

C. Soil Aeration
   1. Decrease in soil O_2 accompanied by increase in soil CO_2 when irrigate by any method.
   2. Found less of above with sprinkling than with flooding (low application rates).

D. Soil Variability
   1. Over large areas -- Sprinklers allow more flexibility in design than borders.
   2. Over small areas -- Patches are not easily handled by sprinklers, and therefore recommend flooding by basins if possible.

E. Soil Stability
   1. Surface systems -- Require soil that will not erode readily. May be necessary to grow grasses under sprinkler before surface irrigating.
   2. Sprinkler systems -- Must be able to move, or use solid set.
   3. Trickle, subsurface -- Stability not a factor.

F. Soil Salinity
   1. Furrow systems -- Not usually applicable (see Water Supply). May use special slopes.
   2. Border method -- Appropriate to leach out salts at first.
   3. Sprinklers -- Sometimes can be used to leach salts out of small pores. Used extensively for establishing stand.

G. Fertilization -- Can be injected into either sprinkler or surface systems, but former usually gives best uniformity, it is believed. Also, some indication good takeup of nutrition through leaves of plant.

H. Soil Profile for Leveling
   1. Depth -- Surface soil depth limits depth of cut, so may rule out border method in some cases. Less leveling needed for furrow, still less for sprinkler.
   2. Stoniness -- Extreme stoniness may rule out land leveling. Thus, sprinkler may be only way.

V Crops

A. Method of cultivation

1. Row crops -- Crops which are intertilled are easily irrigated with furrows, or sprinklers. Borders out.
2. Close-growing crops -- These include small grains and forage crops, indicate border or sprinkler.
3. Orchards -- Furrows, contour checks, sprinklers, or trickle.

B. Height of growth

1. Sprinkler irrigation -- Difficult to irrigate high-growing crops, because must get spray over top of plants if not to cause uneven distribution. Portable equipment hard to handle.
2. Surface irrigation -- Usually furrow is most applicable to tall crops.
3. Trickle irrigation -- Crop height not a factor.

C. Depth of Roots

1. Depth of root system -- Usually deeper systems can be irrigated less frequently with heavy irrigations, requiring less labor. Shallow systems must be irrigated frequently, often making sprinklers or trickle most suitable.
2. Extent of root system (development) -- Some plants (such as bananas, lettuce, red kidney beans) have poorly developed root systems, require smaller doses of water, more frequently given, implying sprinklers or trickle.

D. Stage of Growth

1. Germination period -- If require frequent irrigation of small amount, or if have very small seeds, then sprinkler irrigation is indicated.
2. Period of growth and maturity -- Most crops have actively elongating root systems and so there is no special preference to a particular method of irrigation.
3. Harvesting -- Those needing irrigation up to harvest, but which must not allow fruit to wet (cotton) may do better with surface systems.

E. Diseases

1. Sprinkling -- May cause disease of some crops. Examples are downy mildew of grapevine, leaf scorch of deciduous fruits such as apples and pears (especially when sun shining), fruit rot of bananas, black pit of lemon. Also, may wash off spray material for diseases and pest control.

2. Flooding -- May cause disease of some crops. Examples are damping off (pythium) of solenacious and leguminous vegetable crops. Also provide place for growth of weeds along ditchbanks, which makes cover for disease and pest. Sprinkler usually allows cleaner cultivation.

F. Special Requirements -- paddy irrigation.
   1. Paddy rice -- Requires flooding
   2. Quality -- Cauliflower must be kept free of dirt to maintain quality. No sprinkling after heading.

VI Economics
   A. Cost of Irrigation
      1. Fraction of water supplied by irrigation -- for fully irrigated areas, can justify high initial cost to reduce operating costs. For supplemental, down on initial with increased operating cost.
      2. First cost and depreciation
         a. Surface
            1) Water supply
            2) Land preparation
            3) Conveyance system (open ditches, closed conduits, drops, division boxes)
            4) Distribution systems (checks, spiles, siphons, gated pipe, valves)
            5) Machinery (floats, ditchers)
         b. Sprinkler
            1) Water supply
            2) Conveyance systems (mains, open ditches, closed conduits)
            3) Distribution systems (sprinkler laterals etc., pump)
            4) Machinery (for moving pipe)
      3. Operation and Maintenance
         a. Surface
            1) Maintenance (land preparation, permanent ditches, permanent structures, distribution equipment)
            2) Operation (cost of water, laying and moving pipe, construction of furrows, borders, and corrugations, construction of annual ditches, filling of annual ditches, operating siphons, gated pipe, etc., disposal of runoff water).
         b. Sprinkler
            1) Maintenance (permanent ditches, permanent structures, sprinkling equipment).

2) Operation (cost of water, cost for increased pressure, laying and moving pipe).

3) Subsurface trickle

4. Efficiency of application -- should consider lack of meeting needs as well as lost water.

a. Sprinkler -- may have evaporation and drift losses, but complete control over water applied can be made. Intake may be a problem on tight soils.

b. Gravity -- May not be able to control runoff, but little evaporation and no drift losses.

B. Value of Irrigated Crop -- If final market value depends upon the type, variety, quality, seasonability, total supply and demand, and marketability, and these are in turn effecte by the irrigation system used, then they become a factor in the economics (and therefore choice of system).

VII Human Factor

A. Undesirability of mud and shovel

B. General mechanical aptitude

C. Social security of small farmer by using his neighbor's system so can help him in case of illness.

APPENDIX B

DRAFT

NOTE: This first draft is currently being revised. We therefore request that its circulation be restricted.

TECHNIQUES FOR ASSESSING HYDROLOGICAL POTENTIALS IN DEVELOPING COUNTRIES

(State of the Art and Research Priorities)

Office of Science and Technology

Agency for International Development

SEPTEMBER 1972

PREFACE

This report has been prepared at the request of the Development Assistance Committee (DAC) of the Organization for Economic Cooperation and Development as a basis for evaluating the current state of the art and research priorities with respect to the assessment of hydrological potentials in developing countries. The sector was one of eleven identified in the spring of 1971, by a DAC Panel of Experts as key areas requiring analyses of research opportunities due to (1) their importance in the development context; (2) the relative neglect of research in the sectors by donor countries and international agencies; and (3) the likelihood that additional research will make major contributions to the solution of critical problems. By applying these criteria, the Experts singled out the following sectors:

-- vector and pest control;

-- utilization of tropical forests;

-- mineral prospecting techniques in tropical areas;

-- buildings and engineering construction;

-- schistosomiasis;

-- processing and preservation of food products;

-- non-conventional energy sources;

-- water and sewage treatment in tropical areas;

-- non-food uses of agricultural products including fibers;

-- industrial uses of non-agricultural natural resources; and,

-- techniques to assess hydrological potential.

This report addresses the last of these eleven sectors. It is based largely on an analysis prepared by the U.S. Geological Survey for the Agency for International Development[1], plus comments subsequently received from numerous reviewers in U.S. Government agencies and universities, other donor countries, and international development institutions. Special appreciation for assistance in reviewing drafts of the report is extended to the Smithsonian Institution; Office of Water Resources Research and the Bureau of Reclamation, U.S. Department of the Interior; Office of Water Programs, U.S. Environmental Protection Agency; Agriculture Research Service, U.S. Department of Agriculture; Engineer Agency for Resources Inventories, U.S. Department of the Army; U.S. National Committee for the International Hydrological Decade, National Research Council, NAS-NAE; Department of Hydrology and Water Resources, University of Arizona; Geological Survey of Alabama; Resources and Transport Division, United Nations; and the International Bank for Reconstruction and Development.

The report considers current capabilities and future needs for assessing hydrological potentials under the following topical headings: Streamflow, Erosion and Sediment Transport, Water Movement in Unsaturated Soils, Ground Water, and Hydrologic Applications of Remote Sensing. The discussion does not cover all aspects of hydrological assessment. For example, the scope of the report does not include evaluation of precipitation and evaporation, nor deal with water quality. Established techniques and methodologies are described under "State of the Art", while the most interesting emerging areas for attention by individual countries and foreign assistance agencies are presented under sub-topics entitled "Current Research" and "Research Opportunities for Application in Developing Countries". Where possible, instrument and survey costs, based on 1971 U.S. prices have been estimated.

Given the close relationship between hydrological assessment and actual water resource development, a separate section has been added to the original scope of the report which identifies some of the more promising research approaches to improved water resource development.

1/ Techniques for Assessing Water Resource Potentials in the Developing Countries (with emphasis on Streamflow, Erosion and Sediment Transport, Water Movement in Unsaturated Soils, Ground Water, and Remote Sensing in Hydrological Applications:) George C. Taylor, U.S. Geological Survey (Open File Report), December 1971.

CONTENTS

INTRODUCTION

Although the earth is impregnated with or covered by vast amounts of water, relatively little is available for man's use. One significant constraint on more effective use of water is the present limited state of scientific knowledge and engineering technology related to water resources discovery, assessment, control and management. Yet ever-increasing demands are placed on available water resources by worldwide population growth and urbanization with attendant needs for greater food production through intensified irrigation and for disposal and dilution of man-generated wastes in the water environment. These demands, in turn, have stimulated rapid evolution of the science of hydrology during the past two decades toward a more sophisticated understanding of the natural role of water in the earth's physical, chemical, and biological processes. Advances in hydrologic science have also stimulated engineering technology to devise more effective ways and means for utilizing available water resources as well as water heretofore not available, notably "fossil" ground water,1/ sea water and polar ice.

All water for man's needs must be obtained from the natural environment. To use and control water effectively requires knowledge acquired through collection, analysis and interpretation of hydrologic data. Such data includes observations of precipitation, snow cover, stream flow, ground water movement, sediment and solute transport, chemical quality, evaporation, soil moisture and many others. Also, the degree to which water resources can be effectively developed and utilized on a sustained basis is directly related to the level of understanding of the hydrologic environment. To draw the first bucket of water is easy enough, but to divert the flow of a large river from one drainage basin to another requires a high level of hydrologic knowledge and engineering technology.

1/ Water derived directly from the interior of the earth which has not previously existed as atmospheric or surface water, or been involved in the hydrologic cycle, it is sometimes referred to as "juvenile water."

At the present time it appears that conventional techniques for the measurement and evaluation of basic hydrologic parameters are well understood in most of the developing countries, albeit much more so in some than in others. On the other hand, application of these techniques is being impeded by institutional and economic constraints in many countries which inhibit the conduct of sustained programs of hydrologic data collection and, consequently, application of the data to priority national water resources development objectives. Moreover, experience in the less-advanced developing countries has proven that it may not always be feasible or even desirable to use more sophisticated methodology in hydrologic data collection and analysis, at least not until national hydrological institutions and local cadres of technicians and professional hydrologist have been developed. In addition -- and this is the major focus of this report -- hydrological assessments in developing countries are sometimes retarded by the unique climate, vegetative and geologic conditions encountered in unfamiliar tropical settings which limit or render inappropriate the use of instruments and methodologies utilized in advanced countries of the temperate regions. Consequently, the application of appropriate technologies to assess water potential must be geared to the circumstances and needs in individual developing countries.

The results of many types of hydrologic research in the more technologically advanced countries, although primarily directed toward domestic needs, are nevertheless potentially applicable to the rest of the world owing to universality of water problems. Such research can be grouped in three general categories as follows:

Process: Precipitation, evaporation, transpiration, infiltration and movement of soil moisture, surface and ground-water flow, channel flow, sedimentation, changes in chemical and physical quality.

Environmental: Study of water behavior in various climatic, geographic and geologic environments (e.g. tropical and arid zones, lakes and estuarine areas, and limestone and volcanic terranes); hydrological aspects of watershed management and water resources engineering, including irrigation and flood control; and water quality analysis, monitoring and protection.

Methodological: Mathematical analyses, use of digital and analog models of transient phenomena, nuclear and physiochemical techniques, automatic processing of data and use of computers, instrument development, water information systems, etc.

The developing countries naturally, place highest priority on research oriented toward water resources development to meet pressing needs for economic growth. On the other hand, the developed countries are currently giving higher priority to research designed to protect and conserve known and utilized water resources and to control deterioration in their quality.

Outstanding among efforts to advance and expand knowledge in scientific and applied hydrology during the past 10 years has been the International Hydrological Decade (IHD), initiated in early 1965 under the aegis of UNESCO with strong participation by UN specialized agencies and national committees of 107 governments. The IHD has played a key role in fostering scientific and technical exchange among participating agencies and governments; in furthering establishment of national networks for collection of basic hydrological data; and in strengthening national programs of hydrologic research on a world-wide scale.

STREAMFLOW

Man's observation and measurement of the stage and discharge of rivers dates from antiquity when such knowledge was particularly important in the hydraulic cultures of the Nile Valley, Mesopotamia and the Indus Basin. Measurements of discharge were admittedly no more than crude estimates, but accurate observations of river stage were possible with simple staff gages. For example, the flood stage of the Nile at Roda near the head of the delta has been observed and recorded for more than 2,000 years.

State of the art

Observation and measurement of streamflow are fundamental to all broadly-bases water resources investigations and particularly so to those dealing with surface-water resources. Also, as the water in streams is the most readily available and widely used component of the water mass in the hydrological cycle, methods and techniques of observation and measurement are highly developed. Consequently, it is possible to measure streamflow with a higher degree of accuracy than most other hydrologic parameters.

Perfected by repeated experiments during the past 80 years, the most basic and universally accepted instrument for measurement of streamflow is the current meter which enables one to measure velocity at selected depths in a vertical section of a stream. With this information and measurements of channel widths and depths, the point (in time) discharge of a stream can be determined. Observations of stream stage are conventionally made by reading a calibrated staff gage at a selected station--usually daily at a specific time. Continuous observations of stage at selected stations can be obtained by means of permanently installed clock-driven recorders with float and cable-driven drums. Graphs of changing stream stage are automatically registered by pen on calibrated charts mounted on the drums.

Records of actual flow volume are obtained from rating curves which are constructed by correlating stream stages with measured discharge. A common unit of flow is "daily discharge", which is the average volume for a calendar day.

Daily discharge in the metric system is expressed in cubic meters or liters per second, and in the English system, in cubic feet per second. Annual runoff from watersheds or river basins is commonly expressed in millimeters of water or units comparable to those used for precipitation and evapotranspiration.

Discharge measurements in small shallow streams are made with the current meter attached to a calibrated staff as the observer wades the stream. For deep, wide and swift streams, the current meter is attached to a weighted cable which is lowered from a calibrated reel into the water by the observer from a boat, a bridge, or a suspended cableway. The number, location and distribution of stream-gaging stations on a river system would depend on such factors as run-off characteristics, diversions from streams for human use, silt and bed load character, and intended use of streamflow information.

One of the most significant innovations in the collection of hydrologic data in the developed countries over the past two decades is the digital recorder used for the measurement of river stages. This instrument punches a digitized record of water level on a paper tape in a manner compatible with systems of computation by high-speed digital computers. The records may be used with any of several stage-sensing devices--floats, pressure transducers, or gas-purge (bubble gage) systems of head-pressure sensing.

The processing of the data begins with a stage record obtained from a digital recorder gage and ends with a computer printout listing mean daily discharge rates, computed monthly and annual averages, maximum and minimum rates of flow during monthly and annual periods, and flood-hydrograph data for floods meeting pre-selected criteria. The entire processing procedure is called a "gage to page" plan, for almost the entire process is accomplished by the use of machines, the only human factor being the introduction of judgment factors into the programming of computer operations. The printout from the computer is ready for reproduction by photographic methods for formal publication.

Another significant development in the collection of river data is the invention of a stage-sensing device called a "bubble gage." This gage was developed to record reservoir and river stages without the use of stilling wells and intake pipes, which are often expensive to construct and difficult to maintain. The gage consists of a specially designed servomanometer, a transistorized control, a gas-purge system, and a recorder. The pressure corresponding to the head of water is brought to the manometer by the gas-purge system. Nitrogen gas is discharged slowly through plastic tubing from the gage house to an orifice located at a fixed elevation in the stream. The pressure at the orifice, and hence at any point in the delving tube, is related to the head or depth of water over the orifice. This pressure is in turn transferred to the manometer and then to the recording device. The manometers have a sensitivity of ± 0.005 foot, and the entire assemblage can be constructed to record ranges in stage in excess of 120 feet. A differential type of manometer may be adapted to the instrument to record directly the slope in a short reach of river channel.

Perhaps the most significant breakthrough in stream gaging in recent years is the "moving-boat" method which is admirably suited to the accurate and rapid measurement of large rivers in remote areas. The method requires no fixed facilities and lends itself to use of alternative sites if necessary. As with conventional current-meter measurements, the moving-boat technique requires information on the location of observation points, stream depth at each observation point, and stream velocity perpendicular to the cross section at each section of each observation point.

During the traverse of the boat across the river, a sonic sounder records the geometry of the cross section and a continuously operating current meter senses the combined stream and boat velocities. A vertical vane alines itself in a direction parallel to the movement of water past it, and an angle indicator attached to the vane assembly indicates the angle between the vane and the true course of the boat.

The data from these instruments provide information necessary for computing the discharge for the cross section. Normally, data are collected at 30 to 40 observation points in the cross section for each run. As a point of interest--individual measurements of the Amazon River at Obidos, Brazil in 1963-64 required 1 1/2 to 2 days to complete by conventional methods. In late 1969, measurements at the same site and of comparable accuracy were found to require only about 20 minutes each by the moving-boat technique.

Dye-dilution methods of discharge measurement, known for more than 100 years, have also undergone considerable refinement in recent years. The development of commercially available fluorescent dyes and fluorometers, which can detect these dyes at concentrations as low as 0.5 part per billion, has greatly enhanced the use of dilution methods. In general, dye-dilution methods for measurement of discharge are not economically competitive with the current meter.

There are, however, several common flow conditions for which dye-dilution methods offer considerable promise. These are turbulent mountain streams, flow beneath ice cover and flow in closed conduits. Continuous or periodic measurement of flow in sand channels by means of automatic dye injection and sampling equipment is in the experimental stage. Dye-dilution techniques have also been used successfully for in-site calibration of orifices, weirs, flumes and laboratory models of spillways. Dilution measurements can be made by injecting a dye tracer at a constant rate for a given period of time, or by injecting a known volume of dye instantaneously. The accuracy of both methods is inherently related to dye loss in the measurement reach. Of course, the accuracy is also dependent on the mixing characteristics of the channel reach and the measurement of dye concentrations.

Much effort is being expended in the developed countries in the perfection of techniques of analysis for the generalization and synthesis of streamflow data. It is never possible to collect information at all potential sites of need. The problem usually faced requires generalization of existing data in such manner as to form a basis for the synthesis of flow data at ungaged sites to acceptable limits of accuracy. For example, methods for generalizing flood experience have been developed. One of these procedures uses statistical methods to choose geographic areas within which flood generation and probability are homogeneous. Flood experiences at all stations within these areas are composited to develop flood-frequency curves of much broader base than possible from records for a single station. The sizes of floods generated within these areas are expressed as ratios to the mean annual flood.

The single-size parameter, the mean annual flood, is related graphically to drainage area size and other topographic factors. To determine the size of a design flood in an ungaged area by this method, the following steps are taken:

(a) determine the mean annual flood for the stream in question, using the graphical relationships and the applicable topographic factors, (b) derive the ratio of the design flood to the mean annual flood from the composite flood-frequency curve for the area in which the stream is located, and (c) multiply the mean annual flood determined in step (a) by the ratio determined in step (b).

Several other more or less sophisticated methods of generalizing flood experience are in common use. The choice between them usually depends on the amount of basic data at hand and on the personal preference of those engaged in the study. Techniques for the generalization of other streamflow data, such as mean annual runoff or low-flow quantities, are in common use in the developed countries. The description of even a sample of these techniques is not possible here.

Perhaps the most difficult problem facing water-data program planners is the design of appropriate networks for the collection of field measurements. Intuitive and judgment factors are utilized in beginning such networks. Appropriate weight is given to sampling areas having different topography, geology, and climate, and to existing needs for data at specific sites. As techniques are improved, and the needs for data increase, networks are expanded. As the network of streamflow gaging stations in a given country grows, it is necessary from time to time to evaluate the entire network. The principal classifications of stations that might be derived from such an evaluation would be as follows: (a) primary stations: those having essential hydrologic significance and operated for indefinitely long periods, (b) secondary stations: those at which continuous flow records are obtained for a period of only a few years (5 to 10), and (c) partial-record stations: those at which flows, or stages, are measured only during extremes of either high or low conditions. In testing the existing design of primary gaging stations, statistical methods are used to determine the degree of independence of stations in the network. With these criteria it is possible to eliminate some stations and to pinpoint new areas needing gaging. Thus the optimum extent of the required primary network is determined.

The basic rationale in the use of networks of secondary and partial-record stations is to obtain a maximum amount of data at minimum cost. Modern statistical methods in hydrology permit records from these shorter or less complete operations to be extrapolated to accurate estimates of flow parameters for longer periods. Networks of such stations become more dense as water development proceeds in an area and the need for more detailed hydrologic information increases.

A final consideration is the preservation of the data in a place and in a form useful and available to all. The emphasis in the developed countries is on data, accurate by high technical standards, centrally filed, permanently preserved, and readily available. High consideration is given to the introduction of new techniques where they have promise of adding accuracy or decreasing costs.

Virtually all the foregoing techniques and methodologies have been applied at one time or another in the developing countries with mixed measures of success. Streamflow measurement by conventional current meter methods, coupled with staff gage observations for river stage, is in almost worldwide use and is still the most trustworthy method in the majority of the developing countries. Graphic style recorders for more complete stage data are also widely and successfully used in the more advanced developing countries. However, even these relatively simple instruments require maintenance of a nature which inhibits their widespread and systematic use in the more remote regions of the world.

The digital recorder coupled with computers has been used experimentally in a few advanced developing countries; however, the high cost and sophisticated technology required mitigate against its wider application in these countries. The same can be said for the bubble gage recorder. Several of these, for example, were installed on the Mekong River in southeast Asia during the early 1960s and all are now inoperative owing to instrument and maintenance problems beyond the ken of the technical staff.

The dye-dilution method for discharge measurement has been used occasionally for special hydraulic model studies in the developing countries, notably in India, Pakistan, Egypt, and Turkey but is generally considered to be too costly for routine use in natural stream channels.

The moving-boat method developed during the past decade by the U.S. Geological Survey has been proven through repeated trials to be unquestionably the most efficient and economic means of gaging large rivers in remote areas. The method has now been applied successfully on the Amazon and Sao Francisco Rivers in Brazil, the Parana River in Argentina and the Mekong River in Thailand and Laos. It has the advantages of speed, high mobility and relatively low cost and thus has wide potential application throughout the developing world.

Office-based operations such as network design and evaluation, analysis and/or synthesis of stream-flow data, and processing and publication of hydrologic records present fewer logistic problems in the developing countries than do field observations and data collection. Nevertheless, the quality of office operations depends on intelligent direction, high standards, adequate financial support, and the personal motivation and competence of assigned office professionals and technicians.

Instrument and Investigation Costs

The costs for hydrologic instrumentation and for construction and operation of gaging stations for streamflow measurement range through a wide gamut and depend among other factors on gaging site location and accessibility, size and physical behavior of the stream at the gaging site, and the nature and duration of the hydrologic records required at the site. Gross estimates of some of the more significant of these costs are given below:

Simple staff gage station:

Construction and material costs----------	$ 250
Observer services and maintenance per year--------------------------------	300
	$ 550

Simple gaging station with automatic graphic recorder:

Construction and material costs----------	$ 2,500
Instrumentation--------------------------	1,000
Hydrologist services and maintenance per year------------------------------------	1,500
	$ 5,000

Complex gaging station on major river with digital recorder, telemetry, cableway, and other instrumentation:

Construction and material costs----------	$25,000
Instrumentation--------------------------	10,000
Hydrologist services and maintenance per year--------------------------------	15,000
	$50,000

Equipping one field hydrologist with current meter and ancillary equipment for simple streamgaging-----------------	$ 1,500
One continuous graphic water-stage recorder with ancillary equipment-------	700
One bubble-gage recorder with auxiliary equipment-------------------------------	1,500
One digital recorder with ancillary equipment-------------------------------	700

Moving-boat technique:

Instrumentation--------------------------	3,500
Boat and motor-------------------	5,000 to 10,000
	$8,500 to 13,500

As an example of field operations for a typical (but hypothetical) surface-water investigations program in a small developing country with a network of 50 gaging stations, costs, (estimated for the U.S.A., 1971) might approximate the following:

Installation of 50 staff gages-------------	$12,500
Observer services and maintenance of the above, per year-------------------------	15,000
Installation of 10 simple gaging stations with automatic graphic recorders--------	35,000
Hydrologist services and station maintenance, per year-------------------	15,000
Equipping 2 hydrologists for stream gaging-	3,000
Costs for 12 discharge measurements (one per month at $100 per measurement) at 50 stations, per year---------------	60,000
	$140,500

Office computations; compilation and processing of data; publication of records; and administrative and technical support of personnel might cost $50,000 to $60,000 a year bringing the initial cost of the program to about $200,000 a year. Continuing costs, however, would be in the order of $150,000 per year. For a large developing country, these costs might well be doubled or tripled.

Recent and Current Research

Recent and ongoing research in streamflow instrumentation and methodology may be grouped into two categories; (1) analysis, manipulation and interpretation of streamflow data; (2) improvement of proven, and development of new, instruments and methods.

With respect to the first category, much research is centered on the use of more sophisticated means of storing, retrieving and manipulating masses of streamflow data which have already been accumulated, as well as those yet to be collected, and also on the production of aids to interpretation of the data by computer methods. Automatic processing of hydrologic data is finding increasing favor in developing countries with large backlogs of unprocessed, unverified, and unpublished hydrologic data, particularly streamflow records. Such data are only of limited value until compiled in usable form so that they can be interpreted by professionals in terms of significant hydrologic parameters.

Several developing countries are resorting to automatic data processing to bring hydrologic records up-to-date and to keep them current, as for example Pakistan and India in south Asia; Brazil, Chile, Argentina and Mexico in Latin America; and Egypt, Tunisia, Nigeria and Zambia in Africa. National data banks with capability for storing, retrieving and manipulating masses of streamflow data could be much more widely used in the developing world in water resources investigations and management.

With respect to the second category, many governmental and private agencies in the developed countries are continuing the search for more accurate instrumentation and improved methodology to lower costs and to increase efficiency and flexibility. Mathematical modelling of hydrologic systems has undergone rapid evolution in the past decade, particularly with the wider application of digital and analog computers to complex water problems.

Such models simulate natural and man-made stimuli for changes in hydrologic systems and may be either responsive or predictive.

Parametric modelling is the most widely used of modelling approaches. Since it requires input data with considerable detail in time it models transient responses well. Parametric modelling includes component modelling on the one hand and integrated system modelling on the other. In the former, individual components such as infiltration, evapotranspirations aquifer response and streamflow routing might be considered. Integrated system modelling might consider, as examples, hydrological forecasting, rainfall-runoff and streamflow-aquifer relations, runoff prediction in various climatic and physiographic regimes, or groundwater basin modelling.

Conventional techniques for measuring discharge of streamflow by current water meter are standardized and well-known. Traditional means of measurement are not well suited, however, to conditions in large rivers influenced by tides, in extreme flood, in shallow turbulent mountain streams or in flow under ice cover. One evolving method for measuring discharge in tidal streams, where no stable stage-discharge relationship exists, is through use of the pendulum-type deflection vane. At gaging sites with stable channels, cross-sectional area is obtained from records of water stage. Mean velocity can be usually related to an index velocity at some point within the cross section. The index velocity can be obtained by the pendulum-type deflection vane. This type of vane can be installed totally submerged reducing the possibility for collecting floating debris near the river surface and for damage from ice jams.

A special depth-sounding and velocity-measuring device has also been recently developed for measuring extreme flood flows. This instrument combines a fathometer, a direction compass, and a Price current meter, and permits measurements of depth, direction of current and near-surface velocity with a single setting and without encountering the hazards of complete depth sounding by sounding weight. The technique of augmenting continous flood records by operation of only crest-stage gages has been enhanced by the development of a small cheap water stage recorder. This recorder may be operated intermittently in a 3-inch pipe well to obtain only flood hydrographs.

Nuclear techniques as applied to streamflow measurement are also evolving rapidly. Radioisotope tracers can be used in stream-gaging where current meter measurements may be impractical, such as in turbulent high-debris floods or mountain torrents. Radioisotopes are also used for time-of-travel flood-flow tracing and for tracing leakage from water conveyance structures or seepage from natural stream channels. Such techniques have already been applied experimentally by the International Atomic Energy Agency (IAEA) in a number of developing countries including Brazil, Turkey, Kenya, Chad, Greece, and Senegal. There is opportunity, however, for much wider application of these techniques in the developing world.

Research Opportunities for Application in Developing Countries

Generally speaking, streamflow-measuring instruments which are currently available appear adequate to meet the spectrum of physical and institutional differences encountered in developing countries. Existing instrumentation runs the gamut from inexpensive, simple measurement devices to highly sophisticated, expensive automated systems, all of which is readily adaptable to the streamflow parameter likely to be encountered in developing countries.

Proven techniques designed in the developed countries for measuring and analyzing streamflow data also appear adequate for most applications in the developing countries. Ongoing research on modelling of hydrologic systems and on automatic data processing (as described in the previous section) should continue to be pursued vigoriously. This research is not of an "adaptive" nature however, and can continue to be carried out by, and for, the more advanced nations. Obviously, benefits from breakthroughs will accrue to all countries which have the trained manpower and technological capacity (e.g., computers) to adopt them due to the apparent direct transferrability of the general concepts and methods. The biggest non-institutional gap with respect to application of new techniques is lack of basic data on streamflow characteristics needed to build acceptable analog or computer models.

EROSION AND SEDIMENT TRANSPORT

Erosion and sediment transport phenomena are operative in greater or lesser degree on most of the exposed surface of the earth. Erosion often begins with the impact of raindrops on the land surface and continues with the cutting force of running water in stream channels. Sediment transport begins in rill wash on exposed soils, continues as suspended and bedload materials in natural stream channels, and ends with deposition in flood plains, lakes, reservoirs and the oceans.

Although commonly included in the science of geomorphology, erosion and sediment transport processes are nevertheless of great importance in hydrology and to practical problems of water use and management everywhere. Questions that the hydrologist might expect to be asked could include, for example --

What is the useful life of the reservoir?
How soon will the reservoir be filled with sediment?
What will happen to the stream (channel) above and below the dam when it is completed?
What will be the effect of the levees after their construction along the stream channel?
What will happen if the reach of the river is straightened?
What type of bank protection is needed to prevent the river bank from eroding?
What depth of scour can be expected at the bridge pier?

To answer questions such as these, a variety of instrumentation and methodology has been developed, some of which are briefly outlined in following sections.

State of the Art

For many years streamflow data collection programs in the developed countries have also included provision for determination of the wash load (about 80-90 percent of the total) of transported sediment in stream channels. The suspended load is conventionally measured with a depth-integrating sampler, which typically consists of a streamlined case carrying a conventional milk bottle as the collecting container. An exhaust vent allows escape of air when water enters the bottle and keeps the inlet velocity approximately equal to that of the stream current. Interchangeable inlet nozzles of various sizes are available to adjust the rate of filling of the bottle. The sampler is suspended in the stream from a wading rod or cable. Tail vanes are provided for large samplers to keep them stable when suspended from a cable. At a uniform speed, the sampler is lowered from the surface to the bottom of the stream then raised to the surface. The sample thus collected is an integrated quantity, with the relative portion collected at any depth proportional to the velocity (or discharge) at that depth.

During recent years several models and sizes of depth-integrating samplers have been developed for use in different types of streams under varying conditions. Continuous sediment samplers are also commonly included as components of stream-gaging stations with automatic recorders.

Bed material sampling under flowing water is difficult because the finer particles are frequently lost in the sampling process. Clamshells(as for example the Foerst bed-material sampler) and similar grabbing devices are commonly used but must be carefully checked for leaks. Bucket-type devices, which sample as they are dragged over the bottom, present similar problems.

Reservoir sedimentation surveys are generally made by measuring the accumulation of sediment in a reservoir of known age against original bottom configuration (commonly from original topographic maps) and adjusting for sediment losses over the spillway. Sediment accumulation can be measured periodically by boat, sextant and fathometer traverses along established range lines with boat position fixed by on-shore transit. Accumulation of sediment can also be determined by periodic sampling of streams flowing into a reservoir.

Radioisotope tracers are also being used increasingly for sediment studies such as determining the direction and velocity of sediment transport in streams; the stream-bed length affected by transport; the effects of transport on stream-bed configuration; and longitudinal and transverse dispersion coefficients. Erosion processes are also being studied by labelling soil particles with suitable radio-isotopes and monitoring the decrease of activity with time in experimental plots. Valuable information can be obtained by this method on the roles played by splash or raindrops and overland rill wash in erosion of soil and the relation between erosion and the duration and intensity of precipitation.

Sediment sampling programs have been undertaken on a small scale in many developing countries in conjunction with basic stream-gaging networks. There are, however, at present few viable or systematic programs of sediment data collection extant among the developing countries. The chief problem is usually cost. In many instances developing countries choose to dedicate limited financial resources to streamflow data collection and neglect in the process to give adequate attention to sediment data. A reordering of priorities is the indicated corrective measure.

Instrument and Survey Costs

Sediment sampling and survey programs are commonly integrated with stream-gaging networks. Costs for sediment sampling instrumentation, however, must be identified over and above those for streamflow instrumentation described in the previous section. Some of the more significant costs for conventional instrumentation and surveys (estimated for the U.S.A., 1971, except as noted) are given below:

Instrumentation for automatic sediment measurement at one stream-gaging station--	$ 2,500
Equipping one field hydrologist with sampler(s) and ancillary equipment for simple sediment sampling--------------	1,500
One hand-operated sediment sampler----------	700
One complete sediment determination laboratory facility with full instrumentation (based on experience in Brazil)----------------------------------	25,000
One complete reservoir sedimentation survey including equipment and personnel costs (based on experience in Afghanistan)	25,000
One large combined outdoor and indoor hydraulic modelling facility (based on experience in Turkey)--------------------	150,000

One small outdoor hydraulic modelling facility (based on experience in Brazil)-- $ 50,000

Recent and Current Research

Most current research in erosion-sedimentation problems is directed toward better understanding of the mechanics of initial sediment movement in stream channels, bed-load movement, suspended-load movement, channel-bed form, sediment yield, scour at engineering structures, riprap, and river-control works and canal design. Applied research on problems of this nature is being actively pursued through studies of operating scale hydraulic models in virtually all of the more advanced developing countries as for example Brazil, Chile, Venezuela, India, Pakistan, Iran, Turkey and Thailand, to name several. Applications of mathematical modelling to erosion-sedimentation problems in the developing countries is of more recent vintage. Mathematical models should, however, gain increasing favor in the near future because they are versatile and require much lower initial investment and continuing cost than operating hydraulic models.

Nucleonic instruments have been developed during the past decade and are now being perfected for estimation of the suspended sediment concentration of streams. They offer some attractive advantages over conventional methods. The nucleonic instruments provide continuous measurement and immediate readings in the field and eliminate the need for collection of samples to be taken to a sediment laboratory for analysis. Two general types of gages have been developed: one for semi-permanent installation and the other a portable unit. Both work on the principle of attenuation of a beam of low-energy electromagnetic radiation by the suspended sediment. These gages operate in the concentration range 0.1 to 50 grams per liter with an accuracy of ± 20% for low concentrations improving to ± 5% for higher concentrations. The two types of gages are complementary. The portable instrument can be used for spot measurements and also for the siting of the semi-permanent gage, which can provide continuous monitoring of suspended sediment concentration.

Nucleonic instruments for sediment studies have been used experimentally in the developing countries and offer considerable promise for wider application if initial costs can be reduced.

Research Opportunities for Application in Developing Countries

As in the case of streamflow measurement and interpretation, the broad range of instruments and techniques currently available for investigating erosion and sediment transport phenomena appears to be adequate for developing country needs. Short-term objectives should now include simplifying and reducing the costs of the more advanced instrumentation, particularly that based on nuclear techniques. A second important need is a better understanding of both sediment source areas (i.e., provenance studies) and the rate of erosion associated with difference rock types, vegetative covers and cultural patterns unique to developing countries. Such research serve as a basis for improving the sedimentation data input into existing and emerging predictive models of specific hydrologic systems.

WATER MCVEMENT IN UNSATURATED SOILS

Soil scientists, hydrologists and engineers are, and have long been, concerned with that part of the hydrological cycle which deals with the transport of water from the land surface through the soil profile down to the water table. A variety of hydrologic processes occur in this zone, including infiltration, redistribution, percolation, drainage, and evaporation. The water content of the zone is in constant flux, being either in the process of abstraction from the soil profile by evapotranspiration, or of replenishment by rainfall or irrigation. Knowledge of water availability requires detailed mapping of water content and pressure-head distributions in space and time. What is needed are techniques for estimating the flux of water past a given point and the pressure head or water content at the same point.

State of the Art

Instrumentation and techniques evolved in recent decades in the developed countries include: the tensiometer for field measurement of point pressure head; buried porous blocks of gypsum or fiberglass; and laboratory "hanging water column" and pressure cell methods for determination of pressure-head and water content of soil samples.

The tensiometer in its simplest form consists of a stoppered water-filled column attached to a porous cup or cell, which is placed in a chosen position in the soil profile. The column is connected to a vacuum gage or manometer. When the cell is positioned in the soil, water moves from the porous cup into the surrounding soil, causing thereby a reduction of pressure within the instrument and the consequent depression of the mercury in the right arm of the manometer. The drier the soil, the greater will be the amount of water leaving the cup and the greater therefore, the depression of the mercury. The level of mercury will remain steady once the suctions in the cup and the surrounding soil are in equilibrium. Tensiometers give fairly accurate results within their operational range.

Buried porous Bouyoucos blocks provide an alternative means of measuring soil moisture suction (negative pressure head) beyond the range of the normal tensiometer. Blocks of gypsum or fiber-glass are buried in relatively undisturbed field situations to measure in situ moisture changes. The method is based on the fact that as the moisture content of the block changes so does its capacitance or its electrical or thermal conductivity which can be readily measured.

The "hanging water column" or Haines apparatus uses a saturated sample of representative soil which is placed on a porous plate attached to a vessel with a water-filled open-armed U-tube. The water level in the open-arm is lowered to a chosen position. The soil solution flows out of the sample and a hydraulic equilibrium is established between the soil water and the water in the "hanging" column. The pressure head at equilibrium is measured by the vertical distance from the soil sample to the free water level in the open arm. The water content of the soil sample is obtained either by direct gravimetry or by indirect means such as measuring the volume of outflow.

The pressure cell method uses gas pressure applied to the top surface of a soil sample resting on a porous plate or membrane whose pores contain water at atmospheric pressure. When the applied pressure just fails to drive water from the soil pores, the applied pressure is considered to equal the soil moisture suction force against which it is working. The expelled water is collected in a container and weighed periodically.

Studies of soil moisture have been undertaken in most of the advanced developing countries during the past 25 years, but mostly in connection with soil surveys and land-use problems. Relatively little attention has been given, however, to movement of water in unsaturated soils as related to hydrologic processes and much remains to be done in this field.

Instrument and Survey Costs

Some of the basic costs for instrumentation in soil moisture determinations are given below(for the U.S.A. in 1971). This list, however, is by no means comprehensive.

One simple field tensiometer----------------	$ 200
One set of Bouyoucos blocks with electrical conductivity meter------------------------	500
One "hanging water column" apparatus for laboratory use with auxiliary equipment----	1,000

Recent and Current Research

Perhaps the most notable advance in recent years in the measurement of moisture in unsaturated soils is the neutron moisture gage, which is still undergoing development. The gage consists of a probe, which can be set at various depths, containing a source of fast neutrons and a detector for slow neutrons, which is connected with an electronic instrument. This instrument displays the slow neutron count rate. The principle of operation is that the fast neutrons are slowed down by elastic collision with hydrogen atoms, which occur primarily in the water molecules. Thus the count rate is a function of the moisture content of the soil. Proper interpretation in use of this technique requires knowledge of the soil bulk density, so it is common now to have a combined soil moisture-density gage. The neutron moisture gage offers a number of advantages over conventional methods previously described, such as being non-destructive, easily repetitive, rapid and convenient.

The development of methods for satisfactory hydraulic conductivity and diffusivity measurement in the unsaturated zone continues to be an important research need.

Research Opportunities for Application in Developing Countries

The assessment of water movement in unsaturated soils of developing countries is not being seriously impeded either by the absence of knowledge of how to measure, or by the lack of adequate instrumentation. A variety of proven conventional techniques and equipment exist which are relatively simple to utilize and available at a fairly modest cost. In addition, a growing array of nuclear-based instruments are being developed which have already greatly advanced the state-of-the-art in this field by virtue of their simplicity and speed of operation, as well as by their improved accuracy.

Based on this perspective, priority research areas would appear to include: (1) lowering the cost of nuclear instrumentation; (2) development of new methods for measuring hydraulic conductivity and diffusivity; and (3) intensive investigation of the behavior of water infiltrating into, or contained within, a variety of pervasive but poorly understood soils of developing regions (e.g., unique chemical, physicial, and biological properties of lateritic soils).

GROUND WATER

Ground water, or water in the saturated portion of the earth's crust that sustains springs and is tapped by wells, is perhaps the most widespread source of available water for the use of man. Because it must be measured and observed indirectly, however, its physical behavior is not as well understood as that of surface water. Nevertheless, ground water is extensively developed for rural water supplies, particularly in areas remote from perennial streams. Also in arid and semiarid regions, ground-water reservoirs assume special importance, as perennial streams may be widely separated or non-existent, and wells may provide the only dependable source of water for domestic, livestock, irrigation, municipal and industrial use. Even in more humid regions, ground water may be developed in preference to surface water because of easy accessibility, superior sanitary quality freedom from suspended material and relatively uniform temperature. Although ground water is mobile, it generally moves at slower rates and through relatively shorter distances underground than does water in open stream channels. Consequently, it must be used essentially where it is found and hence from a practical standpoint usually is not exportable.

State of the Art

During the past two decades, important emphasis has been given to the search for and the exploitation of ground water in the developing countries, particularly those in the arid and semi-arid tropics. Optimum utilization of the resource demands adequate appraisal through collection of relevant data by appropriate surveys and the analysis and synthesis of such data both before and subsequent to development. Ground water, of course, is a phase of the hydrologic cycle, but the investigation of this water involves techniques and methods that may be distinctly different from those appropriate to other phases of the cycle.

The study of ground water entails evaluation of the interrelations of the biological, physical, and chemical characteristics of the water in terms of its geological environment as well as evaluations of other phases of the hydrologic cycle, both in time and in space. Such study includes as important elements the areal occurrence, rate and direction of movement, the natural recharge-discharge balance, the geochemical balance of dissolved solids in the water resulting from natural and artificial causes, and the hydraulic response of aquifers to man-made changes in the natural regimen.

The techniques employed in ground-water investigations depend in large measure on the relative sophistication, complexity, and scope of the actual or proposed development of a ground-water system. A total evaluation might include surface and subsurface geological, surface and subsurface geophysical, geochemical, hydraulic, and hydrological studies. A simpler ground-water investigation, however, might include only a few selected segments from among these.

Good aerial photography and topographic maps are fundamental to all surveys related to ground water. Also, as the rocks are the natural reservoirs in which ground water is stored, and the natural conduits through which it circulates, knowledge of the geologic framework of a ground-water system is essential to its understanding. Surface and subsurface geologic surveys provide important information on structural features, such as faults, folds, and unconformities, and on the areal distribution of water-bearing formations (aquifers) and associated impermeable formations (aquicludes). All these geologic features affect the head, direction, and rate of movement of ground water; the chemical quality of the water; and the design of development programs.

During the past two decades, geophysical studies have been used extensively in the developing countries in quantitative and semi-quantitative evaluations of ground-water systems. Among surface geophysical methods, electrical-resistivity, seismic, aeromagnetic, gravimetric, and sonar surveys have been employed with varying degrees of success, depending upon accessibility and the geologic character of the area surveyed. Surface electrical-resistivity surveys 1/ are used successfully in one-, two-, and even three-layer systems, where marked discontinuities occur in the electrical-resistivity profile and where the thickness of each layer is appreciable in relation to the depth of the discontinuity. Such surveys are particularly useful in establishing fresh water-salt water interfaces in coastal aquifers.

1/ Electric-resistivity surveys induce electricity into the ground and measure the resistence of earth materials to its flow.

Seismic surveys are used mainly to map discontinuities between impermeable bedrock and overlying water-bearing unconsolidated or semi-consolidated sediments. The method is adequate only where there is a marked contrast in the elastic properties of the two types of rock.

Aeromagnetic and gravimetric methods are also used to locate buried bedrock surfaces where appreciable discontinuities in rock magnetism and density exist in two-layer systems. Aeromagnetic methods are particularly useful where rapid reconnaissance interpretation of the occurrence of aquifers is required over broad regions. Mapping of bedrock surfaces and thickness of unconsolidated overlying deposits by techniques and equipment using low-frequency sound waves also is finding increasing application, particularly in underwater problems in coastal areas. The principles employed are the same as those used in sonic depth finders.

Subsurface or borehole geophysical methods are now widely employed in practically all moderately intensive or detailed ground-water investigations in the developing countries. Electrical logging is perhaps the most useful probing tool in distinguishing aquifer contacts, formation porosity, water quality, and fresh-salt water interfaces in uncased boreholes. Also, this method can be used quantitatively, if other supplementary field data are available. Gamma-ray, gamma-gamma, neutron-gamma, and neutron-neutron logging is also increasingly used for stratigraphic correlation; and for determining porosity, water saturation, bulk density, and water quality in subsurface formations. Proper interpretation, however, of such radiation logs requires a considerable fund of knowledge of the local lithology. Limestones and dolomites, for example, have radioactive intensities similar to sandstone.

The importance of depth-temperature relations in ground-water systems is increasingly recognized, particularly with respect to water viscosity and the effective permeability of aquifers. An important tool in the analysis of these relations is the temperature log, which utilizes conventional electrical logging circuits to measure resistance change of a temperature-sensitive metallic conductor. By this method, which can be used in both cased and uncased wells, a temperature log and a corresponding reciprocal-gradient log are derived. From these logs it is possible to identify the aquifer or aquifers tapped by wells.

Borehole diameter or caliper logging is an important tool in long-range stratigraphic or aquifer correlation. The caliper log is also used to determine the condition of an under-reamed section of a borehole prior to placement of a gravel pack and well casing, and to estimate the volume of cement necessary to fill the annular space between the well casing and the borehole wall. This technique is based on variation of borehole diameter which reflects differences in the lithologic character of the rocks penetrated by the drill.

Another borehole technique of wide application is flow-meter logging which provides a record of the velocity and direction of movement of water in a well. The log may be made while the well is discharging water at the land surface, while water is being introduced, or while the well is idle. The flowmeter log serves to identify and evaluate the aquifers tapped by cased wells having multiple screens, leaks in cased wells, and permeable zones penetrated by cased wells.

Still another borehole probing technique is fluid conductivity logging which provides a record of the electrical conductivity of the borehole fluid at all depths. Such a log provides useful information on the position of salt-water leaks in cased artesian wells, and the depth and relative artesian head of salt-water aquifers penetrated by cased wells. More recently, compact television cameras with wide-angle lenses of short focal length have been designed for on-site inspection of well casings and examination of the lithologic character of borehole surfaces.

One of the more sophisticated techniques now in use in the analysis of simulated ground-water systems and the effects of man-made changes on these systems is the passive element analog model which is based on the direct analogy between electric and fluid force fields. For any ground-water system, an analog model employing resistor-capacitator networks with analysers can be constructed with a degree of complexity dependant upon the nature of the ground-water system and the available basic data. The electric analog model affords a useful means for computing the distribution of potential (or head) at any point in the system under complex boundary conditions, as well as variable recharge and withdrawal by pumping. Increasingly, also, the digital computer is being utilized to analyze hydrologic inter-relationships including streamflow-aquifer behavior.

Knowledge of the chemical characteristics of ground water is very important in planning its optimum development and utilization, and also for understanding and analyzing the functioning of ground-water systems. Geochemical techniques based on the presence of identifiable chemical constituents in minute concentration are particularly useful in tracing the direction and velocity of water movement through the rock skeleton, but must be used in conjunction with adequate geologic and hydrologic knowledge of the ground-water system. Introduced tracers such as salt solutions, fluorescein, and radioisotopes commonly are used for this purpose. For example, radioisotope tracers are being used extensively for geohydrologic studies in many areas of the developing world including the Chad Basin and Nile-Lake Victoria Basin of Africa, the Parana Basin in Brazil, and Cheju Island in Korea. Also radioisotopes, such as carbon-14 and tritium, are proving useful in determining the relative age of water in different parts of a ground-water system and the span of the "life cycle" of such a system.

Chemical quality and temperature relationships also enter into the quantitative evaluation of other ground-water problems, including salt-fresh water relationships in coastal aquifers, base exchange, influx of mineralized waters or brines, aquifers as heat exchangers, induced infiltration, artificial recharge, and disposal of radioactive wastes.

Hydraulically, an aquifer serves a dual role as both a transmission conduit and a storage reservoir. In the former role, it transports water from areas of intake to centers of interception by wells or to areas of natural discharge such as the sea, a stream, a lake, a marsh, or a drain or locale of evapotranspirative consumption. 1/ Secondly, as a storage reservoir, the aquifer provides a reserve of water that may sustain base flow in streams or well discharge during extended periods when net intake from precipitation is exceeded by the aggregate discharge of wells, leakage to the sea, to springs, drains, or streams, and consumptive use in vegetated areas.

1/ "Evapotranspiration" embraces that portion of the precipitation returned to the air through direct evaporation or by transpiration of vegetation, no attempt being made to distinguish between the two.

Because of the importance of the transmission and storage characteristies in the hydraulic behavior of aquifers and ground-water systems, a considerable number of methods have been evolved for the mathematical analysis of problems of fluid mechanics as they apply to ground-water flow systems. To enumerate, borehole and well methods for analyzing aquifer hydraulics include those involving constant discharge or recharge without vertical leakage, instantaneous discharge or recharge, constant head without vertical leakage, constant discharge with vertical leakage, and variable discharge without vertical leakage. Channel or drain methods include those applicable to constant discharge, constant head, and sinusoidal head fluctuations. Numerical analysis and flow-net analysis provide the chief areal methods of aquifer evaluation. Also, the analysis of hydrologic boundary problems has been built on a number of methods involving the theory of images.

Quantitative evaluation of ground-water systems by hydrologic methods has had a considerably longer history of evolution in the developed countries than the genesis and use of hydraulic methods. Appraisal of the ground-water resources requires an accounting of the perennial intake, discharge, and changes in storage with relation to man's existing and future needs for ground-water supplies. In addition, water quality must be adequately defined with regard to temporal and spatial changes in ground-water systems and the effects of such changes on man's use of the water.

Among the methods for evaluating the recharge-discharge balance in ground-water systems are seepage surveys keyed to streamflow records from gaging stations and analysis of stream hydrograph analysis, and water-budget studies. Methods for estimating recharge or discharge from changes in ground-water storage include lysimeter or tank studies, observation-well hydrographs, isopachous 1/ maps of net change in water level, saturation or drainage techniques, and indirect methods. In all storage methods, specific yield must be known to convert changes in storage volume to water volume.

1/ Analoguous to contour lines, but representing thickness.

Instrument and Investigation Costs

The instrumentation and costs for ground-water surveys and investigations run the gamut and depend on such factors as extent of the area to be studied; intensity of areal coverage; and duration of the study. Many ground-water development programs begin with a broad reconnaissance and then are followed by more detailed investigations as development proceeds. It is not uncommon for an investigation of a given ground-water basin to continue over a term of several years. Indeed where intensive ground-water development occurs, as for an example in the Punjab region of West Pakistan, the Ganges Plain of India, and the alluvial plain of Taiwan, almost continuous ground-water observations and study are required to monitor changing conditions during and following development. Representative samples of some of the more common instrument and survey costs (in the U.S.A. in 1971) are given in the estimates below.

Light reconnaissance by one hydrogeologist of 1,000 square miles with minimum instrumentation and no test drilling for a 3-months term----------------------	$ 10,000
Moderately intensive reconnaissance by one hydrogeologist of 5,000 square miles with minimum instrumentation and no test drilling for a 1-year term---------------	25,000
Intensive investigation by 2 hydrogeologists of 10,000 square miles with full instrumentation, hydrogeologic mapping, aquifer testing, test drilling (excluding drilling rig) and report for a 3-year term------------------------	150,000
One weekly graphic water-stage recorder with auxiliary equipment for use in observation well---------------	250
One continuous graphic water-state recorder with auxiliary equipment for use in observation well---------------	700
One borehole geophysical logger, fully instrumented------------------------	6,000

Test drilling:	
One combination percussion-rotary drilling rig------------------------	$ 80,000
Drilling costs, 8-inch hole, per foot	
Dolomite and limestone--------------------------	5
Unconsolidated sediments------------------------	2
Sandstone---------------------------------------	4
Quartzite---------------------------------------	25
Basalt and granite------------------------------	15
Analog model of small ground-water basin----	15,000
Digital model of a stream-aquifer system----	25,000

Recent and Current Research

There have probably been few major break-throughs in ground-water science since the work of C.V. Theis, who founded modern well hydraulics in 1935, and Muskat's and Hubbert's formulation of the theory of ground-water flow in the late 1930s and early 1940s. Nevertheless, ground-water hydrology has evolved substantially toward more sophisticated applications of basic principles during the past two decades.

Most solutions to ground-water problems are concerned with one aquifer. When more than one aquifer is to be considered, a system of simultaneous differential equations with appropriate boundary conditions has to be solved and the results become very complicated and difficult to evaluate. For this reason, practical multi-aquifer problems can only be solved by analog models and digital computers, both of which have been much refined in recent years and are now widely used.

Analog models have been and still are widely used to study ground-water problems. They have the advantage of being pictorial or graphic in the analytical presentation, but they are bulky and difficult to store or transport. Moreover, they lack the mathematical flexibility of digital computers. Thus, digital modelling is currently growing in favor in the analysis of more complex multi-aquifer ground-water problems, as well as surface-water to ground-water and other hydrologic relationships.

Knowledge of hydrodynamic dispersion has advanced in recent years through study of the movements of contaminants in ground-water flow and the intrusion of sea water in coastal aquifers. Solutions for flow equations pertaining to such problems, however, are available only for relatively simple and idealized cases. Practically, it must be assumed that the zone of diffusion between fresh and salty water is very thin and that conditions of immiscible flow prevail. Radioisotopes also have been used to determine specific yield and hydraulic conductivity of aquifers and to identify the origin of saline water that contaminates some coastal aquifers.

In recent years, mathematical solutions have been developed for evaluation of problems in aquifers of non-uniform thickness, with sloping impermeable bedrock floors, with varied lateral replenishment and under various conditions of upward or downward leakage. Non-linearities in ground-water flow have been analyzed by analog models. Also by means of computers it has been possible to arrive at simplified solutions to problems relating to two-phase fluid systems in heterogeneous porous media.

Studies of ground-water in recent years have been predominantly deterministic in their approach. Stochastic processes have been employed in ground-water problems to considerably less degree than they have in surface-water hydrology. There is, however, growing emphasis on the use of statistical methods in the evaluation of ground-water interrelationships.

There are few if any significant research deficiencies in instrumentation and methodology insofar as needs for ground-water exploration in the developing countries are concerned. In the area of ground-water development, a number of such countries -- India, Pakistan, Iran, Turkey, Egypt, Libya, Tunisia and Chile to name a few -- have already embarked on moderate to large-scale ground-water development projects which equal or exceed in scope comparable projects in developed countries.

More critical are institutional and socio-economic factors such as the training and motivation of ground-water scientists;level of technical and administrative support of existing ground-water agencies; and requirements for establishing new institutions at both the national and regional levels.

Research Opportunities for Application in Developing Countries

It was noted earlier in this chapter that there are few significant research deficiences in instrumentation and methodologies with respect to ground-water exploration in developing countries. This does not mean, however, that we know all there is to know about locating and appraising ground-water, and that it is simply a matter of obtaining the necessary tools and applying them. What is meant is that the non-institutional factors encountered in developing countries (e.g., climate, geology, vegetation) are not constraining or limiting with respect to applying the present state-of-the-art. Aerial and ground-based geophysical techniques which have been developed to meet domestic needs of the advanced countries can be applied in developing countries at a reasonable cost, either under contract or by local experts.

The major research requirements and opportunities related to developing country needs are associated with improvement of modelling techniques; description and interpretation of water movement throughout river basin systems of major importance in developing countries; and in the development of new remote sensing techniques for ground-water location and appraisal.

Modelling of ground-water systems, including surface water interactions, is an extremely complex undertaking which requires an expansion of ongoing work. Special attention should be given to the application of both analog and digital models to ground-water systems in desert areas with sandy, porous soils (e.g., Kalahari Desert of Botswana and Southern Africa) and in the vast areas of the developing world underlain by thick sequences of crystalline and volcanic rocks (e.g., Deccan Plateau of India, Ethiopian Plateau; and Southern Brazil.

In view of the rapidly growing demand for water in urbanizing areas of the developing world, model studies should be carried out to determine the water supply/demand relationships for major aquifers, and requirements and options with respect to ground-water recharge.

Since basic data on parameters such as rainfall frequency and amount, rate of infiltration, evapotranspiration, and runoff is essential to building predictive capabilities, an intensification of research designed to expand and upgrade the data base should be carried out for major water systems in developing countries.

Finally, our present technology is incapable of rapidly locating and appraising ground-water reservoirs, regardless of their geographic location. Research has lagged in this field because the advanced countries have not, generally speaking, suffered from insufficient water. Many developing countries of the arid zone do not enjoy this same luxury, and their entire mode of living and economic development is tied to water availability. Thus, new techniques for ground-water identification in the arid zone are urgently needed. New remote sensing techniques (e.g. multi-spectral scanning) offer a potential for rapid reconnaissance over vast areas, and these techniques should be carefully and systematically explored on a priority basis.

HYDROLOGIC APPLICATIONS OF REMOTE SENSING

Remote sensing is the technique of detecting the nature of an object from a great distance without actually touching it. In a restrictive sense, remote sensing activities include only those involving the detection of electro-magnetic radiant energy. Aerial photography, the most widely used form of remote sensing, records an image or picture on film sensitive to the electromagnetic energy constantly emitted in some degree by all objects or matter. Such energy travels as waves, with a spectrum or range of various wave lengths. The longer wave length forms of electro-magnetic energy are known as infrared radiation, microwaves, and radio waves. The shorter wave length forms include ultraviolet radiations, X-rays, and gamma rays.

Instruments are in use that can produce images, both phtographic and nonphotographic, of energy distribution in each part of the electromagnetic spectrum. These instruments include photographic cameras, scanning radiometers, and radars. The observations made with such equipment are limited to the surface or to very shallow penetration. They provide, however, a basis for discriminating among natural materials because of the contrasts, in black and white or in color, produced by the detection of differences in heat radiation and light reflectance from the surface below.

In most instances, as a practical matter, remote sensing data are interpreted and used in conjunction with information from surface observations acquired independently of the remote sensing system. Such "ground-truth" information obtained at precisely known, key locations enables the interpreter to correlate patterns, colors, or shadings on his images or photos with known ground-based phenomena, and to extrapolate to other areas which have not been examined on the ground.

Remote sensing has perhaps the greatest potential of all advanced techniques thus far evolved for identifying, appraising, and monitoring -- on a regional or even continental scale.-- the earth's mineral, land, and water resources and its environmental processes, including the hydrologic cycle. Whereas water development and control has traditionally been carried out on an ad-hoc, local basis, remote sensing now offers a capability for approaching water-resources develop ment and management on a more rational and integrated basis, and also on a regional scale. A number of excellent possibilities in this regard are apparent.

Surveys of Water Resources - As noted earlier, good aerial photography and topographic maps are fundamental to surveys of both ground water and surface water. Remote sensing provides a means for rapid reconnaissance of geologic units, rock structures, surface water, and soil moisture over large areas. This in turn can provide the basis for selecting the most promising areas for more detailed ground-water surveys. Multispectral imagery, from aircraft or satellites, can greatly assist in mapping surface waters and drainage areas, and in planning and managing irrigation and hydroelectric projects. The selection of appropriate remote sensing techniques for these purposes will depend in each case on the types of terrain and vegetation cover, the general nature of the geologic materials to surveyed, and other factors.

The feasibility of using thermal infrared techniques to locate outflows of fresh water along coastal areas has been demonstrated in the Philippines and in the Hawaiian Islands. In these instances, remote sensing revealed discharges of fresh water into the sea in the form of submarine springs or as surface runoff.

Watershed Management - Remote sensing offers a variety of new tools for comparing the moisture input of watersheds with total water availability and potential output for such purposes as hydroelectric power, municipal water systems, irrigation and the other needs of society. In many regions, the accumulation of snow at high elevations provides a major source of water supply. By means of space photography, coupled with a limited ground-truth sampling program, the season's snowpack can be surveyed as to area, depth, and moisture content to provide estimates of expected seasonal runoff. The prediction of flood conditions and the monitoring of flooded areas are important applications of this technique.

In a very large and relatively inaccessable watershed, such as that drained by the Indus River in southern Asia, synoptic satellite observations have been used successfully to monitor total snow-cover, snow line delineation, and other hydrological features. Infrared radiometer images were obtained for this same watershed and used to establish a close relationship between the percentage of snow cover and the mean monthly runoff.

Another application of remote sensing to watershed management involves the analysis of the disposition of precipitation through surface runoff, infiltration, and evapotranspiration. Through remote imagery, a given watershed can be classified by areas of homogeneity with respect to types of vegetation, water absorption characteristics, and runoff coefficients of the ground surface. Equipped with such a classification of the watershed and a table of coefficients, it is then possible to predict the quantities of precipitation which will be absorbed by the watershed and lost through evapotranspiration under varying conditions.

Monitoring Surface Water Resources - Through synoptic coverage of surficial water resources via aircraft or satellite, it is possible to monitor variations in the areal extent of surface water bodies, bank and beach erosion, seasonal variations in sedimentation patterns, and the degree of siltation in reservoirs and waterways. Changes in the distribution and density of water plants or aquatic weeds, and fluctuations in surface water temperature also can be determined.

Remote imagery will reveal the intrusion of salt water into freshwater streams, showing the shape, size, and position of saltwater wedges. The sources and extent of thermal pollution and industrial effluents also can be detected and monitored. In regions where the formation and melting of ice covers is of practical importance, space imagery is a promising technique for the regional monitoring of ice thickness and ice jams, and for tracking ice masses.

Current and potential hydrologic applications of remote sensing are covered fully by C.J. Robinove in his report entitled "Space Technology in Hydrologic Applications" (see Selected Bibliography) and are herein summarized in the tabulation that follows. The tabulation includes both conventional aerial photography as well more as more recently evolved remote sensing techniques which are still in the experimental stage.

A. General Sensor Characteristics and Applications for Hydrologic Studies

Remote-Sensor System	General Comments on Potential Value and Use of Remote-Sensor System for Hydrologic Studies
Panchromatic Photography	Panchromatic photography is the most widely used remote-sensing technique because of its availability and relatively low cost. Interpretative techniques are well developed and formal training in its use is available. Much aircraft data has been taken for many purposes. Some special data and some space data available.
Multispectral Photography	Multispectral photography interpretation requires a background of spectral-signature studies of terrain and water from multispectral systems. Large data return may complicate interpretation. Some experimental aircraft data available, primarily 9-lens photography. Much work has been done with the use of special film-filter combinations for specific purposes. Little work has been done on interpretation for hydrologic purposes.
Infrared Photography	Infrared photography is primarily of value in mapping drainage features and shorelines. The water is always black in a positive print. Some vegetation characteristics are discernible. Its most valuable use is as an adjunct to, but not a replacement for, standard aerial photography. Much aircraft data is available.
Color Photography	Color photography, in spite of its built-in spectral redundance, promises to be a major tool of the hydrologist in many special fields and is sufficiently better for recognition of significant hydrologic features that it may replace panchromatic photography for many uses. The interpretation capability of the potential operational hydrologic users of color photography must be greatly increased. Methods for spectral and density extraction of data are being developed. Much aircraft and Gemini spacecraft data is available.

Infrared-Color Photography

Color-infrared photography may be superior to standard photography in some respects. It shows differences in vegetation more clearly and provides a slightly higher contrast on water surfaces. Its general superiority to standard color photography has yet to be proved but it may be highly useful and is worthy of much additional research. Aircraft data is available.

Infrared Radiometry

Infrared radiometry is very useful for sequential measurements of changes in land and water surface temperatures because it is a simple measurement technique and data reduction simpler than for infrared imagery. Radiometry is routinely used for periodic surveys of near-shore oceanic areas. Data is available from aircraft and from Tiros and Nimbus Satellites.

Infrared Imagery

Infrared imagery has shown its value as a tool for measuring water-surface temperature and as a means of qualitatively differentiating some terrestrial features. The lack of a simple means of determining emissivity hampers its quantitative usefulness. Analytical techniques for proper use of the reduced data need to be developed. Data is available from aircraft and from Tiros and Nimbus Satellites.

Radar Imagery

Side-looking airborne radar has an all weather capability for coverage of large areas. Its ability to penetrate foliage and accentuate topographic features enhances its value. Water-surfaces are excellent reflectors of microwaves, resulting in a uniform black-tone image. For these reasons stream drainage systems and water surfaces are easy to identify. The black-tone precludes measuring the physical, chemical or biologic characteristics of water. Radar may be of value in terrain analysis for ground-water exploration. Aircraft data available for U.S., Brazil, Panama, and Venezuela.

Microwave radiometry and Imagery

Passive-microwave sensors measure the brightness and temperature of terrain and water surfaces. Spatial resolution is lower than infrared systems but radiance is directly proportional to temperature. Probably will find greatest application in oceani and snow-field mapping. Aircraft data is available.

B. Application of Sensor Systems to Measure Physical, Chemical and Biological Water Properties

Remote-Sensor System	Measurement of Physical Characteristics of Water Surfaces	Measurement of Chemical and Biological Characteristics of Water
Panchromatic Photography	Largely unproved, with the exception of the ability to sense streamlines on water surfaces that may be indicative of movement of pollutants or other effluents. Small data use.	Useful only for assessing some vegetation types. Small data use.
Multispectral Photography	Largely unproved but may be useful in special situations Small data use.	May be valuable as a supplement to other photography but specific interpretation criteria have not been developed. Small data use.
Infrared Photography	Not usuable because water surfaces always appear black in infrared photography. No data use.	Not usable because water surfaces always appear black in infrared photography. No data use.
Color Photography	Of some value but rigorous evaluation has not been made. Small data use.	Probably a high potential for use but it must be supported by basic research in the spectral response of waters of various types. Small data use.
Infrared-Color Photography	May provide a higher contrast for mapping of discontinuities on water surfaces than any other type of photography. Small data use.	Probably not helpful in detection and identification of substances in water but may be useful in mapping their distribution. Small data use.

Infrared Radiometry	Valuable for measurement of water-surface temperature but will not achieve its greatest potential until there is full development of analytical equations that express the temperature distribution within a water body as a function of the surface temperature. Moderate data use.	Valuable only if the chemical or biological factors have an effect on the temperature or emissivity of the water surface. Small data use.
Infrared Imagery	Valuable for measurement of water-surface temperature over large areas but will not achieve its greatest potential until there is full development of analytical equations that express the temperature distribution within a water body as a function of the surface temperature. Small data use.	Valuable only if the chemical or biological factors have an effect on the temperature or emissivity of the water surface. Small data use.
Radar Imagery	Water is an excellent reflector of microwaves and, therefore, water surfaces show as a uniform black tone on radar imagery. Radar imagery, therefore, is of little value in measuring physical, chemical, or biological characteristics of water but is useful in locating and mapping areas of open water. Small data use.	Radar imagery is of no value in measuring physical or chemical, or biological characteristics of water. No data use.
Microwave radiometry and imagery	May be used for measurement of temperature. Small data use.	Probably not useful. No data use.

C. Application of Sensor Systems to Assessment of Ground Water, Geomorphology And Liquid-Vapor Transfer

Remote-Sensor System	Mapping and Description of Ground-Water Features	Geomorphology and Assessment of Changes in the Hydrologic Regimen	Measurement of Liquid-Vapor Transfer in Hydrologic Cycle
Panchromatic	Highly useful for hydrogeologic mapping, drainage mapping, and identification of vegetation features associated with ground water. Large data use.	Excellent for measurement of geomorphic parameters. Small-scale photography allows systhesis of large features on a regional basis. Large data use.	Not applicable to this problem.
Multispectral Photography	May be useful but perhaps not superior to panchromatic photography. May be useful in differentiating vegetation types as indicators of ground water.	Not yet evaluated for this purpose.	Not applicable to this problem.
Infrared Photography	Valuable as adjunct to panchromatic photography because some rock units have different contrasts and are, therefore, more recognizable. Moderate data use.	Helpful in addition to normal aerial photography but not normally used alone. Small data use.	Not applicable to this problem.
Color Photography	High potential for hydrogeologic and aquifer mapping as an adjunct to the more readily available standard panchromatic photography. Small data use.	Helpful in determination of types and composition of surficial deposits. Small data use.	Not applicable to this problem.
Infrared-Color Photography	Probably superior to standard color photography in defining vegetation and soil characteristics. Small data use.	May be superior to standard photography. Small data use.	Not applicable to this problem.

Remote-Sensor System	Mapping and Description of Ground-Water Features	Geomorphology and Assessment of Changes in the Hydrologic Regimen	Measurement of Liquid-Vapor Transfer in Hydrologic Cycle
Infrared Radiometry	May be helpful in measurement of soil and ground-water discharge to streams but is less helpful than infrared imagery because of the small area covered and the difficulty of locating the trace of the radiometer on the ground. Small data use.	Probably not useful for this purpose. Small data use.	Helpful in determining radiative transfer of energy
Infrared Imagery	Now being evaluated as a tool for locating points of ground-water discharge to streams. Small data use.	Not yet evaluated. Small data use.	Useful in regional atmospheric physics but not used in small-scale studies. Small data use.
Radar Imagery	Moderately valuable in mapping geologic structure and in some lithologic differentiation for ground-water exploration. Small data use.	Now being evaluated. Small data use.	Not applicable to this problem.
Microwave radiometry and imagery.	May not be useful because of coarse resolution. No data use.	Probably not useful for this surface. No data use.	Usable only for high altitudes. Doubtful use for micro-climate. No data use.

WATER DEVELOPMENT PRIORITIES

The focus of this report thus far has been on the assessment of hydrologic potential in developing countries. Inventorying and appraising the location, amount, quality and overall potential of the water which exists on or near the earth's surface is obviously but a precursor to development of the resource in the full sense of the term. Since water development programs in developing countries are limited by an inadequate capacity to actually obtain, utilize and conserve water, as well as by the aforementioned lack of assessment capabilities, it appears proper and useful to briefly acknowledge several potentially high-pay-off-research areas related to the developmental phase of water resources. These priorities include:

- -hydrological research related to the use of brackish waters for irrigation;
- -desalination of seawater for urban supply in coastal zones;
- -evaporation suppression from relatively small open-water reservoirs;
- -artificial recharge of ground-water reservoirs (aquifers) with surplus or reconditioned surface water;
- -conjunctive use and management of surface and ground water in irrigation systems;
- -analog and digital computer modelling of alternatives in water development and management;
- -optimization of development and management of water resources of desert (non-renewable) aquifers; and
- -optimization of ground-water extraction from aquifers in crystalline and volcanic flow rocks.

Brackish water aquifers are widespread in arid and semiarid regions of the underdeveloped world as, for example, North Africa, southwest Asia and the arid coast of western South America. If strains of salt-tolerant food and fiber crops can be evolved by plant geneticists, such water could be used for extended irrigation in these regions. The disposal of saline waste water from such irrigation projects would constitute an area for applied research.

Desalination technology is rapidly approaching the stage where desalted ocean water may become economic for use in large urbanized and industrialized coastal zones of developing countries. In such situations, the concentration of population, user demand, water availability, and presumably financial resources should converge to offset high water costs. Such desalted water might even be blended with poorer quality water to obtain larger volumes of acceptable or potable quality.

Evaporation suppression is a promising area of research which has important and immediate application in developing countries. The water yield of reservoirs could be markedly increased if it were possible to suppress effectively natural water losses by evaporation. Research in this area is still in its infancy and much more work needs to be done before evaporation suppression techniques can be applied to large man-made reservoirs.

Artificial recharge of ground-water reservoirs with reconditioned waste waters of surpluses of natural surface runoff is now practiced in Europe. Water spreading and recharge wells are the two most common methods used in artificial recharge. Because of cost and the complex technology required, recharge wells probably have limited applicability in developing countries. Water spreading by flooding, basin, ditch or furrow, and natural channels is relatively nominal in cost, however, and has wide potential application. Strong emphasis is now being given to large-scale ground-water development for irrigation and other uses in developing countries such as India, Pakistan, Iran, Egypt, Turkey, Taiwan, Chile, and elsewhere. As such development proceeds and intensifies, increasing attention will need to be given to artificial recharge for replenishment of depleted ground-water storage and for control of water quality. In anticipation of such needs, applied research on artificial recharge methodology appropriate to local hydrogeologic conditions needs to be undertaken in many of the more advanced developing countries.

In most developing countries, surface-water and ground-water resources are considered to be wholly independent of one another and are frequently developed and managed by separate governmental agencies which have very little or no communication with one another. The fact is that streams and ground water are intimately inter-related and inter-dependent in many hydrologic environments. The development and use of one sooner or later effects the other. Disregard of this relationship can lead to disaster, particularly when withdrawals of substantial quantities of water are involved. For this reason the concept of conjunction use and management of all water resources in a given hydrologic basin is gaining increasing favor in the more advanced developing countries, as for example in the Punjab region of West Pakistan, and in the lower Nile Valley and delta of Egypt. The concept needs to be extended, however, to other critical areas such as the Ganges Plains of India, the river valleys of Tunisia and Morocco, and the river valleys and basins of Chile, Argentina and Peru. Through conjunctive use, all the available water resources of a given valley or basin can be developed and managed optimally and equally, but much local research, hydrologic assessment and attention to removing socio-economic constraints is needed to achieve this goal.

Modelling of hydrologic systems through use of analog and digital computers is now well-established in the developed world, but is not widely practiced in the developing countries. There are, however, analog models of the Nubian aquifer system of the Western Desert of Egypt, the Punjab region of West Pakistan, and the Chad Basin of west-central Africa that are functional and that are used extensively for interpretive evaluation of the response of hydrologic systems to development stress. Digital modelling is being employed in Chile to study stream-aquifer relationships in the transverse valleys of the central part of the country and is being considered for use in Argentina and Brazil. Much wider application of modelling is potentially possible in most of the developing countries particularly for guidance of water managers in making optimum choices from among arrays of alternativesin water-resources development.

Many productive aquifers in arid regions of the world contain large volumes of excellent water in storage which can be tapped by well-known deep well extractive techniques. The water in such aquifers is, however, non-renewable under prevailing climatic conditions. This water is not naturally replaced once it is withdrawn and hence must be considered a "wasting asset" just as any other mineral commodity. Aquifers of this type are wide-spread in North Africa beneath the Sahara and in the deserts of eastern Saudi Arabia and elsewhere in southwest Asia. Development of water from such aquifers must be undertaken with the full understanding that ultimately the supply will be depleted, usually within a term of a few decades, and that capital investments will have to be amortized within the life-span of economic withdrawal. Development of such aquifers is now proceeding apace in several parts of Algeria, Libya, Egypt and Saudi Arabia, but frequently with inadequate foresight and understanding of the hydrologic and socio-economic implications of ultimate depletion.

Many arid and semi-arid areas in the developing world are desperately short of water, yet lacking in perennial streams or productive aquifers that might be tapped for irrigation or public water supplies. Such areas which characterize large parts of sub-Saharan Africa, western Saudi Arabia, western India and elsewhere are commonly underlain by crystalline or volcanic flow rocks which form poor or mediocre aquifers. They could benefit substantially by creation of large subsurface cavities for water storage, possibly through underground nuclear explosions. Another possibility is explosive-induced fracturing in near-surface impermeable zones, and creation of shallow craters into which water could be accumulated for percolation and storage underground. Such techniques may be uneconomic at the moment and would have to take into account national and local political sensibilities involved in the utilization of explosives on a large scale, particularly those of a nuclear type. They have, however, considerable future promise and need to be fully evaluated.

CONCLUSIONS

Many conventional techniques for the measurement and evaluation of basic hydrologic parameters as well as for the assessment and monitoring of water resources potential are directly applicable to the needs of developing countries. In those countries with adequate manpower and institutional capabilities and with the necessary investment resources, approaches to water resources assessment and development can essentially parallel the approaches used in developed countries. Unfortunately, few developing countries have these characteristics, and therefore they have been obliged to attempt to utilize off-the-shelf technologies in an *ad hoc* and piecemeal fashion as the need for specific bits of data climbed higher on the overall development priority ladder.

Clearly, a principal thrust of efforts to upgrade hydrological assessments in developing countries should be a strengthening of local capabilities to use the fruits of the decades of research directed to similar problems in developed countries. However, this will be a long and extensive effort and will always be faced with the need for foreign exchange investments to acquire the necessary equipment. Thus, a complementary approach should be undertaken in the field of adaptive research -- a type of research to which developed country specialists have devoted only minimal attention. This research should emphasize techniques which are capital-saving, which stress limited improvement in assessments rather than high precision, and which provide data in a form usable by operating agencies which have minimal technical capabilities.

The previous sections identify several interesting approaches to this type of adaptive research. While the developed countries will continue to push the frontiers of hydrological science without the need for intervention by foreign assistance agencies, the benefit to the developing countries of the hydrological sciences will depend in significant measure on adaptation of well established and still undeveloped approaches to match their particular manpower, institutional, and financial capabilities.

The impetus for greater investment of talent, time, and financial resources in adaptive research will require action at a number of levels. Expanding the awareness of research opportunities and technology needs in this field among the scientific and development assistance communities is a prerequisite. Hopefully, this report will contribute toward that objective. Increased attention to the freer and more rapid dissemination of the results of water research investigations throughout the international scientific community is also required.

Although scientists and technologists in the advanced countries can, with proper direction and support, be expected to pay greater attention to the particular needs of the developing countries, solid improvement will probably be made only through the initiative of the developing countries themselves. The continuing evaluation and articulation by these countries of constraints and requirements they face with respect to water resources development is of fundamental importance. Ultimately, however, the degree of improvement will hinge on the capacity of the developing countries to build indigenous capabilities which will allow them to address their own particular problems with R & D programs, and to adapt foreign technologies as required. Consequently, institution building and manpower training should be viewed by both developing countries and assistance agencies as key components of development planning in the water resources field. As such, the strengthening of existing facilities or the establishment of new institutions, and the training of professional and sub-professionals, warrant priority attention both through the pursuit of specially designed projects, and also through their inclusion as basic components of all water research and development projects in developing countries.

Finally, water *assessment* is but one aspect of water resources development. Attention must be paid concurrently to requirements for improved methods and techniques for harvesting, controlling, conserving, and protecting the resource; an increased effort in one area should not be at the expense of the others. Effective use and management of water resources requires a strong, balanced, across-the-board supportative infrastructure of research workers, planners and managers, institutions, and laws. This particular report has focused, by design, on a single section of a spectrum of requirements -- the assessment of hydrological potential -- not because it is the *most* important aspect, but because it is *an* important aspect, and by virtue of its current relative neglect, an area in which additional research can have significant payoffs.

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APPENDIX C

SOLUTION OF ENGINEERING PROBLEMS

In developing an applied research program, the steps to be taken are essentially identical to those taken in solving enginering design problems. This process has been step-wise delineated by many authors. (Woodson, 1966, summarizes those of nine writers). The steps suggested by Buhl (1960) are listed below.

a. Recognition
b. Definition
c. Preparation
d. Analysis
e. Synthesis
f. Evaluation
g. Presentation

The first step in a solution is to recognize that the problem exists, and further that there is a necessity to do somethin about it. It is axiomatic that a problem will be initially unclear--that is, it will be difficult to define exactly what the problem is. However, there will be a general feeling that there is a "mess" that needs tidying. Recognizing the true needs which are to be met is a large step toward the solution of most problems. Questions that must be answered are similar to the following. "What is the need that is to be satisified in this problem?" "What are the disadvantages of the present solutions (if there are any) to this problem?" "What compromises have been made in the present solutions and what compromises are necessary in future solutions?" "Can we improve current solutions by increasing the efficiency of the system, by reducting costs, by making better use of labor and resources?"

Once questions such as the above have been answered, it is possible to take the second step--redefinition of the overall problem as sub-problems, in familiar terms and symbols. Goals are delineated and necessary limitations and restrictions to the solution of the problem are clarified. Sentences such as the following must be completed. "The purpose of this design is....." "The following obstacles or sub-problems must be overcome:....." "The following limitations or specifications will have to be met:...." In a program of engineering irrigation planning the sub-problems will center around those functions already mentioned--supply, storage, transmission, production and reclamation. Each of these sub-problems may in turn be sub-divided further, perhaps according to scales, perhaps according to some other criteria. As an example, the production function might be broken down on the basis of the transmission of water to fields and the distribution of water within fields.

The preparation stage is basically one of accumulating information which will be useful in the solution of the problem. One first determines what facts are known and then what additional facts are needed. Possible useful physical laws and effects which apply to the problem should be considered, along with extant methods of analyzing the problem. If there are solutions to problems in any way similar to the current problem, these solutions should be considered. The quantity of information that can be gathered in this manner will overwhelm the investigator and so it must be carefully weighed before being accepted. The investigator should ask questions such as the following: "Is the information reliable?" "Will it contribute significantly to the solution of this problem?" "Is this information so remote as to be of only marginal importance?" Often, this step will take as much time as the solution steps which follow. In fact, this is a step which is returned to frequently in order to fill gaps that are unknown when a solution is attempted.

Once the preparatory material has been gathered, analysis of it in light of the defined problems and their interrelations must be made. This requires a comparison and evaluation of the information bearing on the solution. It is extremely important that the material be related to the sub-problems as previously defined. Otherwise, the task of relating materials and problems will be insurmountable.

The next step is synthesis, the actual process of arriving at solutions. Solutions of specific sub-problems, based on the analyzed information, are made. Suppose our problem is to determine the appropriate length of run and flow into a furrow in order to give good distribution under a certain set of soil and antecedent moisture conditions. Our literature search has shown that this problem has not been solved analytically. We go to another method of solution, and the most immediately obvious one is the use of empirical methods. We also have in our compendium of useful information a handbook in which methods of evaluating furrow irrigation systems are suggested. This gives an approach to determining the proper lengths of run, inflow rate, etc., for a given set of field conditions. We have a solution, and are ready for the next step.

Evaluation of our solution is equally as important as arriving at a solution in the first place. We must ask the following questions. "Will it do the job?" "What can I compare the solution to which I know works?" "What checks can I make on the analysis and the solution arrived at?" "Does it meet specifications?" "Will it work in actual practice?" "Is it a balanced solution?" "Is it simple--the simplest way of solving the problem?" Negative answers to any of these questions will imply that the solution will probably need refining. This may require the accumulation of additional data (preparation) with the corresponding analysis of that data, or it may merely mean the synthesis of another solution, which will again be evaluated. Evidently, arrival at a solution which is satisfactory is an iterative process.

When we are satisfied with our solution we must present it to others in order to have it executed. The presentation audience can be of group of company executives, other scientists, farmers, etc. It is obvious that the particular method of presentation will be dictated by the backgrounds of that audience.