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DRAINAGE AND SALINITY PROBLEMS IN IRRIGATED AREAS

HOW TO AVOID OR MINIMIZE THEM

by

J. E. Christiansen
Professor Emeritus

and

Edwin C. Olsen III
Associate Professor

Department of
Agricultural and Irrigation Engineering

Utah State University
Logan, Utah

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INTRODUCTION

Agricultural drainage is required in both irrigated and non-irrigated areas for removal and disposal of excess water from the land. The sources of excess water may be from precipitation or irrigation. These sources may occur on the land in question or on higher land, and affect the area by either surface or subsurface flow.

In irrigated areas drainage is required for two distinct purposes:

1. To maintain an aerated root zone.
2. To provide for the removal of salt from the root zone in order to maintain a favorable salt balance.

A discussion of drainage and salinity requires the use of a number of technical terms not in common usage. To clarify this discussion some of these terms are defined in the Glossary of Terms, Appendix I. They are listed in approximate alphabetical order by main headings but not by paragraph headings. Many of the terms are defined very briefly, but are discussed in more detail in the report.

This discussion is not intended as a manual or handbook on drainage and salinity. It is intended as a guide for those interested in developing irrigation projects, and for those who are concerned with such problems in irrigated areas. Suggestions are made as to what might be done to minimize drainage and salinity problems. The reader is referred to literature that discusses certain subjects in much more detail.

DRAINAGE PROBLEMS IN IRRIGATED AREAS

Necessity of Drainage

One might start with the thesis that all irrigated land needs drainage for two purposes: (1) the maintenance of an aerated root zone and (2) the maintenance of a salt balance at a low salinity level. Irrigated areas, however, often have adequate natural drainage and no man made works are necessary to maintain adequate drainage conditions. Such areas are very fortunate because man-made works could be considered as a necessary evil. To achieve completely adequate drainage may be very expensive and not feasible or economical under present conditions. Many drainage systems provide only a partial solution of the problem and are in a sense a compromise between a desirable solution and what can be financed. Since drains increase in cost very rapidly with depth, most drains do not maintain the water table at the most desirable depth but at a somewhat lesser depth which might be considered marginal. If one were to plot both the cost of a drainage system and the benefits to be gained against the depth at which the water table could be maintained, the graph might look like that illustrated in Figure 1.

At some point, the cost of maintaining the water table below a given depth would exceed the benefits to be gained. The point of intersection of the two curves could be considered the optimum depth at which the water table should be maintained. Both curves, however, would be difficult to define and the point of intersection might vary appreciably with specific conditions, such as water quality and crop grown.

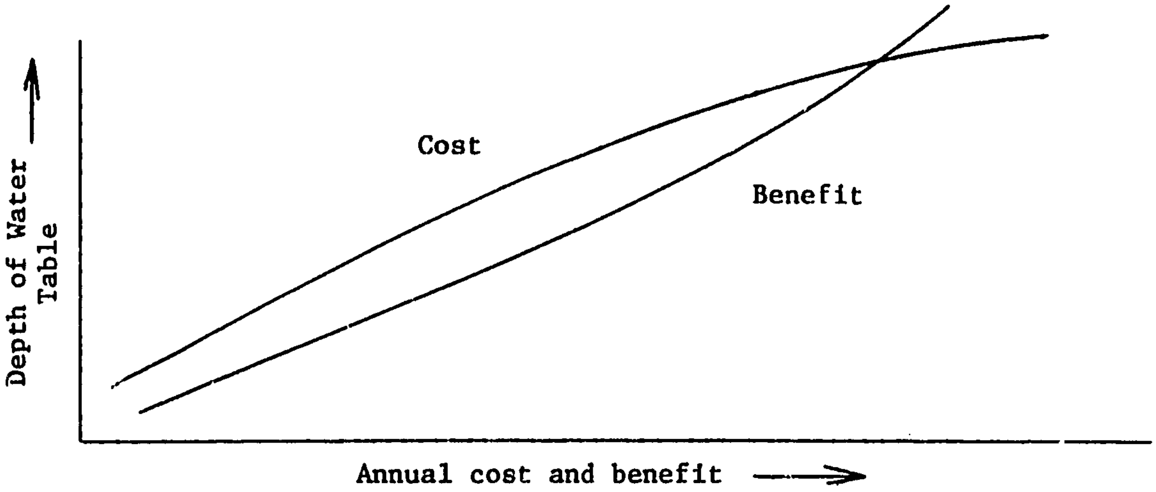

Figure 1. Generalized relation between cost and benefit as depth of water table is increased

Basic Considerations

There are two sets of conditions that will be discussed. One is an existing irrigation project where drainage has not been adequate, and where both a high water table and salinity conditions have developed. What should and what can, under financial restraints, be done to improve this situation?

The second condition would be that of a proposed project where the land is not presently irrigated. What considerations should be given to drainage at this stage in the development?

In many instances, insufficient attention was paid to drainage requirements before serious problems developed. In some cases serious salinity conditions could have been prevented if the need for drainage works had been anticipated at the beginning, and if proper steps were taken to minimize the problem at an early date.

EXISTING IRRIGATION PROJECTS

In an existing irrigation development where drainage and salinity conditions have developed in parts of the area, it is urgent that steps be taken as soon as possible to diagnose the problem and to do what is feasible to rectify it. The first step would be to determine the magnitude and cause of the problem. The second would be to decide what should be done. The third step would be to undertake the necessary works at the earliest possible date because delay would generally lead to an increase in the affected area and an increase in cost of the necessary works. Drainage systems pose many problems in design that are not present in the design and construction of irrigation systems. Hence the construction of drainage systems must often be accomplished over a longer period of time on a learn-how as you go basis.

Drainage Investigations in Irrigated Areas

The investigations to be undertaken in presently irrigated areas should be for the purpose of answering the following questions:

1. What is the basic or principal cause of the problem?
2. What is the main source of the excess water? Is it from
    a. excess irrigation?
    b. seepage from unlined canals?
    c. precipitation?
3. What is the present condition?

   a. size of the area needing drainage?
   b. depth to water table over this area?
   c. annual fluctuation of water table?

4. What is the quality of the irrigation water?
   a. salinity?
   b. sodium status?
   c. boron?
   d. classification?
5. What is the nature of the soil profile with respect to its drainability?
   a. texture and stratification?
   b. presence of underlying barriers to downward water movement?
   c. geology to greater depths to determine presence of aquifers, etc.?
6. What is the salinity and sodium status of the soil?
   a. soluble salts in the soil profile?
   b. sodium status, soluble and exchangeable sodium?
7. What about the topography?
   a. are adequate topographic maps available?
   b. average slopes?
   c. presence of natural surface drainage channels?
8. What might be done to improve conditions?
   a. improve efficiency of irrigation?
   b. line irrigation canals to reduce seepage?
   c. improve natural drainage by cleaning and deepening natural channels?
   d. construct a main network of deep open drains?

e. Install tile drainage system, now or in the future?

f. Pump water from wells to lower water table?

    1. What about quality of water from wells?

    2. Could it be reused for irrigation?

    3. Availability and cost of energy for pumping?

    4. Relative cost as compared with other drainage system?

    5. Relative benefit?

FIELD STUDIES AND OBSERVATIONS

Observations of Natural Conditions

The presence of a high water table in an irrigated area can be detected by observing the following:

1. Water levels in ponds, streams, existing wells, and drainage channels relative to the surrounding ground level.
2. Presence of natural springs or flowing wells.
3. The presence of marshy areas having luxuriant aquatic weed growth.
4. The presence of large trees that can tolerate and thrive under high water table conditions .
5. Presence of barren areas with a salt crust on the surface.
6. Presence of abandoned areas with only salt tolerant species.
7. Presence of dwarfed or dead trees that cannot tolerate a high water table or saline conditions.

These observations generally indicate that drainage and/or salinity problems exist, but in themselves are not adequate to determine the magnitude of the problems, or what should be done to improve the conditions.

Water Table Observations

Water table observations can best be made by installing suitable observation wells in which measurements can be made over a period of time to determine the water table levels as they fluctuate seasonally. Generally, it is not sufficient to use uncased auger holes which may provide some information at a given time, but which fill-in or become lost, and are not suitable for monitoring over a period of time.

The following procedure is suggested:

1. Install permanent observation wells in which readings can be taken at appropriate intervals.
2. Locate these wells where they do not interfere with cultural practices, and where damage by vandalism would be a minimum. They should be on an approximate grid pattern over the area in question, although this is sometimes difficult to achieve.
3. The spacing should be such that water table maps could be prepared to show both highest and lowest levels during the irrigation and/or the rainy season.

Observation Wells

A type of observation well that has been found desirable consists of a small diameter (20 to 40 mm) rigid PVC plastic tube, perforated to within one meter of the surface. It can be installed in an auger hole, 75 to 100 mm diameter. This type of tubing is available in six meter lengths. Preferably, where soil conditions permit, the hole should be augered to a depth of about 3 meters so as to provide for readings below the desired water table level or drain depth. About 10 cm of sand or fine gravel is placed in the bottom of the hole and the plastic tube firmly placed on this bed in the approximate center of the hole. This will prevent subsequent settlement of the tube and provide a stable level from which measurements are made. The annular space around the tube is filled with a sand, or a sand-gravel mix, to within about 1 meter of the surface, then with the soil augered from the hole.

Perforations can be readily made in this tubing with an electric drill, by driving a nail through the wall, or by cutting a slot with a hack saw. All these methods are rapid and have proven satisfactory.

Leaving the top of the tube from 10 to 20 cm above the ground level facilitates the measurements, but this often results in damage or destruction of the wells by vandalism. Such wells also may be damaged by machinery when it is necessary to place them in cultivated fields. Under some conditions it has been found necessary to keep the tops at about ground level and to cover them to hide them from view. Protecting the top with a short length of steel pipe may be found desirable. The top should be covered with a suitable plug or cap to keep out insects and debris.

Locations along fence lines, away from irrigation canals and drains, are often feasible. Wells should be located where they are accessible during rainy periods, or after the irrigation of nearby fields. Locations that require walking a considerable distance from the nearest roadway are not desirable, but sometimes cannot be avoided. When it is necessary to place them in cultivated fields, they should be protected by posts.

Records

Permanent records of observation well measurements should be kept, preferably in a bound notebook. The notes for each observation well should include:

1. Permanent identification number, date of installation, and by whom.

2. Location sketch showing distances to at least 2 permanent objects (if feasible) so well can be relocated if lost or destroyed.
3. Elevation of measuring point, usually the top of the tubing.
4. Approximate average ground or field level in vicinity of the well. Usually this is not the same as the ground level at the well, but it is more meaningful.
5. Date of measurement.
6. Distance from the measuring point to the water level.
7. Space for elevation of water level to be recorded. This is usually done in the office.
8. Space for remarks.

A good set of field notes is greatly appreciated when these records are summarized or transferred to maps at a later date.

Groundwater Piezometers

Sometimes groundwater movement may be either upward or downward within the saturated zone. For example, water infiltrating into the soil at a higher elevation may enter an aquifer and then move horizontally under a stratum of low permeability to a lower part of the area, and then slowly upward through this confining layer. When the hydrostatic pressure in the aquifer is above ground level it may produce flowing wells or springs. The water table under such conditions may be near the surface and the principal outflow of groundwater may be by transpiration from vegetation and evaporation from wet soils. This situation usually leads to saline and sometimes sodic conditions because this outflow does not remove salt.

Under such conditions, conventional drainage methods are not always effective, and where possible, the better solution may be to pump water from the underlying aquifer to lower the hydrostatic head.

Groundwater conditions of this kind can best be investigated with piezometers with which the vertical hydraulic gradients can be determined.

Groundwater piezometers are used in much the same way as observation wells, but the water level in the piezometer is not necessarily the water table. It may be either higher or lower depending on the vertical direction of flow. With two or more piezometers, installed to different depths at the same location, the existence and magnitude of vertical hydraulic gradients can be measured. Under some conditions, the groundwater under high water table conditions may be moving slowly downward into a more permeable aquifer under a lower hydrostatic head. The use of piezometers for groundwater investigations has been discussed by many writers including Christiansen (1943), Donnan and Christiansen, (1944), Pillsbury and Christiansen (1947), Grassi (1969), and the Soil Conservation Service, U.S. Department of Agriculture (1973).

Piezometers are very satisfactory devices for use in groundwater studies. Where vertical hydraulic gradients are negligible or of no importance to the studies, they can perform the same function as a perforated observation well. When properly used for this purpose they are generally much more economical than observation wells. The time required to install a piezometer to a depth of 2 to 3 meters is usually much less than is required to install an observation well. The materials used, a 3/8 or 1/2 inch galvanized pipe, may be less expensive than the larger diameter plastic tube. The important saving, however, is in the labor cost of installing piezometers in comparison with observation wells.

Piezometers have some disadvantages. They tend to seal up at the lower end and may require fairly frequent checking and cleaning to obtain reliable records. A careful inspection of the measurements, when they are being made at frequent intervals, will usually indicate when they become insensitive to changes in the groundwater pressures. This condition can be readily checked in the field by filling the piezometer with clean water and observing the rate of drop in the pipe. If the rate of drop is much slower than normal, the flushing tube is inserted and the piezometer is flushed again and afterwards checked for sensitivity by refilling. In some very tight strata, piezometers are so insensitive that they cannot be used successfully.

Installing Piezometers

Driving Piezometers.

The procedures for installing piezometers is described here very briefly. For piezometers not more than 4 meters in length, and for most soil conditions, they can be driven into the soil with a special driving hammer. Sometimes very hard strata are present and driving is slow and difficult. For lengths up to about 3 meters they can be in one piece, for 4 meters they could also be in one piece and started from a portable platform or step ladder. Longer ones, can be started in shorter lengths and connected with conventional pipe couplings. A special driving head can be used to protect the threads when they are to be connected, and a pipe die should be used to clean the threads after driving before the next section is connected.

Another method of driving piezometers is with a special driving hammer with a hole in it so that it can be slipped over the piezometer. The driving is done on a special hardened clamp on the piezometer. With this equipment, full length pipes, 21 feet (6 m) can be started from the ground. The clamp is moved up the pipe in increments of about one meter as the piezometer is driven into the soil to the desired depth. This method, together with the first one described, is discussed and illustrated by Grassi (1969).

Jetting Piezometers. When a large number of piezometers are to be installed to depths of 2 meters or more, installation by jetting is to be preferred. This requires a portable source of water (tank or barrels on a pickup truck) and high pressure pump that can deliver a flow of 5 to 10 gpm (0.3 to 0.6 l/sec) under a pressure of 100 psi (7 atmospheres) or more. A positive displacement pump with by-pass valve or high pressure centrifugal pump is satisfactory. The pump is connected to the piezometer with a high pressure hose and the piezometer is held in a vertical position and with an alternate upward and downward motion is pressed into the soil. The water jetting from the end of the pipe creates a hole in the soil and it flows upward around the outside of the piezometer carrying with it the soil removed in suspension. When the piezometer has penetrated to the desired depth, the valve on the pump is closed rapidly and the soil in suspension around the pipe is allowed to flow back into the annular hole around the pipe to provide a seal around the piezometer. Additional soil, preferably clay or silt, can be washed down into this annular space to fill it. This filling and sealing of the annular space around the pipe is very important when piezometers are used to measure vertical hydraulic gradients, but of no importance when the piezometers are used only as observation wells for water table measurements. In this case it is better to install them to a depth of about a meter below the lowest water table level expected and to allow the jet stream to remove all of the sediment from the annular space and then fill it with sand.

Drainage Maps

There are three kinds of maps that are very useful in drainage investigations. They are:

1. Topographic maps of the ground surface.
2. Water-table contour maps.
3. Depth-to-water-table maps.

The topographic map of the ground surface is essential because it shows the natural surface drainage features. The water-table contour maps are essentially topographic maps of the water table and they show the direction and gradients of ground water flow. The depth-to-water-table maps show conditions with respect to the adequacy of the drainage, and especially the critical areas where the water table is near the surface.

The scales and contour intervals of these maps will vary with the area covered and the average slope of the contoured feature. For relatively small areas, and for sections of larger areas where considerable detail is desirable, a scale of 1:10,000 (10 cm = 1 km) and a contour interval of 10 to 50 cm., depending on the slope, is desirable. For larger areas, and where considerable detail is not warranted, scales of 1:20,000 to 1:100,000 are suitable, and contour intervals of 20 to 100 cm may be more appropriate.

Topographic maps are essential to the solution of surface drainage problems. They show all surface features, especially the natural drainage channels that may need cleaning or deepening. They are also very useful in locating a main network of deep open drains. In general, the main drains should follow the natural surface drainage and connect the depressions. Where topography permits, they should follow field boundaries and roadways. Without good topographic maps, it is difficult to decide on drain locations.

Water-table Contour Maps show directions of flow and hydraulic gradients. Often, they reveal the principal sources of groundwater, such as seepage from canals where they cross gravelly areas, etc. They may, in connection with soil profile studies, indicate whether interceptor drains, or relief drains, would be most appropriate.

Depth-to-water-table maps show by contours the depth to the water table, and hence the adequacy of drainage. They reveal the critical areas where the water table is nearest the surface, and where remedial action should be undertaken at the earliest possible time.

The depth-to-water-table maps are often colored to show ranges in depths. Examples of all three kinds of drainage maps are shown in Figures 2 to 4.

Unlike topographic maps, the water-table contour maps and the depth-to-water-table maps represent transient conditions. They show conditions existing at a certain time, or for example, they may be plotted to show the highest water table conditions during the irrigation and/or the rainy season.

Water Quality Criteria

Sometimes the quality of the irrigation water used is largely responsible for the salinity conditions, especially where the drainage is inadequate. In any drainage investigation, the quality of the water should be determined, if not already known. The extent of these investigations might vary from a few conductance measurements during the irrigation season, where the conductance is low and the quality obviously good, to more detailed studies where the quality is marginal or poor.

Complete analyses of water samples are very desirable. Conductance determinations alone may be misleading. They do not reveal the sodium hazard or a possible high boron content. Complete analyses should include, on a limited number of samples taken at different times during the irrigation season, the following determinations:

a. Electrical conductance

b. Cations: Ca^{++}, Mg^{++}, Na^{+}, K^{+}

c. Anions: HCO_3^{-}, CO_3^{--}, Cl^{-}, SO_4^{--}

d. Total dissolved solids

e. Boron

The conductance of water samples is usually reported in micromhos per cm at 25°C (EC x 10^6), but it may be stated in mmhos/cm, (EC x 10^3). Total dissolved solids are determined by evaporating to dryness a given amount of water and is usually reported in parts per million (ppm) or its equivalent, milligrams per liter (mg/l). It is a check on the conductance measurement since one mmho (EC x 10^3), or 1000 µmhos (EC x 10^6) averages about 640 ppm. A large departure from this relationship would indicate an error. Total dissolved solids always includes dissolved silica, which may be negligible.

Determinations of the soluble ions should be reported in milliequivalents per liter (me/l) rather than parts per million (ppm). This provides a ready check on the accuracy of the determinations as the sum of the cations should equal, approximately, the sum of the anions. Absolute equality is not to be expected because the accuracy of determination is not absolute, and also because small amounts of other salts including nitrates may be present. Nitrates should be included in the analyses, and possibly fluorides, if the water is used for human consumption. A difference of more than five percent in total anions and cations would suggest that the determinations should be repeated for a check. When there is absolute equality, it suggests that one of the ions was not determined but was calculated by difference. This practice provides no check on the accuracy of the analyses and should be discouraged.

From the determinations mentioned, the following values can be computed:

a. Percent Na, percent of total cations
b. Sodium adsorption ratio, SAR
c. Residual sodium carbonate, Na_2CO_3
d. Effective salinity, me/l

Water Quality Classification

The writers have proposed the classification scheme as given in Table 1.

Table 1. Proposed Classification of Irrigation Waters, Maximum Values.*

Classification	EC µmhos	Na^+ %	SAR	RSC me/l	Cl^- me/l	Eff.Sal. me/l	Boron ppm
1	500	40	5	0.5	3	3	0.5
2	1000	60	10	1.0	5	6	1.0
3	2000	70	15	2.0	10	12	2.0
4	3000	80	20	3.0	15	18	3.0
5	4000	90	30	4.0	20	24	4.0

* See Definition of Terms for column headings

This classification considers all of the parameters that are normally considered detrimental. It differs from the Salinity Laboratory Classification, SLC, (Richards, 1954) in that it does not attempt to combine the salinity and sodium hazard into a single class such as C1-S2 (conductance-sodium hazard, as SAR). In the proposed classification, a water might be classified as No. 1 or No. 2 for all parameters except for sodium percentage or residual sodium carbonate (RSC). That was the case with a well water from Guatemala which was classified No. 1 on the basis of conductance and Chloride, Cl^-, No. 2 on SAR and effective salinity, but was No. 5 on sodium percentage and No. 4 on residual sodium carbonate. According to the SLC, this water was rated as C2-S1. The water proved detrimental to the soils and its use was discontinued. (Christiansen and Olsen, 1973)

In judging the suitability of a water for irrigation, one must also take into consideration the soils on which it is to be used, the adequacy of drainage, and the crops to be grown. A water classed No. 1 should generally be satisfactory for all soils and crops when drainage is adequate. Soils rated No. 2 or 3 for any of the parameters must be used more cautiously.

For example, a water rated No. 3 on the basis of conductance and SAR, or one rated C3-S3, according to the SLC, might not be injurious to a fairly salt tolerant crop on a permeable soil with adequate drainage. It probably could not be used successfully on a clay soil with a marginal drainage, or for a salt sensitive crop. If it is rated No. 3 on the basis of sodium percentage it is more likely to develop sodic conditions, especially on easily dispersed soils such as silts where low infiltration rates might develop. A water with a low conductance but relatively high sodium percentage has a greater tendency to disperse soils than a more saline water.

Highly saline waters, that might be classed No. 4 or 5 on the basis of conductance, effective salinity and Cl^-, might be used on some salt tolerant crops on sandy soils where the water table can be maintained well below the surface.

In one locality a water that would be classed as No. 5 on the basis of conductance and SAR was being used with fair success on a salt tolerant crop under excellent drainage conditions when large applications of water were made by flooding to provide continuous leaching. In this instance the water was pumped from a well, and the water table was more than 15 meters below the surface. Saturation extracts from the soil irrigated had a lower conductance than the irrigation water.

Soil Profile and Drainability

A knowledge of the soil condition is important in drainage investigations. Ordinary soil classifications for agricultural purposes are not adequate where drainage is needed because they include profile depths to only one or two meters. The drainability of a soil, where open or tile drains are used, depends much more on the hydraulic conductivity of the soil below the drain depth, than upon the permeability of the upper two meters of the profile. Highly permeable strata at depths of 5 to 10 meters may be very effective and permit wide spacings of drains. A stratum of very low permeability (barrier) at a depth of 2 or 3 meters underlying a fairly permeable soil, may require a relatively close spacing of drains because of the shallow depth through which the horizontal flow must take place.

Drainage investigations should include a sufficient number of soil borings to depths of 5 to 10 meters, depending on the depth to the first stratum of relatively low permeability, and where possible a few deep borings to determine whether or not a suitable aquifer may exist from which a satisfactory drainage well could be developed. In some cases the well logs from existing deep water wells in the area can supply this information. Drainage wells have many advantages as compared to other types of drains and the possibility of developing this kind of drainage should always be investigated and evaluated.

Auger-hole Tests

The most common method of evaluating the hydraulic conductivity of a soil in place in order to estimate the required drain spacing is by the so-called auger-hole test. When such tests are carefully made under soil profile conditions that are favorable, they yield valuable information regarding possible spacings of drains. Unfortunately there are limitations to such tests. If a barrier is present at depths of 3 or 4 meters, and the hole is made to this depth, the average hydraulic conductivity can be determined quite accurately. The soil profile must be such that the hole does not cave in when the test is performed, or a suitable well screen must be used. To make holes to depths of more than 2 meters, and to install and extract suitable screens, may require special drilling equipment, such as has been developed by the U.S. Bureau of Reclamation. Such equipment is generally not readily available, and often auger-hole tests are made on rather shallow holes. More permeable materials at greater depths that may be very important to the success of drainage are overlooked.

A recent report by Enos J. Carlson, (1968) of the U.S. Bureau of Reclamation, showed that horizontal drains installed to a depth of 8 feet (2.4 m) would be effective in removing saline water from an aquifer at a depth of 40 to 80 feet (12 to 24 m) underlying a finer textured soil. In a model of uniform material representing a prototype, with drains at a depth of 8 feet (2.4 m) and a spacing of 630 feet (190 m), saline ground water was removed from the soil midway between drains to an equivalent depth of about 60 feet (18 m). These figures are mentioned to indicate that with permeable materials to a considerable depth, horizontal drains at conventional depths of 2 to 3 meters are effective in removing saline groundwater to many times that depth, except just under the drain. Since hydraulic conductivity (permeability) is fairly well correlated with texture, soil profile studies that determine soil texture classifications with depth are useful in judging the drainability of the soil. The limitation is generally the inadequate depth to which soil texture determinations are made. Sometimes, however, the soil structure has a greater effect on permeability than texture. (Christiansen, 1947).

Soil Salinity

A knowledge of the present soil salinity is essential to any drainage study. This generally requires the collection and analysis of a large number of samples from sites representative of the area under investigation. Such samples should be taken to a depth of about 2 meters with a limited number to greater depths, 3 or 4 meters, providing equipment is available to sample to these depths.

If the purpose of the salinity survey were only to evaluate present conditions, conductance determinations on saturation extracts of samples based on textural stratification might suffice. The writers believe, however, that salinity is a dynamic condition that can and should be changed with improved water management. In order to make comparisons of before and after treatments, such as before and after drainage followed by leaching, or before and after more efficient water applications, conductance measurements on *fixed ratio* extracts, such as 1:1 extracts, permit a more accurate determination of the amount of salt involved. Instead of trying to sample separately the different textural classifications of the profile, samples taken to specified depths, such as 0-50, 50-100, 100-200 cm make it easier to check conditions at the same locations at a later date.

In any event, it is desirable to make some analyses on *saturation extracts* and to find the saturation percentages for each determination in order to compare the results obtained from both types of extracts. Also, when the soils may contain precipitated gypsum, which is important when such soils are leached, some analyses on 1:10 extracts could be made. If gypsum is present the more dilute extracts should bring into solution more gypsum so that the conductance ratios may be much greater than 10 to 1 as would otherwise be expected.

Exchangeable Sodium Status

Complete analyses should be obtained on a limited number of *saturation extracts* in order to evaluate and classify the soils with respect to sodium. From the relative amounts of soluble Na, Ca, and Mg present in these extracts, an estimation of the exchangeable sodium percentage can be made from relationships given in Handbook 60, Diagnosis and Improvement of Saline and Alkali Soils (1954). Such estimations should be carefully checked, however, with direct determinations of exchangeable sodium. Relationships reported in Handbook 60 may not be applicable to completely different kinds of soils developed under different climatic conditions. This situation was found by the writers in Colombia (1973) where there was a very poor correlation between the exchangeable sodium estimated from the formula and that determined directly. Also there was no apparent correlation between the exchangeable sodium estimated from the formula and that determined directly. Also there was no apparent correlation between the results obtained by either method and the results from the leaching study.

Leaching Study

Where high values of Na^+ are found in the soluble salts, or where high exchangeable sodium values are found, there may be a question as to whether or not the soils can be economically reclaimed by adequate drainage and leaching. Sometimes, upon attempts at leaching, the soils disperse and infiltration rates become extremely low. Applications of gypsum to the soil may be required to provide the necessary Ca^{++} for the replacement of Na^+ on the exchange complex. In many cases, however, there is sufficient Ca^{++} in the soil in the form of $CaCO_3$ or possibly as $CaSO_4$ to provide this Ca^{++} and the reclamation of the soil takes place without the addition of any amendments, although it may take a longer time.

Leaching tests might be required to determine the feasibility of leaching to reclaim sodic soils. They can be performed by constructing levees around small plots and applying the irrigation water in increments of 10 to 15 cm until a meter or more in total depth has been applied. Measurements should be made to determine the infiltration rates as the water enters the soil. Where the rates are very low, it may be advisable to establish a vegetative cover in the plots, preferably a grass that will withstand flooding, after the initial application of water. Allowing the soil to dry as much as possible between applications of water may facilitate leaching.

During leaching tests, the infiltration rates may be governed more by the rate at which the ground water can move from the plots toward a drain, or simply spread out into the adjacent soil, than it is by the infiltration capacity of the soil. This build-up of a groundwater mound under the leaching plots can be determined by installing observation wells on two or more radial lines from the leaching plots. By keeping a record on these wells during the leaching tests the rate of build-up and subsidence of this ground water mound can be observed.

Water Management

Sometimes improvements in the drainage and salinity **conditions** can be effected by minimizing the cause of the problem. The investigations should include the determination of the principal reasons for the situation as found. They may suggest what might be done to help solve the problem. The following items might be considered.

The irrigation efficiency might be very low and steps may be taken to improve it. Sometimes, where irrigation water is plentiful and charges are not made for the amount of water applied, farmers are prone to apply much more water than necessary. Some of this excess water may result in unnecessary surface runoff, and much of it may pass through the root zone, especially in the higher parts of the irrigated area where drainage is not a problem. This extra ground water will flow through the soil toward the lower parts of the area and create high water table conditions. Improvement in irrigation practice to obtain better uniformity of applications with less deep percolation and runoff may be very effective in reducing the drainage and salinity conditions.

Lining irrigation canals, especially in places where the groundwater studies indicate that canal seepage is contributing to high water table conditions may be helpful. Although canal linings, usually concrete, do not eliminate all of the seepage loss, they usually reduce it to small amounts. Linings are also effective in improving the distribution of water in the canal system and in reducing waste at the end of the laterals.

Improvements in Surface Drainage may also be effective in reducing the amount of water that infiltrates into the soil in low places. In a study of a drainage and salinity problem in Colombia (1973) the writers found that the surface irregularities and depressions accumulated water following every rain storm and irrigation. This water remained in these depressions until it seeped into the soil raising the water table in these places. This excess water from surface depressions was one of the principal causes of the rise in the water table, and when all of the depressions were incorporated into a surface drainage network, a noticeable lowering of the water table resulted.

A sufficient amount of land grading should be done in all irrigated areas to eliminate all depressions where water accumulates from both rain and irrigation. This should be done even where irrigation by sprinkling is practiced.

DRAINAGE METHODS

In most instances, where the drainage is inadequate, some positive methods of drainage must be introduced in order to correct the situation. Before any one method is adopted, all possible methods should be considered. The two basic methods are pumping from wells and the installation of open and/or closed drains.

Pumping from Wells

Because of the inherent advantages of pumping from wells as compared with other methods, the investigations should explore the possibility. Pumping from wells can be effective only where the geology is favorable. There must exist at some practical depth aquifer materials that will produce water in sufficient quantity to make the method economical. Because of the many factors that must be considered, the specific capacity of a well that would prove economical might vary appreciably from one place to another. The following factors should be considered.

The presence of an aquifer. One that will produce an adequate flow is essential. If fine textured materials are present to great depths, and there are no indications that coarse textured materials are present, there is no possibility that drainage by wells would be feasible.

Impermeable barriers. Strata of tight clay materials may overlay aquifers, as is the case where the Corcoran clay strata is present in the San Joaquin Valley of California, which limits the use of wells for drainage. This tight clay barrier inhibits the downward movement of groundwater into the aquifer and a high water table develops over it.

Well logs . An examination of the well-log records for existing wells in the project area may suffice to determine both the existence of aquifer materials and barriers to the downward movement of groundwater. Where there are no wells present in the area, this can be determined only by drilling test wells.

The quality of the groundwater. Even where aquifers are present and wells of sufficient capacity can be developed, the economics of this method of drainage might depend on whether or not the water from the wells can be used for irrigation, either directly or when mixed with gravity water from surface sources.

Power requirements. If the quality is satisfactory for irrigation use, and wells of adequate capacty can be developed, the next question that must be answered is the availability and cost of power for pumping. Well pumps may be powered by electric motors, if a source of electric power is available or could be provided, or by internal combustion engines, diesel or gasoline. Where the water is pumped only to control the water table, the required pumping head will not be excessive. The amount of water that must be pumped will generally provide less than one-third of the total irrigation requirement, as is the case in the Modesto and Turlock Irrigation Districts in California where this method of drainage has proved very successful and has replaced deep open drains initially installed.

Specific Capacity. The specific capacity of wells that can be developed is of considerable importance in connection with a decision of whether to drain by pumping from wells or by other methods. When one has estimated the drainage requirement in terms of the amount of water that must be removed from an area during a certain period of time to achieve adequate drainage, the specific capacity of proposed wells is a major factor that determines the number of wells and spacings required. It is more important than the radius of influence of the well, although both are related, because one should be more concerned with the general lowering of the static water table in the area than with the apparent lowering within the radius of influence. In general, the greater the specific capacity, the lower the cost of pumping ground water. This is of major importance when determining the comparative economics of drainage by pumping and by other conventional methods.

Salt Balance in Pumped Areas. One problem in areas where drainage is achieved by pumping from wells is the overall salt balance for the area. Where water tables are lowered some distance below the surface by pumping, there may be no subsurface outflow of groundwater from the groundwater basin. All of the salt in the irrigation water imported into the area may remain in the ground water basin, and there may be a gradual increase in the salinity of the groundwater with time. This may or may not be a serious problem depending largely on the salt content of the imported or gravity water and the storage volume of the groundwater basin. This problem is much more acute when a large part of the water used in the area is pumped from wells which usually results in an overdraft on the groundwater and lowering of the water table to great depths. Such overdrafts have occurred in many places in the United States.

Sometimes only a small part of the required water supply comes from drainage wells and this groundwater, which has a higher salt content than the gravity water, is pumped into the irrigation canal system as in the

Turlock and Modesto Irrigation Districts. The resultant mixture is usually then of very acceptable quality. Furthermore, this mixed water is always used downslope from the drainage well. The expected net result might be a gradual increase in salinity of the groundwater as it slowly moves downslope. A salt balance might be achieved by pumping some of the more saline groundwater at the lower end of the project area into a surface channel and removing it from the area.

Drainage is provided in the Welton-Mohawk area along the Gila River in Arizona by pumping the saline groundwater into a lined channel which carries it out of the project area. This was found to be a more satisfactory method of drainage than by conventional open and/or closed drains. The solution was described by Moser (1967).

In the Punjab, Pakistan, salinity control and reclamation of several million acres of irrigated land is accomplished by a network of deep wells pumping from the sometimes saline groundwater reservoir. The water is pumped directly into the older surface distribution system of irrigation canals, and is used undiluted or mixed with surface water according to the degree of salinity of the groundwater. The long term effect of this method of drainage and irrigation on the salt balance of the groundwater reservoir was a prime subject of consideration in the planning of the reclamation of the water-logged and saline soils of the Punjab , as reported by Revelle (1954).

Shallow Drains

Shallow drains as previously defined are those excavated primarily to take care of the surface drainage. They need not be deep, and are generally less than 1.5 meters, but they must have sufficient carrying capacity to take care of the runoff following the maximum expected storms to avoid flooding.

Surface drainage can sometimes be taken care of adequately by cleaning, enlarging, or deepening natural drainage channels. In areas that will require deep drains to remove groundwater, these drains can often be used to remove surface water, but special inlet structures should be installed to avoid erosion of inlet channels and silting of the deep drains.

Deep Drains

Deep drains for removal of ground water are generally excavated to depths of 2 meters or more. They are of two types, open channels and closed drains, usually called tile drains. Generally drainage systems, as in the Imperial Valley of California, consist of both kinds. The main network is composed of deep open channels, generally from 2 to 3 meters in depth. They provide the outlets for the more closely spaced tile drains.

Large Open channels are often required, but they are undesirable because they occupy a considerable area of land, they are barriers to field operations, must be bridged at all road crossings, and they must be properly maintained to be effective. In warm climates, aquatic vegetation may have to be removed from open drains more than once each year to make them function properly.

Closed drains are much more desirable for the above reasons, but because of their relatively high cost, are often not considered economical for the main network where large pipe sizes are required. For the field drains, which require only small sizes, 6 to 15 cm diameters, and which are generally installed at a depth of 1.8 to 2 m, tile drains are economical and much more desirable than open channels. Ceramic tile has been used for drainage for more than a century. Concrete tile, or concrete irrigation pipe with open joints, has also been used for many years. Concrete, however, may disintegrate under the influence of sulfate salts and should be used only if it is known that the sulfate salts in the groundwater are not sufficiently concentrated to be detrimental to concrete. The durability of concrete tile depends to a large extent upon its density and imperviousness to water.

The more recent developments in connection with tile drainage has been in the development of special trenching and laying machines for ceramic and concrete tile, and in the development of perforated stic (PVC) tubing for drainage and special machinery for installing it. This tubing is flexible and is furnished in large coils. It is available in sizes from 3 to 8 inches (75 to 200 mm) diameters. The installed cost of plastic tubing is appreciably less than for ceramic or concrete tile of the same size.

The Imperial Irrigation District, California

An excellent example of such a network of drains on a large scale is in the Imperial Valley in California where both the irrigation and drainage are provided by the Imperial Irrigation District.

This District was organized in 1911 to take over the operation and maintenance of the canal systems formerly operated by 13 mutual water companies, some of which began operations in 1901. It soon became apparent that drainage work would be required to control the water table, so the District undertook the excavation of a network of deep open channels. These were usually spaced about one-half mile (0.8 km) apart over an area of about 400,000 acres (162,000 ha). This system did not prove adequate and farmers were encouraged to install tile drains. The District agreed to provide outlets for the tiles into the deep drains for each 160 acres (65 ha) of irrigated land. From 1929 to 1943 a total of 536 miles (863 km) of tile drains were installed on 25,000 acres (10,000 ha) of land. The amount of tile drains installed each year increased from 60 miles (100 km) in 1944 to 1037 miles (1660 km) in 1970, with an additional 919 miles (1470 km) in 1971 and 1019 miles (1630 km) in 1972, the last year of available data. During this period, 1929 to 1972, a total of 17,834 miles (28,700 km) of tile drains were installed in 377,115 acres (152,678 ha) of land.

The drainage program in the District is continuing because some areas need additional drainage. This illustrates the point that successful drainage is often a process of both learning how and paying as you go, rather than an undertaking that is planned, designed, and constructed in a short period of time.

RECLAMATION OF SALINE AND SODIC SOILS

Where saline and/or sodic conditions have developed as a result of inadequate drainage, such soils often can be reclaimed economically after drainage has been provided. The procedures were discussed in some detail by Christiansen and Grassi (1969).

Reclamation of Saline Soils

Saline soils (non-sodic) are generally more easily reclaimed than sodic soils. Leaching is required to remove the salts from the soil, and to accomplish this, there must be an adequate opportunity for the groundwater to escape from the area. This requires drainage.

There are two procedures used for leaching soils. One is to construct basins of the type used for irrigation in many places, and to hold water in these basins for a sufficient length of time to achieve the desired amount of leaching. A small continuous stream is often admitted to the upper basin and allowed to pass from one basin to another through small structures in the levees. These basins may be rectangular where slopes are very flat, or they may be formed by levees on contours. This method of flooding is essentially the same as is used for irrigating rice.

The second procedure is to form similar basins to retain the water but to apply it intermittently with an application of 20 to 30 cm each time, and to encourage the growth of vegetation that will aid in the drying and aggregation of the soil between water applications. This is essentially over-irrigation with enough water applied at each application to move water through the root zone. A grass that will withstand flooding for many days provides an ideal vegetative cover. Often such vegetation will develop naturally when water is applied in increments as described.

Reclamation of Saline-Sodic Soils

The reclamation of saline-sodic soils involves, in addition to the leaching of salts from the soil profile, the replacement of some of the adsorbed sodium, Na^+, by calcium, Ca^{++}. The leaching procedure is essentially the same as described above, but it is accomplished after an application of an amendment to the soil.

Where gypsum is applied as the amendment, the basic reaction that must take place can be represented by the equation:

$$CaSO_4 + 2NaX \rightleftharpoons CaX_2 + Na_2SO_4$$

in which X represents the soil exchange complex. This reaction may proceed in either direction depending upon the relative concentrations of Ca^{++} and Na^+ in the soil solution. To reclaim the soil the reaction must take place toward the right. Soils become sodic when the reaction proceeds to the left. As the salinity increases and $CaCO_3$ precipitates out of solution, high concentrations of Na^+ develop in the soil. This is why saline soils, formed under poor drainage with relatively good irrigation water, often become sodic.

Other chemical amendments that can be, and are sometimes, used to aid in the reclamation of sodic soils are: sulfur, sulfuric acid, lime sulfur and iron sulfate. All of these amendments either provide the Ca^{++} or they dissolve the $CaCO_3$ in the soil to provide the Ca^{++} for the reaction. The chemical reactions involved are discussed by Richards (1954).

The writers experience indicates that most calcareous saline and sodic soils can be reclaimed without additions of gypsum or other amendments. The process may be slower, but it can be accelerated by establishing a vegetative cover which increases the drying rate of the soil between applications of the water. The root activity in the soil also produces carbon dioxide, CO_2, which reacts with the water to form a weak acid. The acid brings into solution $Ca(HCO_3)_2$ from the $CaCO_3$ present in the soil. The alternate wetting and drying of the soil also improves the aggregation of the soil which is effective in increasing the infiltration rate.

Low Infiltration Rates

Sometimes when reclamation of saline and sodic soils is undertaken, the infiltration rate becomes so low that leaching becomes impractical. Evaporation from the flooded area may exceed the infiltration rate. The procedures mentioned above; the application of an amendment or intermittent application of leaching water, should improve infiltration rates during leaching but the rates may still be very low. The low rates result from the dispersion of the soil when the concentration of the salts in the soil solution in the upper part of the profile is reduced to the low concentration in the leaching water. Doering and Reeve (1954) have demonstrated that the hydraulic conductivity can be maintained at a higher level when the leaching is started with a saline water (drainage water) and the concentration is gradually reduced (by mixing irrigation and drainage waters) during the leaching process. This may not be practical under all conditions.

Reclamation with Rice

Where climatic conditions are favorable, rice can be grown as the vegetative crop during the reclamation process. The return from the rice crop may more than offset the cost of the leaching. To be successful, adequate drainage must first be established so that the saline groundwater can be removed from the soil. (Pearson and Ayers, 1960)

Reclamation of Saline Soils, Imperial Irrigation District

The drainage construction in the Imperial Irrigation District, together with a leaching program, has resulted in a decided improvement in water table and salinity conditions. During the five-year period 1944-1948, a total of 12,929,500 tons (11,754,000 metric tons) of salt came into the District in the irrigation water and 11,588,600 tons (10,535,000 metric tons) left in the drainage water. A net of 1,340,900 tons (1,219,000 metric tons) remained in the soils and groundwater of the District, an average of 268,180 tons (234,800 metric tons) per year.. From 1949 to 1972 inclusive there has been a favorable salt balance each year, with an average net loss of more than 366,300 tons of salt (333,000 metric tons) per year from the District. This net loss averaged more than 0.8 ton of salt per acre per year for a period of 24 years. This indicates that there was, and probably still is, a large amount of salt present in the soils and groundwater within the district.

The composition of the irrigation water and the drainage water and the change in composition is illustrated in Table 2.

Table 2. Salt Balance Constituents, Imperial Irrigation District, 1972*

Constituents	Equivalent Weight	Inflow (Irrigation Water)		Outflow (Drainage Water)		Net Balance
		Tons	me/1	Tons	me/1	Tons
Cations:						
Ca	20.04	396,950	5.12	295,920	10.21	- 101,030
Mg	12.16	133,510	2.84	147,330	8.38	+ 13,030
Na + K	23.00	550,620	6.18	816,160	24.54	+ 265,540
Total Cations		1,081,080	14.14	1,259,410	43.13	+ 178,330
Na, percent			43.71		56.90	
SAR			3.10		8.05	
S L Class			C3-S1		C4-S3	
Anions:						
HCO_3	61.01	355,940	1.51	175,280	1.99	- 180,660
SO_4	48.03	1,343,390	7.23	1,189,330	17.12	- 154,060
Cl	35.46	528,110	3.85	1,126,350	21.96	+ 598,240
Total Anions		2,227,440	12.59	2,490,960	41.07	+ 263,520
Total Salt		3,308,520		3,750,370		+ 441,850
Na + K + Cl		1,078,730		1,942,510		+ 863,780
Ca + Mg + HCO_3 + SO_4		2,229,790		1,807,860		- 421,930
Water acre feet		2,846,600		1,063,500		-1,783,100
Acre Feet Per Acre		6.4		2.4		- 4.0

* From IID Report, Excludes water and salt from Mexico (1972)

** Considered as Na

A number of interesting things are shown in this table. There is an overall favorable salt balance of 441,850 tons of salt, or about one ton per acre. The balance of the Na, K, and Cl ions is much more favorable, 863,780 tons or approximately 2 tons per acre. This indicates precipitation of $CaCO_3$ and $CaSO_4$ in the soil and possibly a cation exchange reaction in which the Ca^{++} from the $CaSO_4$ replaces the Na^+ and accounts for some of the Na_2SO_4 in the drainage water.

The irrigation water is from the Colorado River through the All American Canal. The drainage water, together with some drainage water from Mexico, flows into the Salton Sea.

PROPOSED IRRIGATION PROJECTS

It is equally important, or possibly more important, to carefully consider possible future drainage problems during the initial investigations and planning of proposed irrigation projects. At this stage, the question as to whether or not the area should be developed for irrigation can be carefully considered. Had consideration been given to future drainage and salinity problems at this time many projects that are economically unsound may not have been undertaken.

Choice of Area for Development

In some cases, there may be an opportunity to select for development one of several possible areas. If drainage is given proper consideration, it may be a determining factor as to what area should be developed, or developed first. Of primary consideration should be the prospects of adequate natural drainage for all or part of the area. Specific questions might be:

1. Is the topography favorable?
    a. not too steep as to cause erosion and difficulties in applying water?
    b. especially, not too flat?
2. Are the soils suitable for irrigation development?
    a. especially, are they drainable?
3. Is the area underlain with coarse aquifer materials from which water might be pumped?
4. Is the quality of the ground water such that it could be reused for irrigation directly?
    a. Could it be used if mixed with gravity supplies?

5. What is the present depth of the water table in the area, and in what period of time might it rise to objectionable levels?
6. If a drainage system is to be required, what type of system should it be? What would be the possible cost?
7. What is the quality of the irrigation water supply?
    a. Would it develop a sodic soil under high water table conditions?
8. What is the annual rainfall, and for what period of the year would irrigation be required?
9. Can crops be grown economically without irrigation?
    a. Would the same crops be grown under irrigation?
    b. Would other crops be introduced?
    c. Would there be an adequate market for introduced crops?

Ordinarily soil surveys do not include examinations of the soil to the depths required for drainage studies. The nature of the soil below the desired water table is of much more importance in connection with drainage than is the first meter or so of the profile.

Feasibility of Project

Most of the questions listed above should be answered in the studies that are made to determine the feasibility of the project, but some are specifically concerned with probable drainage and salinity problems. Drainage investigations should be an integral part of the feasibility studies. The difficulty is that positive answers cannot be given to some of the questions, and reliance must be placed on judgement and knowledge based on experience, preferably under similar conditions. Sometimes mistakes are made when too much reliance is placed on experience gained under completely different conditions.

Relationship of Rainfall to Salinity

When one compares salinity problems with the annual rainfall for the area there appears to be a good correlation. In general, areas with an annual rainfall in excess of 1000 mm (40 inches) seldom have serious salinity problems. Salinity is generally more of a problem in areas with an annual rainfall of 400 mm (16 inches) or less. This is probably due to three factors: areas with high rainfall generally have a better quality irrigation water, the soils are partially leached during the rainy season, and virgin soils in these areas are generally free of salts.

In the higher rainfall areas, drainage may be required more for removal of excess water, and in the more arid areas, for the removal of salt to maintain a favorable salt balance. Where salinity is a problem, the water table should be maintained at a greater depth, preferably below 2 meters, than may be necessary in the more humid areas.

Drainage Studies for Proposed Projects

Most of the questions posed for existing projects are also valid for proposed projects. There are, however, some additional questions that must be answered.

Ordinarily there will not be a high water table or salinity condition before irrigation water is brought into the area. The questions are: will such conditions develop, and if so how soon? What can be done to avoid or minimize drainage and salinity problems in the future if the area is developed for irrigation? Under normal irrigation practices, the water table may rise at a rate of 30 cm or more per year except where natural drainage is adequate. In the more humid areas, the water table initially may be near the surface. The existing water table levels before the introduction of irrigation should be determined from water levels in existing wells where available, or by installation of some deep observation wells or piezometers, if necessary, to a depth of about a meter below the existing water table.

Records on these wells will indicate the effect of the irrigation on the rise of the water table and provide some lead time for more detailed observations. This lead time is important because it is more desirable and economical to prevent a salinity problem from developing than to reclaim saline and sodic soils at a later date.

Coachella Valley, California

In the Coachella Valley northwest of the Salton Sea, all of the land that was irrigated prior to the introduction of Colorado River water through the All American Canal extension in the late 1940's was irrigated from groundwater pumped from deep wells. There was no drainage problem except in the lower part of the valley near the Salton Sea.

At that time the U.S. Bureau of Reclamation and the Coachella Valley Water District undertook a study of groundwater conditions through the installation of a large network of observation wells and piezometers so that as the water table rose it could be monitored. Preparations were made to take whatever drainage measures were required without delay. This proved to be a very wise decision and the installation of drains proceeded as required.

Feasibility Economics of Developing Land for Irrigation Where Drainage Costs May Be High

In some places, new areas have been developed for irrigation with little consideration being given to future drainage costs. The feasibility of development depends largely on the expected increase in net return from the land. Where farmers are expected to pay all costs of irrigation and drainage, over some specified period of time, it is important that all costs be included. All too often, future drainage needs were not included, and the development proved to be economically unsound.

The net return from agriculture depends largely upon the annual value of crops produced. Sometimes irrigation is introduced but the crops grown remain essentially the same as before irrigation, possibly because of climatic limitations, or because of limited markets for other crops. This lack of change may have resulted from a lack of research and guidance by the developing agency. Where crops can be grown without irrigation, one seldom finds that the increase in yield from the same crop will pay the costs of irrigation development. The greatest increase in net return is more likely to occur where irrigation may make it possible to grow a high return crop where it could not be grown without irrigation. For example, where the climate and soils are suitable, a change from an annual crop to a citrus orchard may be very profitable. In such cases, the market for the introduced crops may be the determining factor. There may be a local market for a limited production of certain produce, but when the production is greatly increased, the price drops. A surplus that cannot be marketed profitably results.

All of these problems need very careful consideration, especially where drainage requirements may add unexpected costs to the development.

Ground Water Development

When a new area is being considered for an irrigation project, the possibility of developing ground water should be considered. Where pumped wells are already in use, their continued use after the introduction of gravity water at a lower cost, may eliminate a drainage problem that would otherwise result. Several examples could be cited where the pumping of private wells was discontinued as soon as a lower cost water was available, and where serious drainage problems resulted in a very short time. Had the developing agency taken over the operation of the existing pumped wells and operated them only as needed to control the water table, the high water table conditions that developed may have been prevented. The pumping of these wells for drainage may have also provided a supplemental water supply that could have been extremely valuable in periods of drought. In one instance, in a Mediterranean country, because of the introduction of gravity water into a profitable citrus area that had been irrigated from wells, the farmers all stopped pumping. The rapid rise of the groundwater in one low area killed most of the citrus trees before anything was done to prevent it. The groundwater rise was due largely to subsurface flow into this low area, and the individual farmers were helpless because there was no place they could waste the water had they continued pumping their wells.

In another location in the United States, the farmer discontinued pumping when a better quality water from a gravity source became available. A very serious drainage and salinity problem developed before the problem could be investigated and funds were made available for the installation of drainage works. The investigation undertaken indicated that pumping from wells and discharging the water into a lined channel to carry it from the area was the most economical solution of the drainage problem. That this could have been determined in advance of the introduction of the gravity water is entirely possible.

SUMMARY AND CONCLUSIONS

Recognition of Problems

An attempt has been made to stress the seriousness of drainage and salinity problems in many irrigated areas. With proper recognition of the need for drainage works before the problem became acute, much could have been done to prevent the conditions that resulted. Unfortunately, not sufficient concern has been given to the need for drainage until the productive capacity of the land has been seriously impaired. Where salinity, or especially sodic, conditions have become acute, it may become a choice of:

1. Abandoning the area for crops.

2. Spending as much or more to drain and reclaim the land than it is worth at present prices.

These are unfortunate choices, especially for farmers who have invested their savings and labor in developing an irrigated farm.

The financial losses that result from lack of adequate drainge most often falls largely on the developing agency, usually a division of the government, or a lending institution that financed the project.

Solution of the Problem

Fortunately, in most instances where the problem is recognized in time, drainage works can be provided that will eliminate the salinity conditions that would otherwise result. Such works are, in most instances, economically sound and should be undertaken at the earliest possible time. Delays most often result in the problem becoming more acute and eventually in the abandonment of agricultural land. With food shortages becoming a world wide problem, every effort should be made to conserve our agricultural resources. Drainage will be an important part of the overall conservation effort.

APPENDIX I

GLOSSARY OF TERMS

Drainage

The term drainage is used with several adjectives to describe specific aspects of drainage.

Adequate drainage is a condition that exists when the water table is maintained at a sufficient depth below the surface to provide an aerated root zone for agricultural crops free from accumulation of salts.

Natural drainage is that provided by nature without man-made works. In some areas, natural drainage is entirely adequate.

Surface drainage refers to the removal of excess surface waters that may originate from either precipitation or irrigation. Natural surface drainage may be adequate.

Subsurface drainage refers to the removal of water that has infiltrated into the soil from sources already mentioned. This removal of subsurface water may occur naturally, or may be accomplished by means of (1) deep open channels, (2) closed drains (often called tile drains), (3) a combination of both open and closed drains, or (4) by pumping from wells and discharging the water into open channels.

Drainage Requirements

The term drainage requirement has several meanings including:

a. The amount of water that must be removed by artificial means to achieve adequate drainage. This amount when expressed in equivalent depth over the area, in inches or millimeters per day, is often called the drainage coefficient.

b. The required depth at which the water table must be maintained to be considered adequate. It depends on the crops grown, the quality of the irrigation water and salinity conditions in the soil.

c. The required depth of deep drains, either open or closed, to achieve adequate drainage.

d. The required size or capacity of either open or closed drains.

Drains

Drains are channels or buried pipes used to remove either surface water or ground water from an area.

Open drains may be either shallow to achieve surface drainage, or deep to achieve subsurface drainage.

Closed drains are buried drains generally consisting of: (1) Ceramic tile in short sections (less than 1 m) with open joints to admit ground water, (2) concrete pipe with open joints, (3) perforated plastic tubing or pipe. All forms of closed drains are commonly called tile drains.

Deep drains are generally more than 1.5 meters in depth and most frequently more than 2 meters. Their primary purpose is to remove groundwater, but are sometimes used to remove surface water which is admitted through special structures to avoid erosion.

Shallow drains are generally less than 1.5 meters in depth and their principal purpose is to remove surface water, or water pumped from drainage wells.

Interceptor drains are those designed to intercept subsurface flow moving downslope. They are effective when a barrier (tight stratum) is present within a short distance from the surface; less than 2.5 meters. They are of primary benefit to the land below the drain.

Relief drains are those designed to admit water from both sides.

Groundwater

Groundwater is the body of water underlying the soil surface in the saturated zone, i.e., below the water table. Groundwater is not static but moves slowly downslope at a velocity depending on the hydraulic gradient. It may also move vertically either upward or downward depending on vertical gradients.

The Water Table is the upper boundary or surface of the saturated zone, or more precisely the locus of points at which the pressure in the groundwater is equal to atmospheric pressure. As defined, the water table is at the approximate depth, or elevation, as indicated in a perforated observation well. Actually, the soil is saturated for some distance above the water table, as defined above, due to capillarity.

Capillary fringe is that zone above the water table in which the soil moisture is above field capacity. In this fringe, the equilibrium moisture content would range from saturation just above the water table to field capacity at a distance of several centimeters. The thickness of the capillary fringe depends on the soil texture and is greater for fine textured soils (clays) than for coarse textured soils (sands). Within this fringe, the soil moisture is under tension, i.e., less than atmospheric pressure.

Observation Wells are small diameter cased wells installed for the purpose of determining the position of the water table. They need to penetrate the soil to only a meter or so below the expected water table after drainage. The casings are usually perforated and installed in a soil auger hole with the annular space around the casing filled with sand to within a meter of the soil surface.

Piezometers. Groundwater piezometers are instruments or devices used for determining the hydrostatic head at a point within the groundwater body. They usually consist of small diameter pipes, usually 3/8 or 1/2 inch, driven or jetted into the soil to the desired depth and then cleaned by adequate flushing.

Piezometric level is the water level in a groundwater piezometer or cased well that terminates in an aquifer, or in a saturated soil at some specified depth. It may be either higher or lower than the water table as defined. When higher it indicates an upward movement of water that may be a cause for the high water table. When it is lower it would indicate that water is moving downward into a more permeable material or aquifer.

Hydraulic Conductivity

This is the effective flow velocity at unit hydraulic gradient. It is the proportionality factor, K, in the Darcy Law of flow through porous media:

$$Q = K\,A\,I$$

in which Q is the flow rate in units of volume per unit of time, A, is the cross sectional area through which the flow occurs, and I is the effective hydraulic gradient or change in head for unit of flow length. Hydraulic conductivity may be expressed in any units of length and time. For drainage purposes, a convenient unit that can be visualized is meters per day (m/day). Hydraulic conductivity and permeability are often used synonymously.

Infiltration

Infiltration is the process of water entry into a soil from precipitation or irrigation. Both gravity and capillary forces affect infiltration.

The infiltration rate is the rate at which the water enters the soil expressed in depth per unit of time (mm per hour or inches per hour).

The infiltration rate for a given soil is not constant but increases with time.

Irrigation

Irrigation is the application of water to the soil for the purpose of making it available for plant growth.

Irrigation application efficiency is the percentage of water applied that is retained within the root zone and can subsequently be used by crops.

Irrigation Methods

Irrigation water is applied to the soil by a wide variety of methods including:

Surface methods by which the soil is utilized to distribute the water from ditches or pipes. Principal surface methods are flooding and furrows.

Sprinkling includes all methods of spraying water through the air to distribute it over the surface.

Subsurface irrigation is where the water is distributed below the surface, often by applying the water to lateral ditches to raise the water table sufficiently to moisten the soil in the root zone by capillarity. This method has limited application, especially where salinity is a problem.

Drip irrigation is a method by which the water is distributed from a pipe system through small plastic tubing equipped with "drippers" or "emitters". This method is generally economical only for high value row crops, vineyards, and orchards.

Leaching

Leaching is the process of removal of salts from a soil by the passage of water through the soil, generally downward to the saturated zone below the water table, from which the saline solution may be removed by drains. Effective leaching can be accomplished only when drainage is adequate.

Leaching requirement is the fraction of water entering the soil that must pass through the root zone in order to prevent the soil salinity from exceeding a specified value. It may also be considered as the excess amount of water that must be applied to maintain a salt balance in the root zone at an acceptable salinity level. The term should be applied to long time average conditions.

The leaching requirement is often exceeded by the excess water applied under normal irrigation practices, and/or by the annual precipitation.

Leaching ratio is defined as the ratio of the water passing through the root zone to the total amount of water applied, irrigation plus precipitation.

The leaching percentage is the leaching ratio times 100, which expresses the leaching fraction as a percentage of the amount applied.

Root Zone

The depth of the soil profile in which roots of agricultural crops are active is called the root zone. It may range from less than 50 to more than 200 cm depending on the crop, the soil aeration, fertility, stratification and barriers to root penetration.

Salinity

Salinity refers to the concentration of salts in a water or soil. Salinity may be expressed in terms of parts per million (ppm), milliequivalents per liter (me/1), electrical conductance expressed in micromhos (μmhos, EC x 10^6) or millimhos (mmhos, EC x 10^3), or as osmotic pressure in atmospheres.

The term mho may be considered the basic unit of conductance. It is the reciprocal of ohm, the basic unit of electrical resistance, and is the word ohm spelled backwards.

For soils, the salinity is usually reported as the salinity of a saturation extract (the solution extracted by suction from a soil saturated with distilled water). It may, however, be reported for extracts for a specified ratio of soil to water such as a 1 to 1 (1:1), one part soil to one part water, or for 1:5 or 1:10 extracts, etc.

The salinity of a soil is not a fixed property but is dynamic and may be decreased by drainage and leaching, or increased by improper water management including the use of saline water for irrigation, inadequate drainage, and insufficient leaching.

Salts

Salts considered here are the natural salts found in waters and soils. They are soluble chemical compounds and consist of equivalent weights of cations (positively charged ions) and anions (negatively charged ions).

Ions are electrically charged particles, either positive or negative, which combine with particles of the opposite charge to form a salt, or other chemical compound. An ion may be a single atom such as sodium (Na^+) or a combination of atoms such as sulfate (SO_4^{--}) or bicarbonate (HCO_3^-).

Cations are positively charged ions. The primary cations in water and soils are: calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^+) and potassium (K^+).

Anions are negatively charged ions. The primary anions are: chloride (Cl^-), bicarbonate (HCO_3^-), carbonate (CO_3^{--}), sulfate (SO_4^{--}) and nitrate (NO_3^-).

Cation exchange is a phenomonen that takes place in a soil when a cation in solution is exchanged for another cation on a surface-active material (clay or colloidal particle).

Cation-exchange-capacity is the amount of cations that a soil can adsorb, usually expressed in milligrams per 100 grams of dry soil.

Calcium (Ca^{++}) is the principal exchangeable cation on normal soils in arid regions. Hydrogen (H^+) may be the principal exchangeable ion on humid soils.

Sodium (Na^+) is an undesirable exchangeable cation. When present in excess of 15 percent of the exchange capacity, the soil is classified as alkali or sodic.

Salt Balance

The term salt balance is used to indicate the difference in the amount of salt leaving with the drainage water and that entering with the irrigation water. The term may be applied to an irrigation project or to the root zone of a crop.

A favorable salt balance indicates that more salt is leaving the project, or soil profile, than is entering with the irrigation water, and is indicated by a plus sign (+).

An unfavorable salt balance means the opposite; that more salt is entering than leaving. It is indicated by a minus sign (-).

Usually there is a good correlation between the salt balance and adequacy of drainage. When the water table is near the surface, the outflow of both ground water and salt usually is not adequate to maintain a favorable salt balance.

Where rainfall is low an unfavorable salt balance may develop in a soil where the water table is well below the surface and the drainage completely adequate. Here the soil may become saline due to the application of irrigation water in amounts that are insufficient to leach the salts from the root zone that are applied in the irrigation water. (See Leaching Requirement).

Salt Tolerance of Crops

The salt tolerance of crops refers to the ability of agricultural crops to grow and produce economic yields under saline conditions. In general, the growth and yield decreases approximately linearly with an increase in salinity as determined from saturation extracts. Plants are classified as to their salt tolerance by considering the saturation extract salinity that produces an approximate 50 percent reduction as yield. Plants with a low salt tolerance are those which suffer a 50 percent decrease in yield with a soil salinity of 4 mmhos per cm, moderate or medium tolerance for 8 to 10 mmhos per cm, and high salt tolerance for those withstanding 10 to 16 mmhos per cm.

Saturation Extract

The saturation extract is a solution extracted by suction from a soil that has been saturated with distilled water. When making a saturation extract, distilled water is added very slowly to a soil sample while stirring continuously until a condition is reached when additional water remains on the surface producing a glistening effect. This point is determined visually.

The salinity of a saturation extract is fairly well correlated with the effect of salinity on plant growth and yield. (See Salt Tolerance.)

The saturation percentage of the soil is the moisture in the soil sample when it has reached saturation expressed as a percent of the dry weight of the soil sample. This saturation percentage is not routinely determined when making saturation extracts. Because the procedure for determining saturation is not precise, appreciable variations may occur in replicated samples. A more precise procedure for determining the amount of salt in a soil in connection with drainage studies is to use a one to one (1:1) soil-water extract.

Soil Classification with Respect to Salinity

Saline soil is one which has a saturation extract conductance of more than 4 mmhos per cm at 25°C.

Sodic or alkali soil is one which has an exchangeable sodium percentage of 15 or more. There are saline and non-saline sodic soils.

Normal soils have less than 15 percent exchangeable sodium and a saturation extract conductance of less than 4 mmhos per cm at 25°C. These amounts are considered to have a minimal effect on the growth of most agricultural crops, although some crops are sensitive to this amount of salinity.

Soil Reclamation is the process of reducing the salinity and/or the exchangeable sodium in a saline or sodic soil by proper water management. This generally consists of first providing adequate drainage, then leaching, in combination with the addition of soil amendments such as gypsum ($CaSO_4$) when required.

Soil Moisture

The soil moisture is that present in a soil under field conditions. This moisture is usually expressed as a percentage of the dry weight of the soil, but for some purposes may be expressed as a percentage of the soil volume.

None of the following terms are precise, but they are useful in describing the soil moisture conditions as related to plant growth.

Field capacity is considered to be the moisture content retained by the soil against the force of gravity after rapid drainage has taken place. It is usually considered to be the soil moisture about two days after an irrigation or heavy rain which completely wets the crop root zone. It is considered to be the upper limit of the available soil moisture range.

Wilting point is the soil moisture content at which plants wilt and will not regain their turger until moisture is added to the soil. Synonymous terms are permanent wilting percentage, wilting percentage, wilting coefficient, etc. It is considered to be the lower limit of available soil moisture.

Available soil moisture is generally considered to be the moisture available for plant growth. It is that moisture retained in the soil between the limits of field capacity and wilting point.

Soil Solution is another term for soil moisture generally used in connection with its chemical properties. It contains in dissolved form the soluble salts in the soil. This solution surrounds and adheres to the soil particles. The salt concentration of this solution is what affects plant growth. At relatively high soil moisture contents, but less than field capacity, the soil solution can be extracted from a soil by suction with suitable equipment. At low soil moisture contents extraction of the soil solution from a soil in place is not feasible.

Soils - Physical Properties

Some of the more common physical properties of soils are:

Texture, which is the size and gradation of soil particles, ranging from clay and collodial materials to sand and gravel. Textural classifications depend on the relative amounts of clay, silt and sand present as specified in the particular classification used.

Structure refers to the aggregation and arrangement of the particles rather than their size. A soil with a well aggregated structure is more permeable and more desirable than one with a poor structure in which the particles are largely dispersed. Dispersed soils generally have low infiltration and hydraulic conductivity (permeability) characteristics and may be difficult to irrigate or leach. Both the size and stability of aggregates are important characteristics of soil structure.

Density refers to the weight per unit volume. Real density is the actual density of the soil particles (approximately 2.65 m/cm^3), and apparent density is the dry weight of the soil in a unit volume in place including the volume occupied by soil particles, water and air.

Volume weight is the ratio of the dry weight of a soil to the weight of an equal volume of water. In metric units, volume weight and apparent density have the same value.

Pore Space refers to the space occupied by air and water within the soil. The size of the pores is very important. Large pores between aggregates provide better aeration and higher permeability than small pores.

Air capacity is the pore space occupied by air at field capacity. It is an index of the adequacy of soil aeration, and is dependent upon the large pores between aggregates. It is expressed as a percentage of the volume.

Water Quality

The quality of an irrigation water generally refers to the amount of salt present (salinity) and/or to the relative amount of sodium (Na) expressed as either a percentage of the total cations or as the sodium adsorption ratio (SAR). A suggested water quality classification is given in this report. The parameters considered in the classification are:

1. Total salinity, expressed in ppm, me/l or conductance
2. Sodium percentage (Na %)
3. Sodium adsorption ratio (SAR)
4. Residual sodium carbonate (RSC)
5. Effective salinity (Eff. Sal.)
6. Boron (B)
7. Chloride ion (Cl^-)

Sodium Adsorption Ratio (SAR) is a ratio used in connection with water or soil extracts to express the relative activity of sodium ions in exchange reactions with the soil. It is expressed by the equation:

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

A similar expression is sometimes used for the potassium adsorption ratio (PAR) although high values of PAR are seldom found.

Residual Sodium Carbonate (RSC). When a solution (irrigation water or soil extract) has greater equivalent weights of carbonate (CO_3^{--}) plus bicarbonate (HCO_3^-) anions than calcium (Ca^{++}) plus magnesium (Mg^{++}) cations, it is said to contain residual sodium carbonate. Upon evaporation to dryness, such a solution would first precipitate $CaCO_3$ and $MgCO_3$ leaving the sodium carbonate (Na_2CO_3), a particularly undesirable soil constituent in a more concentrated solution. Waters that contain more than about 1 me/l residual sodium carbonate may be detrimental for irrigation, and those containing more than 2.5 me/l are not considered suitable for irrigation. The amount of the residual sodium carbonate, if present, is determined by:

$$RSC = (HCO_3^- + CO_3^{--}) - (Ca^{++} + Mg^{++})$$

Effective Salinity. Since calcium and magnesium bicarbonates and carbonates have relatively low solubility, and calcium sulfate ($CaSO_4$) has only an intermediate solubility of an amount that can be tolerated by plants, these salts do not contribute effectively to soil salinity. Doneen (1959) has defined effective salinity as the total salinity expressed in me/l minus these less effective salts.

Effective salinity is a major parameter in a classification of irrigation waters proposed by Doneen (1959), and is included in the classification proposed by the writers.

Boron is an element usually found in relatively small amounts, but which is toxic when present in amounts of only a few parts per million. It should be considered in a classification of irrigation waters. Boron in very small concentrations is an essential plant nutrient.

Water Requirement

The water requirement is that amount of water required, including precipitation, for satisfactory production of agricultural crops. It depends on the climate and the crop grown. Climatic parameters include the amount of energy received from the sun, the temperature and humidity of the air, and the wind velocity. Crop factors include the percentage of ground shaded by the crop, crop height, and color. Annual crops have a water requirement which increases from the time of emergence, reaching a maximum as maturity is approached and which then decreases rapidly. Perennial crops have a more uniform demand during the growing season which varies primarily with climatic factors. Many formulas are available for use in estimating water requirements, which are usually expressed as a depth per unit of time such as mm per day or per month.

Irrigation requirement is that required by irrigation to supplement precipitation in order to produce optimum crop growth and yield.

Dependable precipitation is the amount of precipitation that can be expected to occur at a stated percentage of the time based on a statistical probability. This has sometimes been taken as the precipitation on a monthly basis that can be expected to occur 75 percent of the time, three years out of four.

Wells, Drainage

Drainage wells are those constructed primarily to remove groundwater in order to control the water table. Water pumped from drainage wells, if of suitable quality, is often reused for irrigation, but if saline, should be discharged into open channels and removed from the area. (See Irrigation Wells.)

Wells, Irrigation

Irrigation wells are those constructed primarily to produce water for irrigation. In many places where most of the irrigation water applied is from pumped wells, the water table is maintained below the depth at which it would affect crops and hence drainage is entirely adequate. Thus, irrigation wells often serve as drainage wells except where impermeable barriers exist between the surface and the aquifers from which the water is pumped. Some terms used in connection with wells are:

Aquifers are strata of highly permeable materials, sometimes found at several hundred meters below the ground surface, from which water can be economically pumped. Most aquifers are composed of sand and gravel, but are sometimes fractured rock formations.

Drawdown is the depth that the water in the well must be lowered to produce the flow pumped from the well. For most wells there is an approximate linear relation between the drawdown and flow (discharge) from the well.

Casing is the pipe or tubing used to line the well. The casing is generally made of steel, but occasionally is of other material. Casings are often perforated to admit the water from acquifers, or the casing may contain sections of well screens.

Well screens are specially designed tubular screens used to admit water but prevent the entrance of sand and other soil particles.

Specific capacity is the discharge from a well per unit of drawdown. It can be expressed as gallons per minute (gpm) per foot of drawdown, or in liters per second per meter of drawdown. The specific capacity of a well may decrease somewhat with an increase in pumping head, especially in unconfined formations, but it is generally an approximate constant for the most economical range of pumping heads. In general, it is a very important parameter to be considered in connection with pumping groundwater for either irrigation or drainage.

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