Development of Ground-Water in the Indus Plains

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Synopsis

The Indus Plains are underlain by an extensive aquifer with large quantities of usable ground water. WAPDA is preparing plans for its development. The ground water will be used in combination with surface water to meet irrigation needs. The ground water will also be used for municipal and industrial supply.

In this paper the following aspects are discussed :

(*a*) The development potential of the ground water aquifer;

(*b*) The relationship between land areas and quality of ground water;

(*c*) The ground water recharge from canals, rivers, rainfall and farm irrigation;

(*d*) The need for mixed use of surface and ground water in areas where the ground water has a high content of total salt, sodium, or sodium bi-carbonate;

(*e*) The salt balance of the ground water as affected by the rate of withdrawal and re-use of the ground water;

(*f*) The need for using the available water supplies on good lands.

To facilitate the discussion, the Indus Plains area has been divided into two major subdivisions: Sind (14 million acres) and Punjab (34 million acres). Ground water conditions in the Punjab Region, which includes Bahawalpur, are discussed in greater detail than those in the Sind. Available data on the Sind ground water regimen are less comprehensive than for the Punjab.

The quality of the ground water as related to established canal areas or barrage commands is shown on two small-scale maps (Figures 1 and 2) and in Tables 1 and 3. Present land use is discussed in relation to the quality of the underlying ground water. The ground water recharge in the Punjab and Bahawalpur is estimated to be 36 million acre feet for an average year with an irrigation intensity of 60 percent in the summer season and 90 percent in the winter season and for a culturable commanded area of about 18.7 million

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acres. The potential recharge in the fresh ground water area in the Sind is estimated to be about 5 to 7.5 million acre feet annually.

The possibility of using the ground water reservoir for storage of flood waters is discussed. Such storage could be accomplished by inducing additional recharge from canals, rivers, old streambeds and nalas, and by over-irrigation of farm lands, possibly by expanding rice cultivation in perennial areas.

GENERAL

Punjab and Bahawalpur

The WASID ground water investigations[1] have shown that virtually the entire Punjab and Bahawalpur areas are underlain to depths of 1,000 feet, or more, by uncemented alluvium which is saturated to within a few feet of the land surface. Assuming an effective porosity of 15 to 20 percent for the saturated sediments, the volume of usable ground water in storage is on the order of 1.5 to 2.0 billion acre-feet for a 300 to 400 feet depth of aquifer. The alluvium varies in texture from medium sand to sandy clay, but sandy sediments predominate. Investigations and experience have shown that large-capacity tubewells yielding four cusecs or more can be developed at virtually any site. The first tubewell project went into operation in 1961. It comprises nearly 2,000 tubewells which serve an area of about 1.2 million acres in Rechna Doab. Tubewell construction has been completed in another small project area, the Lalian scheme, in Chaj Doab. Development of the ground water will be continued until the tubewell system covers the presently irrigated areas and other areas where irrigation by tubewells is possible.

Sind

Thus far, the ground water investigation program has not been as extensive or as comprehensive in the Southern Region of the Indus Plains (Sind Area) as that in the Punjab and Bahawalpur. Investigation results indicate that the Sind aquifer is less uniform with respect to both depth and lithology. Ground water of good quality appears to be restricted to a 3 to 15-mile wide strip along the Indus River. Tubewell development is both feasible and desirable in the Sind but, on the average, the tubewells will be less deep and they will have a somewhat smaller capacity than those planned for the Punjab and Bahawalpur. Construction plans are available and will soon be implemented for the Khairpur and Gaja projects.

Ground Water Development

The ground water reservoir is recharged by the rivers, canals and water-courses, and by deep percolation from farm irrigation and rainfall. Water table studies indicate that leakage from the existing canal distribution system has been the principal cause of the sub-surface drainage problems in the Indus

Plains, and it is also the major component of ground water recharge. Studies of historic recharge show that approximately one-third of the total canal discharge has been diverted to ground water storage.

Tubewell reclamation methods are generally feasible in the Indus Plains. That is, with respect to drainage, the position of the water table can be controlled by pumpage; and with respect to supplemental irrigation supplies, there is adequate recharge and sufficient ground water in storage to sustain large-scale withdrawals for an indefinite period. Furthermore, ground water supplies offer some unique operational advantages that do not exist in a surface irrigation system. Unlike canal supplies they are not subject to seasonal variations, and they can be developed to serve lands that cannot be commanded by the canals. Thus ground water can be used to meet seasonal deficiencies in canal supplies and to extend irrigation to areas that cannot be brought under command of canals.

In view of the above facts, it is evident that the alluvial aquifer underlying the Indus Plains is an unexploited resource of enormous economic value —the more so, because it is highly susceptible to flexible operation and management. It is now recognized that development of the ground water resources is the key to a permanent, greatly intensified irrigated agriculture in the Punjab. A long range program[2, 3] is being prepared for development of the ground water. The essential feature of the program is a proposed network of tubewells, located with an average density of about one per square mile.

Where the ground water is of acceptable quality, the tubewells discharge into the water-courses or minor canals and the pumping rate of each well is determined by the supplemental irrigation requirement of the land under its command and/or the sub-surface drainage requirement. Thus ground water withdrawals serve the dual purpose of satisfying irrigation requirements and providing sub-surface drainage, eliminating the environment that has led to widespread: soil salinization. The system offers a permanent solution to the problem of leaking canals because it both controls the effects of leakage and salvages the canal losses. Under these conditions, canal leakage is an asset to the overall water supply system rather than a liability, because it constitutes the major component of recharge to the groundwater reservoir.

In areas where the quality of ground water is unsatisfactory the tubewells should discharge into drainage ditches or into large canals, and the pumping rate of each well should be determined by the subsurface drainage requirement of its area of influence. In these areas the tubewells offer only a compromise solution to the problems of canal leakage. They control salinization and waterlogging but do not provide usable irrigation supplies, hence canal leakage remains a liability and puts an extra burden on the tubewell drainage system.

Despite the feasibility and inherent advantages of tubewell reclamation methods, it is inevitable that, just as superposition of the canal system on the native environment caused undesirable side-effects, the tubewell reclamation projects again will disturb the environment and introduce new problems. From the stand-point of ground water hydrology there are two distinct, but related, problems which must be considered in the design and management of the tubewell projects. These probelms are :

(*a*) Distribution of ground water availability and withdrawal.

(*b*) Maintenance of a favourable salt balance in the ground water supply.

LAND USE AND LAND AREAS RELATED TO QUALITY OF GROUND WATER

Punjab and Bahawalpur

General.—The Punjab area under discussion is situated on the left bank of the Indus River and is bound by the Sutlej River on the south-east, by the Jhelum River and the Salt Range on the north-west, and by the Indian frontier on the north-east.

The Bahawalpur area lies to the southeast of the Punjab, from which it is separated by the Sutlej and Panjnad Rivers. The canal commands in Bahawalpur parallel the rivers in a strip 35 miles wide. Beyond the canal areas the Thar Desert stretches off into India.

Table 1* shows that the gross area in the Punjab and Bahawalpur for which ground water quality data are available is about 34 million acres. Of this total area, about 21.5 million acres lie within the gross commanded area (G.C.A.) of the canal systems with a culturable commanded area (C.C.A.) of about 18.7 million acres. There are about 34—18.7=15.3 million acres of lands that are not irrigated from the principal canal systems. Except for the Gujrat Plain, which covers about 0.6 million acres, the non-canal irrigated lands are identified in Table 2 by land use categories specified in the Colombo Plan Co-operative Project Report.[4]

Most of the non-canal irrigated lands can be identified roughly as to geographic location. About 5.6 of the 15.3 million acres comprise large, contiguous blocks; another 5 million acres are estimated to lie in overflow areas along the rivers. The remaining 4.7 million acres are interspersed within the limits of adjacent gross commanded areas.

The 5.6 million acres which are easily identified, include the Gujrat Plain in Chaj Doab of 638,000 acres; the Sialkot area in Rechna Doab of

*This Table has been prepared using a WASID map with groundwater quality isogram contours. The canal areas were superimposed on this map and the isogram contours were planimetered for each canal area—see Figure 1 for summary map.

1,053,000 acres; a sandy desert of 1,971,000 acres and an undeveloped area of 391,000 acres, both within the Thal Doab; and non-irrigated areas, comprising 1,502,000 acres, situated adjacent to the Bahawal and Eastern Sadiqia Canal commands in the Bahawalpur area.

The riverain belt within the study area comprises about 5.0 million acres. This area is estimated by assuming a total river length of about 1200 miles and an average width of 6.5 miles for the over-flow areas. The remaining 4.7 million acres of the non-canal irrigated acreage include the 2.7 million acre difference between the G.C.A. and C.C.A., and 2 million acres of land which are most likely "barani" lands and land irrigated by wells. The 2.7 million non-irrigated acres within the canal commands are not easily identified as they include hundreds of plots which vary from only a few acres to thousands of acres. They are distributed over the eight land-use categories listed in Table 2.

Water-logged and saline lands constitute a significant portion of the unused land categories.

Land Areas Related to Quality of Ground Water

Available information on the relationship between land areas and quality of ground water is summarized in Table 1. This table shows the gross, gross commanded and the culturable commanded areas, and the gross acreage underlain by ground water of specified salinity in ppm. The salinity levels apply to ground waters between 100 to 400 feet below ground surface. The quality of the surficial ground water is generally better and is not shown on Figure 1 or in Table 1. The surficial ground water is largely derived from canal seepage and irrigation recharge since the inception of canal irrigation.

Twenty-five of the 34 million acres in the study area are underlain by ground water with 2,000 parts per million of total dissolved salts or less. There are over 20 million acres with ground water having 1,000 ppm or less salts. It is significant to note that, of the gross area of 34 million acres, there are 25 million acres of land with ground water of good or acceptable quality, whereas the C.C.A. constitutes only 18.7 million acres. In developing the water and land resources of the Indus Plains, consideration must be given to the reclamation of areas with very poor ground water. However, most of the available surface and ground water supplies could be used to irrigate lands underlain by ground water of usable quality.

When taken on a doab basis, it is evident from Figure 1 that the areas of poor ground water are concentrated in specific locations. The lower ends of Chaj, Rechna and Bari Doabs have ground water of very poor quality, with concentrations running as high as 20,000 parts per million. In Thal Doab, there are two major saline ground water areas: one in the north-east corner and another in the centre of the Doab. Another highly saline ground water area lies in the upper centre of Bari Doab. In Bahawalpur the quality of ground water rapidly deteriorates from the Sutlej River toward the Thar desert.

There are many contiguous areas of good to excellent ground water, two of which should be noted here because they lie outside the canal commands and are readily exploitable. They are the Gujrat Plain in Chaj Doab and the area around Sialkot in the upper Rechna Doab.

The most extensive area with highly saline ground water is located in the Lower Jhelum Canal command. About one-third of the gross area of this command is underlain by ground water with 2,000 to 20,000 parts per million of salts. The areas in Bahawalpur, listed in Table 1 as uncommanded, are generally underlain by poor quality ground water.

As might be expected, the saline ground water areas lie more to the centre of the doabs away from the rivers. Part of the good quality ground water occurs in the riverain area. This riverain belt which constitutes 15% of the gross area, is not included in canal commands. It comprises sailab, well irrigated, grass, swamp and unused lands. The concentration of poor quality ground water in the lower ends of the doab is probably brought about by the combined effects of the unfavourable rainfall pattern, regional ground water movement, and evaporation and capillary rise of water from the water table. The average annual rainfall is only one-fifth to one-half as much in the lower areas as in the upper reaches of the Doabs and, conversely, temperatures are higher in the lower ends of the doab than they are at the upper ends. Before the introduction of irrigation, the water table was deep in the upper ends of the doabs and shallow in the lower ends near the confluence of the rivers.

Fresh Ground Water in the Sind

Ground water and aquifer investigations were carried out in the Lower Indus Plains, the former Sind Province, in the three barrage commands of Gudu, Sukkur and Ghulam Mohammad[5-9]. The major part of the investigated area of 7.0 million acres lies in the Gudu and Sukkur commands, while completed investigations in the Ghulam Mohammad Command are confined primarily to two small areas, the Gaja and Thatta project areas.

The limits of the areas of investigation in the Gudu Command and Sukkur Right-Bank Command were determined primarily by the limits of irrigation. The Khairpur Command on the Sukkur Left Bank has also been investigated.

Figure 2 shows the area underlain by ground water with salinities ranging up to 2500 parts per million of total dissolved salts. Ground water of usable quality has not been found in the Ghulam Mohammad Command. The salinity isogram contours of Figure 2 are based upon data obtained from analyses of water samples collected from existing wells, test boreholes and test tubewells at a density of about one for each 100,000 acres. The ground water isogram contours on the map apply to aquifer depths up to about 250 feet below ground surface.

The map thus prepared has been planimetered to determine the area underlain by usable ground water (Table 3). Within the areas for which ground water data are available, there are about 2.3 million acres underlain by ground water with a salt content of 1500 p.p.m. or less. About 1.0 million acres of this area are located between the bunds of the Indus River. Within the area investigated there is an additional area of 0.4 million acres with ground water salinities ranging from 1500 to 2500 p.p.m. By extrapolation of the data on ground water in the Northern Sind area southward to the Ghulam Mohammad Barrage, it is estimated that there is an additional area of at least 1.2 million acres underlain by ground water with salinities less than 1500 p.p.m., of which about 1.0 million are outside the river bunds. This brings the total estimated area in the Sind with ground water of good quality (less than 2500 p.p.m.) to about four million acres. Of this total, 1.2 million acres lie inside the river bunds with estimated salinities less than 1500 p.p.m. and 2.2 million acres lie between the river bunds and the 1500 p.p.m. isogram contour.

GROUND WATER RECHARGE

Punjab and Bahawalpur

The recharge budget for a basin water study for a 60/90 irrigation intensity is given in Table 4. The recharge components are canal and river seepage, and farm irrigation and rainfall throughout. It is believed that the recharge estimates in Table 4 are conservative. A brief discussion of the recharge components follows :

(*a*) Link canal seepage has been estimated on the basis of a seepage factor of 6 cusecs/million sq. ft. and it is assumed that 10 percent of the seepage water is lost to non-beneficial evapotranspiration.

(*b*) The seepage from rivers is discussed in a separate section. Preliminary calculations indicate that the estimated 3 m.a.f. will be low if extensive tubewell development takes place along the 1000-mile length of Punjab rivers. Such tubewell development would greatly reduce present high non-beneficial evapotranspiration losses and increase river seepage.

(*c*) Rainfall recharge is calculated to be 3.5 m.a.f. for a C.C.A. of 18.5 million acres. The method of computation and the results are presented in a separate section of this paper. No credit is taken for any recharge from non-irrigated lands inside or outside canal commands. Nor has the effect of soil wetting by antecedent rains been taken into account. Rains less than 0.5 inches/day have not been considered. It is believed that the estimated rainfall recharge represents a minimum for future conditions.

(*d*) Canal losses have been estimated by assuming that 30 percent of the canal diversion seeps into the ground. Of this amount, 20 percent is assumed to be lost to non-beneficial evapotranspiration. The latter figure equals that calculated for the Gaja project by Hunting and MacDonald who calculated it for an average water table depth of 7 to 8 feet below ground surface and an irrigation intensity of 135 percent. Releases from Mangla and Tarbela reservoirs have been included in the total canal head diversion of 53.9 m.a.f./yr.

(*e*) For the water course flow, it is assumed that 10 percent seeps into the ground and that half of this amount is lost to non-beneficial evapotranspiration. This loss factor is high and reduces the total recharge to 3.5 m.a.f.

(*f*) In calculating irrigation water requirements at the field, we have assumed a farm efficiency of 75 percent. Such a high farm efficiency is possible in West Pakistan because the border system of irrigation is used throughout. The 25 percent loss is made up of evaporation and seepage from ditches; water lost by percolation through the soil to levels below the plant roots due to uneven or excessive applications, low places in the fields, too slow a rate of application, uneven soil permeability, etc., and waste due to failure of overtopping of the borders, failure to stop irrigations at the proper time, or other operational factors. In calculating the recharge from farm irrigation we have assumed that, of the loss of 25 percent, one-fifth will be wasted on the land surface and is lost by evaporation; and that, of there maining four-fifths, twenty-five percent is lost by non-beneficial evaporation. In other words, we have assumed that $(80 \times 75)/100 = 60$ percent of the "farm waste" will be added to the ground water as recharge.

The future recharge will be unevenly distributed over the gross areas. Rivers and large canals act as line sources of recharge, and their effect is localized. Rainfall and rainfall recharge both decrease from the upper doab areas towards the points of river confluence. There are more large canals in the upper ends of the doabs. Recharge from farm irrigation and smaller canals depends on the irrigation intensity which has historically been high in the upper doab areas and low near the lower end of the doabs. WASID has found that the historic and present recharge in the doabs are unevenly distributed; they are high in the upper doab areas (Table 5).

Sind

The fresh ground water area in the Sind comprises about 4 million acres (Table 5). Of this area, 1.3 million acres are situated between the river bunds and 2.7 million acres are outside and along the bunds.

After canals have been remodelled in the fresh ground water area outside the bunds, it appears that deliberate recharge of the ground water reservoir will be feasible in this area. The amount of recharge could be as much as 2 to 2.5 ft. per acre annually during the flood season. This recharge would consist of seepage from canals and watercourses, and downward percolation induced by over-irrigation, possibly rice cultivation. After the flood season the area could then be irrigated by tubewells, for which about $2 \times 2.7 = 5.4$ million acre feet would be available. The water table would then fluctuate annually some 10 to 15 ft. from a high of, say, 4 ft. to a low of about 20 ft. below ground surface.

Between the bunds, the ground water is recharged annually during the flood season when most of these lands are inundated. Some of these lands are now being cropped during the non-flood season and they could be irrigated by tubewells. Alternatively, it is possible to pump fresh ground water between the bunds and carry it to lands outside them. Whatever use is made of the recoverable ground water between the bunds it appears reasonable to assume that 2 million acre feet of water can be recovered there. Water can also be drawn from the river by lowering the water table alongside it. Ultimately, it may be possible to recover more ground water than the total of 7.4 million acre feet estimated here.

Recharge from Rivers

Future recharge from the rivers can only be dealt with in very general terms. For the Punjab, it is conservatively estimated to be 3 million acre-feet per year in the recharge budget (Table 4). The recoverable recharge along these rivers depends on several factors which are listed below :

(*a*) *Average water table slope away from the rivers.*

The slope of the area water table influences the ground water recharge from the rivers. A water table slope of 6 ft./mile away from the river causes an estimated river recharge of 2 million acre-feet per year, in the Punjab.

(*b*) *Tubewell pumping along the river.*

Tubewells located along river channels create a local drawdown, thus steepening the immediate gradient of the water table away from the river and increasing ground water recharge.

(*c*) *Seepage of flood waters into the river channel bed.*
Seepage into the channel bottom is important in areas where the river between the natural levees (bunds) is wide. In several places, the basin rivers are roughly four miles wide between these levees. Assuming that the river bed slopes gradually up from the thalweg to the natural levees, there is a considerable earth reservoir which fills with water during periods of flood flow. A simplified section of this channel would be two triangular widths with the apex at the thalweg, a base length of 2 miles, and 8 to 12 ft. height at the river levees. If the river stage rises by 8 feet over this 4 mile width, the volume of temporary underground storage would be, with a 25% storage factor for the earth, 2,500 acre-feet per mile of river length. Part of this water flows back to the river after the floods recede and a significant portion is lost by non-beneficial evaporation.

(*d*) *Periodic water table rises outside the levees.*
During the flood season, a transient "bulge" will develop in the water table outside the natural river levees. Some of this water recharges the aquifer below the doabs, some returns to the river following the flood, and the remainder is lost by non-beneficial evapotranspiration. Much of this water can be used beneficially for irrigation by ground water pumping adjacent to the river.

(*e*) *Flooding of active and abandoned flood plains.*
Flooding of active and abandoned flood plains takes place periodically. Some of these areas are not commanded by the canals.

Lowering of the water table adjacent to the river channels will cause a greater than historic recharge from floods into the aquifer underlying lands along the river. Extensive ground water development along the rivers will also reduce river base flow during the low-flow season. Therefore, any development of this nature should be preceded by an investigation of the effects of the ground water withdrawals on historic river supplies. Changes in historic diversion patterns and/or supplies from surface storage may be required to make up for decreased base flow, of which the feasibility depends on the efficiency of recovery of bank storage by tubewells.

Rainfall Recharge in the Punjab and Bahawalpur

General: Potential ground water recharge from rainfall has been calculated for an average rainfall year for four geographic zones which centre around Multan, Lyallpur, Lahore and Sialkot. These zonal recharge values have been used to roughly estimate recharge for the four doabs of the Punjab and Bahawalpur. Tabulations of recharge depths by doabs and zones are presented in Table 6. The rainfall recharge for a CCA of 18.5 million acres is calculated to be 3.5 million acre-feet per year.

To arrive at rainfall and recharge depths, individual rainstorms have been tabulated by 1-inch increments for 71 stations[10], generally for periods of 30 years each. In calculating recharge, adjustments have been made in each 1-inch increment from 1 to 10 inches to account for surface runoff and antecedent soil moisture conditions due to irrigation. Wetting of soils due to antecedent rainfall has not been taken into account. This results in underestimating the net recharge in high rainfall zones.

Rainfall : Average point rainfall events have been determined by calculating, for the period of record, the number of events of magnitudes up to ten inches, in decimals, for four groups of stations. An event can occur at any given station without occurring over the entire study area but, over a 30-year period, events of equivalent magnitude will occur at many of the stations. In calculating average rainfall recharge in this way, individual events and area-wide return periods are not significant. In computing the increment of recharge to the ground water, only daily rainfall depths have been considered. It is recognized that some storms are of longer duration, but recorded rainfall data are readily available only for daily periods.

Surface Runoff and Moisture Retention

The net recharge to ground water due to any given daily storm event is the rainfall depth minus evaporation, surface runoff and soil moisture retention. Surface runoff and evaporation have been accounted for as follows :

A 1-inch storm has been reduced by 10 percent and a 10-inch storm by 25 percent; for intermediate storms it has been assumed that the amount of runoff would progressively increase from 10 to 25 percent with increasing amounts of rainfall.

To account for moisture retention, the actually irrigated area (CCA) was divided into four general categories: fallow (40%), recently irrigated (20%), middle of irrigation interval (20%) and just prior to next irrigation (20%). The fallow area comprises the uncropped lands during the kharif season within a 60/90, kharif/rabi, irrigation intensity. The 40 percent fallow is believed valid even though the rainfall events were taken for the entire year, because the majority of the storms that will recharge ground water occur during the monsoon period. It has been assumed that the fallow areas retain 7 inches of water as soil moisture before ground water recharge will occur. Recently irrigated areas were assumed to pass all infiltration to the water table, while areas in the middle of the irrigation interval were assumed to retain 2 inches of water, and those waiting a new irrigation application would retain 4 inches of water. Using these assumptions, the amount of recharge from rain storms of various magnitudes has been calculated in Table 7.

Annual Rainfall Recharge by Zones

The study area has been divided into four zones with respect to rainfall. Zone *A*, the Multan Zone, comprises the lower half of Thal and Bari Doabs and most of Bahawalpur. This is an area of low precipitation, with an average annual rainfall depth of about 6 inches. Zone *B*, the Layllpur Zone, comprises the upper Thal, lower Chaj, lower Rechna and central Bari Doabs and the remainder of Bahawalpur. Average annual rainfall in this area is about 10 inches. Zone *C*, the Lahore Zone, comprises the central Chaj Doab, central Rechna Doab and upper Bari Doab. Average annual rainfall is about 16 inches in Zone *C*. Zone *D*, the Sialkot Zone, covers the upper Chaj and Rechna Doabs. Average annual rainfall in this zone is about 25 inches. These zones are not of equal size but become progressively smaller from *A* to *D*. Table 6 shows that the average annual recharge for zones *A*, *B*, *C* and *D* amounts to 1.0, 2.3, 3.6 and 5.6 inches respectively.

Rainfall Recharge for Four Doabs and Bahawalpur

Doab-wide average annual recharges have been calculated from zonal recharges by weighting the doab area falling in each zone, as shown in Table 6. The annual ground water recharge thus calculated for Rechna, Chaj, Thal and Bari Doabs and the Bahawalpur Area amounts to 3.2, 3.7, 1.6, 2.1 and 1.1 inches, respectively. The average annual recharge for the whole study area is 2.3 inches.

The rainfall recharge of 2.3 inches applies to the CCA as presently distributed over the various climatic zones and for an irrigation intensity of 60 percent during kharif. With a higher irrigation intensity and more irrigation in the high rainfall zones, recharge from rainfall will increase. Further development of intensive irrigation in the Gujrat and Sialkot areas will increase rainfall recharge. If the assumed areal distribution of the CCA and kharif intensity are representative of future conditions and if the future CCA irrigated with canal and tubewell water amounts to 18.5 million acres, the rainfall recharge will be at least $(2.3/12)18.5=3.5$ m.a.f./yr.

The area of several million acres, comprising the difference between GCA and CCA, is assumed not to contribute to rainfall recharge. It is assumed that antecedent moisture conditions in these areas are equivalent to those on fallow lands, which do not contribute to rainfall recharge. The absence of rainfall recharge from fallow lands is due to the high moisture retention capacity of fallow lands, and because the effect of antecedent wetting of soils by prior rains has not be taken into account. Additional irrigation development will bring more areas under cultivation which in turn increases rainfall recharge.

QUALITY OF GROUND WATER

General

Suitability of water for irrigation depends on four factors[11]: total dissolved salts (ppm), the Na-concentration in relation to the (Ga+Mg)-concentration, the (CO_3+HCO_3)-concentration, and the boron concentration. Data are available concerning the acreage underlain by ground waters with specified amounts of total dissolved salts. The information is summarized in Tables 1 and 3, which are discussed in a subsequent section. The Na-content and (CO_3+HCO_3)-content of the ground waters have been determined in the course of the investigations. An analysis of data from selected areas of Rechna Doab is presented in Table 8, which is discussed in later paragraphs. Determinations of boron—which is harmful at very low concerntrations (0.3 to 3 ppm, depending on the crop)—have not yet been made under present investigation programs but will be made in the future. It is quite possible that the more saline ground waters contain harmful concentrations of boron.

Total Dissolved Salts

The salt content or concentration of water is usually expressed in parts per million (ppm) or in terms of the specific electrical conductance of water. Salts in solution increase the osmotic pressure and so decrease water availability to plants. Salt-tolerance of plants varies widely but, with appropriate irrigation practices, normal cropping patterns can be developed for irrigation with waters containing up to 2000 ppm. of salts.

Sodium

High sodium contents adversely affect soil stability and cause dispersion of clay particles, thus reducing the infiltration rate, soil permeability, and soil aeration. The permissible Na-concentration depends on the relative concentration of (Ca+Mg) to which it is related by the so-called sodium adsorption ratio, SAR, a measure of sodium hazard, which is calculated from the following equation[11]:

$$SAR = Na^{+}/[(Ca^{++}+Mg^{++})/2]^{\frac{1}{2}}.$$

The adverse effect on soil stability of a high sodium content in irrigation water varies with the soil. The clay mineral composition of the soil is particularly significant in determining when sodium becomes harmful to soil stability. It is commonly assumed[11] that clay particles will be dispersed, if the adsorbed sodium exceeds 15 percent of the total exchangeable cations. For low-carbonate waters there exists a simple relationship between ESP and SAR (USDA Handbook 60[11], Figure 23, page 103).

In evaluating the sodium hazard of Punjab tubewell waters—which is discussed in subsequent paragraphs—Bower and Maasland[13] have made the assumption that the safe exchangeable-sodium percentage (ESP) might be 20 percent.

Carbonates and bi-carbonates

In evaluating the effect of CO_3 and HCO_3, it is significant to note that their effect is an indirect one. They cause precipitation of dissolved Ca and Mg which increases the relative concentration of Na.

High CO_3 and HCO_3 contents in conjunction with high Na-contents also cause deterioration of irrigated soils by reducing infiltration rates, permeabilities and soil aeration. This makes it difficult to irrigate the lands and results in a reduction of crop yields.

To evaluate the effect of CO_3 and HCO_3, the concept of "residual sodium carbonate" is often used, which is defined as the milli-equivalents of (CO_3+HCO_3) per liter of water remaining after the meq/lt. of (Ca+Mg) are subtracted from the meq/lt. of (Ca+Mg) are subtracted from the meq/lt. of (CO_3+HCO_3) in the irrigation water. If this calculation results in a negative figure the water is said to be free from residual carbonate.

The adverse effects of residual Na_2CO_3 have been demonstrated clearly in several irrigated areas. Amounts of residual Na_2CO_3 exceeding 2.5 meq/lt. of water have proved harmful to irrigated soils. Permissible amounts of residual carbonate vary with the soil and climate.

Many ground waters in the Indus Plains have undesirably high contents of CO_3 and HCO_3. The CO_3 and HCO_3 contents are generally high particularly in waters with contents of total dissolved salts between 300 and 3000 ppm.

The validity of the "residual Na_2CO_3"-concept as developed in USDA Handbook No. 60[11] has been questioned by several authorities. For that reasons, Bower[12] developed recently a new method for evaluating the effect of CO_3 and HCO_3 on water quality for irrigation. This new method was used by Bower and Maasland[13] to evaluate the quality of Punjab tubewell waters. A detailed analysis was made of the characteristics of waters from 74 tubewells in the Hafizabad, Khangah Dogran, Jaranwala and Beranwala Reclamation Schemes in Rechna Doab. These waters were selected on a random basis from water analyses for several hundred wells in Rechna Doab. It was concluded that, of these tubewells 33 percent may be considered safe, 28 percent are marginal and 39 percent are hazardous.

Using the traditional standard that waters with amounts of residual Na_2CO_3 exceeding 2.5 meq/lt are hazardous for irrigation use, it follows from Table 8 that 39 percent of 729 Rechna Doab tubewells are hazardous. The fact that, with the new method, the percentage of hazardous tubewells is also

39 per cent for only 74 tubewells is fortuitous but may indicate that the concept of "residual Na_2CO_3" has more validity than is sometimes believed.

Methods of Improving Water Quality

It has been proposed to overcome the adverse effects of the high-carbonate contents of tubewell waters by dissolving gypsum in the tubewell water or applying gypsum to the land. The former appears impractical because of the relatively low solubility of gypsum (30 meq/lt). Both appear infeasible in view of the high quantity of gypsum that is required (Table 9). For example, 1.4 short tons of pure gypsum are required per day per 3-cusec tubewell to precipitate 2 meq/lt of residual Na_2CO_3; or, with an annual utilization factor for tubewells of 50 percent, 256 short tons of pure gypsum per 3-cusec tubewell per year. Many wells will require more gypsum because CO_3+HCO_3 contents are very high (Table 9). Gypsum should not be used to improve irrigation water but rather to improve soils which are alkaline.

A feasible way of reducing the residual Na_2CO_3-contents is to arrange for mixed use of surface and ground waters. Three mixing ratios have been calculated for the waters from each of the 29 out of 74 tubewells (or 39 percent) considered to be hazardous. The average mixing ratios required to lower the ESP's of these tubewell waters to 10, 15 and 20, were thus found to be 1: 3.8 1: 2.1 1: 1.2, respectively, for the ratio of tubewell water to surface water. The results of these computations are summarized in Tables 10. Instead of mixing, it appears possible to alternate the use of "good" and "hazardous" water. This would make it possible to use ground water in the winter and combined surface and ground water in the summer, as long as mixing requirements are met on, say, an annual basis.

Precise limits for "Marginal" and "Hazardous" irrigation water have not yet been established for Punjab soils. The marginal range of irrigation water is defined as water which will bring about ESP's from 10 to 20 in the soils. Additional samples need to be analyzed for various doabs and areas to develop representative mixing requirements.

GROUND WATER WITHDRAWAL SALINIZATION

Ground Water Availability and Withdrawal

Distribution of ground water availability and withdrawals is a question of immediate concern. Ground water supplies must be developed and generally be used where they are available. However, there is not a favourable relationship throughout the Indus Plains between the availability of ground water and the need for supplemental supplies. Ground water availability for irrigation use diminishes from north to south in the Indus Plains as welll as down-doab, and is negligible in the southern parts of Chaj, Rechna, and Bari Doabs; and the southern Sind, where the ground water is too mineralized for use.

On the other hand the demand for irrigation water and the need for supplemental supplies both increase toward the more arid southern areas. Under these conditions it is evident that the criteria for a program of maximum exploitation of the ground water resources must be based on regional ground water hydrologic factors as well as on local water demand factors.

Areas underlain by saline ground water are also in need of additional water supplies for irrigation. This would involve transfer of more water into the southern part of the Indus Plains generally, and into the southern parts of Rechna, Chaj and Bari doabs. Remodelling of the existing canal systems or construction of new canals would be required. This in turn, would increase the area recharge and the sub-surface drainage requirement in areas where the quality of ground water is unfit for use and where the canal leakage cannot be salvaged for irrigation use. In these areas, in the interests of conservation of water and economical drainage operations, it may be feasible to inhibit canal leakage by lining or by using emulsion-type sealants that can be applied while the canals are in service. Alternative methods of conserving water are ground water utilization after an initial period of desalinization of ground water by surface-water recharge and saline-water displacement, abandonment of land and/or non-increase of the water supply.

Salt Balance in Areas with Ground Water of Good Quality

Maintenance of a favourable salt balance is related to ground water supply and withdrawal—related in the sense that pumpage will trigger changes in the hydrologic environment, which in turn will influence the quality of water relationships in the aquifer. Several inherent factors in the tubewell system will cause a depreciation of the quality of ground water with time, if there is no disposal of water to outside areas. Among the more important factors which affect the salt balance of the ground water are :

(*a*) *Leaching of upper soil layers.*

This will occur when full irrigation supplies are made available. It will add appreciable amounts of salt to the ground water in storage. The effect will be most pronounced in the early years of reclamation, when the salts accumulated in the upper soil layers will be added to the ground water.

(*b*) *Recirculation of aquifer salts.*

In the cycle of recirculation of water from the aquifer to irrigated fields and back to the aquifer, most of the salts will remain in solution whereas most of the water will be lost to evapotranspiration.

(*c*) *Salt accretions from irrigation with surface water.*

The annual increment of salts derived from canal irrigation supplies will also be transported downwards to the water table.

(*d*) *Salt accretions from canal and river seepage.*

The relatively large volume of low-salt recharge has a net diluting effect but the annual increment of seepage water (250 ppm) adds to the total salts dissolved in the ground water.

(*e*) *Reduction of gronnd water volume with mining.*

A reduction in volume of the ground water in storage will cause a proportional increase in the mineral concentration of the ground water.

(*f*) *The amount of ground water removed by drainage.*

The chemical reaction between the percolating recharge water and the un-watered sediments will also bring more salts into solution.

In addition to the above factors which essentially involve mobilization of salts, there are the added hazards of lateral and upward intrusion of saline water into fresh ground water zones in response to pumping. The extent of saline water intrusion is dependent on piezometric head differentials between the fresh and saline ground water zones, pumpage in and around saline ground water zones, and the capacity of tubewells and size and location of tubewell strainers in relation to the depth of a horizontal fresh-saline ground-water inter-face. These factors must be considered in project layout and design for which detailed knowledge of the aquifer characteristics and salinity conditions of the ground water is required.

Ground Water Salinization and De-Salinization

Depreciation of tubewell water quality in areas with ground water of good quality will only be gradual because :

(*a*) The saline leaching water moves slowly from the water table towards the tubewells through flow tubes between stream lines.

(*b*) The river waters have a very low salt concentration.

(*c*) The saline recharge water is blended with ground water in storage in the aquifer.

Rainfall recharge has the effect of improving ground water quality but its effect is very small in the Indus Plains because the rainfall recharge is low. A first study of ground water salinization has been made by the Water Resources Group of Harvard University[14] in which it is assumed that factors *a* through *d* of the listing in the previous section are operative uniformly over the whole area and that uniform mixing of saline components occurs. However, the seepage from larger canals and rivers, which constitutes a significant portion of the recharge balance, is localized. Nevertheless, the study gives a valuable indication of the average rate of salinization but salinization will be more rapid far away from large canals and slower near these canals.

Particular cases studied by Harvard are given in Table 11. The results of the study have been reproduced here as Figures 3 and 4 from Figures 11 and 13 of reference 14. The conclusions of the Harvard report[14] on salinization of ground water are listed below:

(*a*) *Tubewell Spacing* has no effect on the salt build-up characteristics of irrigation water.

(*b*) *Tubewell Depth* (*a*) increases the rate of build-up inversely proportional to the depth and (*b*) increases the concentration of the irrigation water due to salt on the surface of the earth inversely proportional to depth.

(*c*) *Drainage* of up to 10 or 15 percent of the tubewell effluent is necessary. In most cases the pumps-to-drain flow can be delayed for 10 or 20 years without excessive salt build-up provided that the total drainage in 50-years is equal to about 10 percent of the total pumpage.

(*d*) *Pumping Rate* increases the rate of salt build-up directly proportional to the pumping rate.

(*e*) *Initial Ground Water Concentration* raises or lowers the entire build-up curve in proportion to the initial concentration.

(*f*) *Deep Wells* (250 ft. or more) should be employed in all areas where there is 60 or more tons per acre of salt on the ground surface and in the upper layers of the soil.

These conclusions are important to long-term water development plans. They affect area development plans and the amount of saline water disposal that must be provided. With mining, ground water salinization will be more rapid than would follow from the Harvard study[14]. If the water table is lowered from 10 ft. to 110 ft. below ground surface with 250 ft. tubewells, the salinity will increase approximately to $(250/150) \times 100 = 167$ percent of that estimated in Figures 3 and 4.

Increased surface water recharge will enhance the quality of the ground water. Ground water salinization will be slower near large canals and rivers. In the latter study, the tubewell water/surface water ratio and the recharge water/surface water ratio are identical and amount to 0.56 for a pumping rate of 0.881 cf/sf/yr and a surface water rate of 1.586 cf/sf/yr, and 0.74 for a puming rate of 1.674 cf/sf/yr and a surface water rate of 2.248 cf/sf/yr.

The results of the Harvard studies[14] indicate that there is no immediate need for disposal of tubewell water where the ground water is presently of reasonable quality. It appears desirable to arrange for disposal of some tubewell water in areas where the initial salinity of the ground water is greater than, say, 2000 to 3000 ppm, depending on the economics of a "saline" agriculture in these areas.

Irrigation with surface water and removal of most of the recharge increment as saline tubewell water will improve ground water quality in saline ground water areas. Knowledge of the rate of de-salinization of ground water is of interest, when developing tubewell systems in irrigation areas underlain by saline ground water. It should be possible to compare the costs and benefits of de-salinization with those of canal lining, if the following factors were known for representative conditions :

(*a*) The rate of canal seepage;

(*b*) The rate of de-salinization of ground water;

(*c*) Ultimate available amount of irrigation water of a specified quality, consisting of mixed surface and ground water;

(*d*) Ultimate drainage requirement for tube-well water to maintain ground water quality;

Ground water salinization and de-salinization require further study for both the Punjab and Sind Regions and various canal areas. In this connection, an analysis of the additional case studies listed in Table 12 would be of interest for basin and project planning.

UNDER-GROUND STORAGE OF SURFACE WATER

The implications of the tubewell program go beyond the immediate irrigation problems of the Indus Plains. Diversion of surface water to ground water storage appears to be a favourable method for reducing river runoff wasting to the sea. The alluvial aquifer that underlies the Indus Plains is well-suited as a storage reservoir with respect to both availability of recharge and to areas of use of the water, and there are no extensive geologic barriers to recharge or to circulation within the aquifer. The storage capacity of the ground water reservoir is very large and the reservoir has an indefinite life, because ground water recharge is free of sediment. Thus, the use of ground water storage would permit more flexible and complete control of the water resources of the Indus Basin. The ground water reservoir can be replenished according to the availability of surface water for recharge, and the reservoir can be tapped according to the demand for water without regard to seasonal or annual variations in runoff. Increased recharge with surface water improves the quality of the ground water.

The major problem involved in the management of the aquifer as a reservoir is that of promoting increased recharge at a sufficient rate to accommodate surface water during the periods of high river runoff. An obvious way to increase recharge is to increase rice growing in tubewell areas which would decrease the rate of salinization of the ground water in addition to storing river water. However, this requires increased canal capacities in tubewell areas and also increased surface storage on the rivers to provide water to meet down-stream water requirements at the beginning and end of the Kharif season. Tubewell development along the rivers will enhance effective utilization of the ground water stored temporarily in the river banks during the flood season, and will increase recharge from the rivers but decrease river flows in the rabi season.

Other methods of increasing recharge are over-irrigating crops other than rice; inducing flooding of the flood plains along the river; diverting flood waters through nalas and abandoned river beds such as the old channel of the Beas River in Bari Doab; diverting flood waters from the western rivers through the eastern rivers; and retaining rainfall on permeable soils rather than removing it by storm drains. Recharge by deliberate over-irrigation appears attractive in areas with permeable soils near the heads of main canals. All of these matters must be carefully studied before the most desirable plan for resource development and utilization can be developed.

EMPHASIZING DEVELOPMENT OF GOOD QUALITY GROUND WATER AND GOOD LANDS

The objective of increasing agricultural production in the Indus Plains is achieved most easily by increasing the water supply per unit area and by intensifying the irrigation of good lands. Development of fresh ground water for use on good lands is a low-cost investment yielding high returns in terms of increased agricultural production. Soil reclamation delays immediate increase of crop production. Development of saline ground water zones requires a high initial investment and immediate development of surface water supplies for intensification of irrigation. It appears inadvisable to develop at this time areas with costly, time-consuming problems because the Indus Plain comprise a much larger area of land than can be adequately served with the available water supplies. This statement does not apply to development projects using locally available water resources that cannot be transferred to other areas.

Reclamation of alkaline and/or saline lands can be costly and slow, and often requires special methods of water use and/or chemical amendments. One method for reclaiming alkaline lands is to initially pond saline water on them. Development of areas underlain by saline ground water zones requires high-cost tubewells, immediate construction of a fully-developed disposal system, additional surface water, and immediate enlargement of canals to carry surface water for increasing the intensity. Water table control in saline ground water zones without concurrent increase in irrigation intensity is hardly justifiable because benefits thus realized are low. This does not mean that no saline or alkaline soils should be developed or that no water tables in saline ground water zones should be controlled. Some soils are easy to reclaim and intensities of some saline ground water zones can be increased at reasonable cost, if there is a nearby source of surface water and/or canal remodelling costs are low. Also, within large fresh ground water bodies, small zones with water of moderate salinity will be developed. In some areas, the piezometric head in the saline grounds water zone may have to be reduced to control salt-water intrusion into the fresh ground water.

This statement merely points out the obvious fact that—with the extensive areas of non-saline and easily-reclaimable lands underlain by good ground water in the Punjab and Bahawalpur—the expense of land reclamation and/or development of saline ground water sould be justified considering the following inter-related factors:

(*a*) *Cost of land abandonment and re-settlement.*
Established agriculture may be well-developed and land abandonment may involve high expenditure for development elsewhere or great hardship.

(*b*) *Land value.*
Saline and/or alkaline lands may occur within a large contiguous body of good lands and land values may be high because of proximity to markets such as Lahore, etc.

(*c*) *Cost of land reclamation.*
Cost for reclaiming lands and possible losses due to a decrement in agricultural production during the reclamation period.

(*d*) *Cost of saline ground-water development.*

(*e*) *Ground-water salinization due to leaching.*

(*f*) *Salt-water intrusion into fresh ground-water zones.*
Development of certain saline ground water zones may be required to maintain water quality in good-quality ground water zones.

(*g*) *Disposal of saline water.*

PRINCIPAL CONCLUSIONS

Punjab and Bahawalpur

1. Of the total area of 34 million acres on the Indus left bank, 25 million acres of the Punjab and Bahawalpur are underlain by ground water containing 2000 ppm or less of salts and 21 million acres of land are underlain by ground water containing less than 1000 ppm of salts.

2. The available water supply for the Punjab could be used on land underlain by good quality ground water, and the need for disposal of highly-saline native ground water into the rivers would thus be limited.
3. Many ground waters of 300 to 3000 ppm of salts contain harmful concentrations of CO_3 and HCO_3 anions, requiring dilution by mixing with surface water. This problem cannot be resolved by using gypsum because the quantities required are too large.
4. Since high-carbonate ground waters are a major problem, it is advisable to prepare maps showing the area with high-carbonate ground water. Maps showing high-sodium ground waters should also be prepared.
5. Existing canal commands do not always coincide with the zones of good-quality ground water.
6. The present uneven distribution of ground water recharge and quality makes it desirable to adjust the development program to fit ground water hydrologic conditions.
7. Areas along the rivers are all underlain by ground water of good quality. Tubewell development along the rivers will increase the total water supply by decreasing non-beneficial evapotranspiration.
8. The extensive ground water reservoir can be exploited as a flexible source of water supply and regulation.
9. Increased recharge by over-irrigation of kharif crops or increased rice growing on permeable soils should be investigated as means of using the aquifer to conserve flood waters and of improving the quality of the ground water. Costs of required increases in canal capacities must be considered in the analysis.
10. Withholding of early flood flows to fill reservoirs, and increasing river seepage resulting from lowering the water table by ground water pumping, can adversely affect water supplies for areas dependent on surface water, particularly in the early and late parts of the kharif season. Additional reservoir storage, controls on filling of reservoirs, and increased use of available ground water may be required to avoid difficulty.
11. The need for pumping of highly saline ground water should be minimised, particularly during the non-flood season. Consideration must be given to:
    (*a*) Desalinization of the ground water;
    (*b*) Skimming of upper "fresh" ground water; or
    (*c*) Reduction in recharge by canal lining, curtailment of rice growing, or restrictions on cropping intensities in saline ground water areas.
12. It may be necessary to dispose of saline and moderately-saline ground water from zones with ground water of usable quality, in 10 to 20

years after the beginning of ground water development, to maintain water quality. This point requires further study.

13. The estimated annual recharge of 36.3 million acre-feet in the recharge budget is conservative.
14. Rainfall recharge will contribute at least 3.5 m.a.f. per annum under future conditions of irrigation water supplies and intensities.
15. A lowering of present water table levels will increase canal seepage and decrease available surface supplies in downstream areas of canal commands, if surface water inputs are not increased.

Sind

1. There are about four million acres in the Sind underlain by usable ground water. About 2.7 million acres of this area are situated outside the river bunds.
2. The area lying between the bunds along the Indus River is also significant in plans for developing the ground water resources in the Sind. This area is subjected to occasional flooding and has ground water of good quality. Exploitation of this ground water would require expensive facilities, if this water is to be transported to areas outside the bunds. It is estimated that about 15 percent of this area is flooded only infrequently and is not subject to river meander changes. Crops and forests are or can be grown there.
3. It appears that there will be a problem with high sodium bi-carbonate in the areas with ground water of low salinity, particularly in the Larkana-Shikarpur area on the Sukkur-Gudu Right Bank.
4. More detailed information is required on ground water quality before a firm plan of development can be prepared for the fresh ground water zone in the Sind. Preliminary evidence indicates that, in the fresh ground water areas, wells of at least 200 to 250 feet in depth will pump fresh ground water, especially near the Indus River. This depth may have to be reduced for wells farther from the river because the depth of the fresh ground water layer decreases with the distance from the river.
5. The amount of recoverable recharge in the fresh ground water area in the Sind is presently estimated to be about 7.5 million acre feet annually.

ACKNOWLEDGMENT

Many of the basic data have been obtained from WASID and the WAPDA Consultants for the Lower Indus Basin. Certain paragraphs of a recent WASID report[1] have been directly quoted by us. An earlier draft of the WASID report was available to the authors at the time this paper was prepared.

TABLE

Gross Land Areas in Punjab and Bahawalpur

Doab	Canal Area		Gross Area	GCA	CCA
Rechna	Sialkot Area	..	1,053	Not commanded	
	Marala-Ravi	..	190	190	160
	Upper Chenab	..	1,964	1,511	1,445
	Lower Chenab	..	4,382	3,703	2,937
	Ravi-Sidhnai	..	290	223	201
	Sub-Total	..	7,879	5,627	4,793
Chaj	Gujrat Plain	..	638	Not commanded	
	Upper Jhelum	..	871	580	541
	Lower Jhelum		2,169	1,622	1,499
	Sub-Total	..	3,677	2,202	2,040
Thal	Thal Main Line	..	3,528	1,855	1,473
	Muzaffargarh	..	1,037	721	714
	Rangpur	..	693	380	347
	Undeveloped	..	391	—	—
	Thal Desert	..	1,971	Desert	
	Sub-Total	..	7,620	2,956	2,534
Bari	Central Bari	..	1,041	704	642
	Lower Bari	..	2,063	1,822	1,460
	Dipalpur		1,226	1,045	983
	Pakpattan	..	1,544	1,396	1,261
	Mailsi	..	1,131	751	688
	Sidhnai	..	1,181	900	810
	Sub-Total	..	8,186	6,618	5,844
	Total Punjab	..	27,362	17,403	15,211
Bahawalpur	Fordwah	..	705	461	425
	Eastern Sadiqia	..	1,170	1,134	937
	Qaimpur	..	120	46	42
	Bahawal	..	992	791	648
	Abbasi	..	163	131	110
	Panjnad*	..	1,964	1,505	1,339
	Undeveloped	..	1,502	—	—
	Total Bahawalpur	..	6,616	4,068	3,501

*Salinity isogram contours incomplete; about 50% of the Panjnad area

1

Related to Salinity of Ground Water

Area with Ground Water of Specified Quality (ppm T.D.S.)								
Less than 500	500-1,000	1,000-2,000	2,000-3,000	3,000-4,000	4,000-5,000	5,000-10,000	10,000-20,000	More than 20,000
—	1,053	—	—	—	—	—	—	—
132	58	—	—	—	—	—	—	—
1,718	246	—	—	—	—	—	—	—
1,408	1,220	968	222	90	155	261	58	—
131	54	28	11	13	11	31	11	—
3,389	2,631	996	233	103	166	292	69	—
—	638	—	—	—	—	—	—	—
412	357	102	—	—	—	—	—	—
1,009	308	204	100	141	90	208	81	27
1,421	1,303	306	100	141	90	208	81	27
863	945	844	274	172	216	200	14	—
516	405	73	25	11	7	—	—	—
443	158	45	25	14	8	—	—	—
11	51	72	163	60	23	11	—	—
33	1,100	627	176	25	10	—	—	—
1,866	2,659	1,661	663	282	264	211	14	—
325	238	184	203	36	37	18	—	—
496	1,043	281	130	49	39	25	—	—
454	421	313	32	6	—	—	—	—
580	540	170	53	45	45	111	—	—
581	205	66	52	48	68	111	—	—
851	140	105	76	8	1	—	—	—
3,287	2,587	1,119	546	192	190	265	—	—
9,963	9,180	4,082	1,542	718	710	976	164	27
303	190			194		18	—	—
—	5			90		635	370	70
120	—			—		—	—	—
254	101			485		146	6	—
6	16			36		61	44	—
—	—			—		—	—	—
10	17			381		687	407	—
693	329			1,186		1,547	827	70

believed underlain by ground water with less than 1,000 ppm. T.D.S.

TABLE 2
Land Use on Non-Canal Irrigated Lands in the Punjab and Bahawalpur

Land Use	*Explanation*	*Acreage* (million of acres)
Sailab	Water is supplied for cultivation by river over-flow. Inundation canal areas are not included.	1.3
Irrigated by Wells	Well water is lifted by mechanical and animal power.	0.7
Barani	The water supply for cultivation is supplied by rainfall.	2.4
Grassland	Generally situated in riverain belts and water-logged areas.	0.3
Swamps and Water	Generally comprising depressions and aban-doned river channels.	0.9
Semi-desert and Scrubland	Both areas of sand dunes as well as seasonal shrubs and grasses, which are grazed, are in-cluded in this category.	6.0
Woodland	Generally reserved or protected forests	0.2
Unused Lands	All land not cropped, grazed or devoted to woodland or urban settlement.	2.9
	Total Non-Canal Irrigated Lands	14.7

TABLE 3
*Land Areas in the Sind Underlain by Useable Ground Water**

Barrage Command	Relation to Bunds	Area in Millions of Acres		
		Up to 1500 ppm	1500-2500 ppm	Up to* 2500 ppm
Gudu	Between	0.47	—	0.47
	Outside)	0.92	0.18	1.10
	Sub-Total	1.39	0.18	1.57
Sukkur	Between	0.60	—	0.60
		0.25 **	—	0.25 **
	Outside	0.39	0.28	0.67
		1.00 **	—	1.00 **
	Sub-Total	2.24	0.28	2.52
Ghulam Muhammad		Nil	Nil	Nil
Three Commands	Between	1.32	Nil	1.32
	Outside	2.31	0.46	2.77
	Grand Total	3.63	0.46	4.09

* Waters with a salt content of 2500 ppm. or less.

** No data available for lower Sukkur Command. Estimate obtained by extrapolation of isogram contours in vestigation area down river to Ghulam Muhammad Barrage.

TABLE 4

*Estimate of Ground Water Recharge in the Punjab and Bahawalpur**

			m.a.f.
1.	**Link Canals**		3.7
	Seepage is approximately 4.10 m.a.f. This seepage loss has been calculated on the basis of 6 cusecs per million sq. ft. of wetted perimeter of canals. If 1p% is lost to non-beneficial evapotranspiration the net recharge is 3.7 m.a.f.		
2.	**Seepage from Punjab Rivers**		3.0 (low)
3.	**Rain throughout to Ground Water**		3.5
4.	**Leakage from Canal System**		13.0
	Canal Loss $=0.3\times53.9$	$=$ 16.2 m.a.f.	
	Non-Recharge loss $=0.2\times16.2$	$=$ 3.2 m.a.f.	
5.	**Watercourse Seepage**		3.5
	Flow=37.7 (canals)+33.3 (tubewells)	$=$ 71.0 m.a.f.	
	Seepage $=0.1\times71.0$	$=$ 7.1 m.a.f.	
	Loss to non-beneficial evaporation $=0.5\times7.1$.	$=$ 3.6 m.a.f.	
	Recharge	$=$ 3.5 m.a.f.	
6.	**Recharge from Farm Irrigation**		9.6
	Farm Supply=71.0—7.1	$=$ 63.9 m.a.f.	
	Infiltration from farm irrigation $=0.20\times63.9$	$=$ 12.8 m.a.f.	
	Non-beneficial losses 0.25×12.8	$=$ 3.2 m.a.f.	
	Recharge from farm land	$=$ 9.6 m.a.f.	
		Total Recharge (m.a.f-)	36.3

* In million acre-feet; for an average year and an irrigation intensity of 150 percent, that is, 60 percent in kharif and 90 percent in rabi.

TABLE 5

Observed Water Table Rises and Recharge[1] *(Feet per year)*

Area	Water Table Rises[2]				Average Recharge[3]
	Avg.	Upper	Middle	Lower	
Rechna Doab	2.10	2.86	1.87	1.42	0.5
Chaj Doab	2.07	2.70	2.30	1.20	0.5
Thal Doab	2.00[4]	NG	NG	NG	0.5
Bari Doab	NG	NG	1.10	0.70	NG[5]

1. All data taken from refernce 1.
2. Annual water table rises in feet per year as read in observation wells while ground water rose linearly in consecutive years. The rises listed refer to doab areas away from rivers.
3. Historic recharge in feet of water per year calculated from historic water table rises using a storage co-efficient of 0.25.
4. For commanded areas only.
5. N.G—not given in reference 1.

TABLE 6

Summary of Ground Water Recharge from Rainfall on Canal Irrigated Areas in the Northern Zone for 60 Percent Irrigation Intensity in Kharif Season

Computation of Recharge by Zones

Rainfall Inches	Recharge Inches	Zone A (Multan)		Zone B (Lyallpur)		Zone C (Lahore)		Zone D (Sialkot)	
		Annual Events	Annual Recharge	Annual Events	Annual Recharge	Annual Events	Annual Recharge	Annual Events	Annual Recharge
1.0	0.18	3.580	0.644	6.250	1.130	10.000	1.800	14.300	2.570
2.0	0.36	0.630	0.227	1.670	0.610	2.500	0.900	3.700	1.330
3.0	0.64	0.125	0.080	0.460	0.290	0.715	0.458	1.250	0.800
4.0	0.94	0.031	0.030	0.132	0.124	0.222	0.209	0.435	0.409
5.0	1.26	0.012	0.015	0.044	0.055	0.085	0.110	0.179	0.266
6.0	1.74	—	—	0.017	0.030	0.036	0.063	0.077	0.134
7.0	2.16	—	—	0.008	0.017	0.016	0.035	0.029	0.064
8.0	2.58	—	—	—	—	0.007	0.017	0.012	0.032
9.0	2.88	—	—	—	—	—	—	0.004	0.012
10.0	3.50	—	—	—	—	—	—	—	—
Total Zone			1.0 in.		2.3 in.		3.6 in.		5.6 in.

[*Contd.*

TABLE 6—*Contd.*

Computation of Average Annual Recharge from Rainfall by Doabs and Northern Zone East of Indus River

Doab	Zones A	Zones B	Zones C	Zones D	Doab Total	Percent of CCA in Doab	Weighted Recharge Inches
Rechna—% in Zone	4	43	41	12			
Weighted Recharge	0.04	0.99	1.48	0.67	3.2	25	0.80
Chaj—% in Zone	0	45	21	34			
Weighted Recharge	—	1.04	0.76	1.90	3.7	11	0.41
Thal—% in Zone	55	45	—	—			
Weighted Recharge	0.55	1.04	—	—	1.6	14	0.23
Bari—% in Zone	49	20	31	—			
Weighted Recharge	0.49	0.46	1.12	—	2.1	31	0.65
Bahawalpur—% in Zone	90	10	—	—			
Weighted Recharge	0.90	0.23	—	—	1.1	19	0.21

Average Annual Recharge for Northern Zone=2.30 in.

TABLE 7

Ground Water Recharge From Rain Storms

	Antecedent Moisture Condition			
	Period Since Last Irrigation			Summer Fallow
	Recent	1 Week	2 Weeks	
Percentage of CCA	20	20	20	40
Soil Moisture Retention (inches)	—	2	4	7

Storm Depth inches*	Infiltration Depth inches	Increment of Ground Water Recharge inches				Total Recharge inches
1.0	0.9	0.9	—	—	—	0.18
2.0	1.8	1.8	—	—	—	0.36
3.0	2.6	2.6	0.6	—	—	0.64
4.0	3.4	3.4	1.4	—	—	0.96
5.0	4.1	4.1	2.1	0.1	—	1.26
6.0	4.9	4.9	2.9	0.9	—	1.74
7.0	5.6	5.6	3.6	1.6	—	2.16
8.0	6.3	6.3	4.3	2.3	—	2.58
9.0	6.8	6.8	4.8	2.8	—	2.88
10.0	7.5	7.5	5.5	3.5	0.5	3.50

*Daily rains less than 0.5 inches have not been considered. Each daily reinstrom value covers a range from —0.5 to +0.5 inches of the amount stated.

TABLE 8

*Summary of Chemical Analyses of Tubewell Waters in Rechna Doab**

Unit Number of Wells

Area	Number of Tubewells	Dissolved Solids (ppm)						Residual Na_2CO_3 (meq/liter)					
		Less than 500	500 to 750	750 to 1000	1000 to 2000	2000 to 3000	More than 4000	0 or less †	0 to 2.5	2.5 to 4.0	4 to 6	6 to 10	More than 10
Baranwala	119	7	16	25	66	4	1	7	25	18	17	45	9
Khangah-Dogran	203	142	41	12	8	Nil	Nil	77	93	16	13	4	Nil
Jaranwala	101	26	15	10	37	13	Nil	30	39	15	13	4	Nil
Hafizabad	306	109	123	51	21	2	Nil	61	112	48	51	34	Nil
Total Number	729	284	195	98	132	19	1	175	269	97	94	85	9
Percent of Total	100	39	27	14	18	2	0	24	37	14	13	11	1

*For four of the twelve tubewell areas in Rechna Doab. (SCARP No. 1).

Note that 39% of the tubewells have Residual Na_2Co_3 content greater than 2.5 meq/it.

†The computation of residual Na_2CO_3 may result in a negative number.

TABLE 9

Gypsum required to Eliminate Sodium-Bicarbonate in Tubewell water

The reaction that takes place is:

$$CaSO_42H_2 + Na_2CO_3 \longrightarrow CaCO_3 + Na_2SO_4 + 2H_2O$$

The equivalent weight of $CaSO_42H_2O = 86.09$, and 1 meq. litre of CO_3'' thus requires 86.9 milligrams of gypsum/liter to complete the reaction.

One acre-foot is $66 \times 660 \times 28.317 = 1.132 \times 10^6$ liters. Therefore, 1 meq./liter of CO_3'' requires :

$86.09 \times 1.232 \times 10^6$ milligrams of gypsum/AF

or 86.09×1.232 Kg/AF

or $86.09 \times 1.232 \times 0.001102 = 0.117$ short tons of gypsum/AF.

For a 3-cusec tubewell discharge, the amount of pure gypsum required $= 3 \times 1.983 \times 0.117 = 0.7$ short tons/day/meq CO_3.''

TABLE

Mixing Ratios for Tubewell Waters of SCARP I considered

	Tubewell Water					
Project Area	T. W. No.	Total Conc.	†Ca+ Mg.	Na	CO_3+ HCO_3	ESP
Jaranwala	1/103	12.30	3.50	8.80	6.51	26.9
	1	19.45	4.94	14.51	7.56	38.4
	51	11.86	3.70	8.16	10.26	27.0
	61	26.00	4.32	21.68	7.05	58.6
	72	46.00	13.80	32.20	8.68	54.7
	81	13.50	2.67	10.83	7.05	36.1
	136	18.50	5.76	12.74	8.14	=33.3
Hafizabad	41	16.07	3.88	12.19	5.15	33.2
	71	10.05	3.19	6.86	6.32	21.8
	81	7.41	2.83	7.41	7.44	25.3
	111	8.47	2.11	6.36	4.29	21.0
	121	11.58	3.64	7.94	7.75	25.1
	131	18.50	4.46	14.04	6.78	37.8
	171	14.15	2.81	11.34	10.58	39.7
	181	20.78	2.75	18.03	10.73	59.4
	191	13.68	3.04	10.64	8.23	35.1
	301	13.62	1.65	11.97	7.90	45.8
Khangah	48	11.00	3.40	7.60	3.69	21.2
Dogran	212	10.90	2.03	8.87	8.56	34.0
Beranwala	1	16.20	4.40	11.80	7.79	33.9
	21	24.20	2.00	22.20	10.25	80.9
	31	10.55	2.30	8.25	3.29	24.2
	42	12.40	2.00	10.40	7.38	36.8
	51	24.11	3.84	20.27	9.43	60.3
	62	15.35	3.37	11.98	10.86	40.1
	71	20.86	3.67	17.19	10.77	50.4
	81	26.72	4.04	22.68	13.30	65.1
	91	24.00	4.44	19.56	13.12	57.7
	101	28.57	3.41	25.16	15.33	80.6

*Analysis of Chenab River at Marala: Total concentration=2.84 meq/lt;

†All concentrations given

10

"Hazardous" Because Residual—Na_2CO_3 is High

Combined Tubewell and River Water*

For ESP about 10			For ESP about 15			For ESP about 20		
SAR	ESP	Mixing Ratio GW:SW	SAR	ESP	Mixing Ratio GW:SW	SAR	ESP	Mixing Ratio GW:SW
2.76	10.05	1:2.00	3.98	15.12	1:0.90	5.10	20.00	1:0.40
2.88	10.40	1:3.66	4.05	14.90	1:2.00	5.21	20.00	1:1.16
2.55	10.05	1:2.00	3.72	15.39	1:0.85	4.63	20.00	1:0.40
3.03	10.18	1:6.00	4.35	15.05	1:3.50	5.65	19.78	1:2.30
2.84	10.11	1:8.50	4.03	14.99	1:4.80	5.02	19.56	1:3.20
2.76	9.66	1:3.00	4.28	15.41	1:1.40	5.49	20.31	1:0.81
2.80	10.47	1:3.00	3.93	15.47	1:1.50	4.84	19.75	1:0.88
2.88	9.91	1:3.00	4.22	14.69	1:1.50	5.38	19.58	1:0.85
2.58	9.76	1:1.40	3.91	15.17	1:0.50	5.03	20.22	1:0.10
2.61	9.70	1:1.80	3.97	15.24	1:0.70	4.98	19.92	1:0.30
3.08	10.42	1:1.10	4.47	15.34	1:0.40	5.64	19.51	1:0.10
2.63	9.99	1:1.80	3.72	14.88	1:0.80	4.80	19.64	1:0.30
2.85	10.03	1:3.60	4.13	15.12	1:1.90	5.26	19.68	1:1.14
2.63	9.68	1:3.40	3.86	14.82	1:1.80	4.96	19.55	1:1.10
2.75	9.63	1:5.80	4.02	14.54	1:3.40	5.48	20.16	1:2.10
2.66	9.69	1:3.00	3.94	14.66	1:1.50	5.23	20.38	1:0.80
2.87	9.81	1:3.50	4.15	14.52	1:2.00	5.90	19.85	1:1.10
3.01	10.29	1:1.30	4.31	14.82	1:0.50	5.49	19.76	1:0.08
2.74	9.98	1:2.40	3.90	14.79	1:1.30	5.42	20.47	1:0.62
2.74	10.08	1:3.00	4.08	15.50	1:1.40	5.06	20.04	1:0.82
2.94	9.94	1:7.00	4.39	15.28	1:4.10	5.79	20.26	1:2.80
2.99	9.69	1:1.80	4.66	15.09	1:0.70	6.23	19.81	1:0.25
2.74	9.54	1:3.00	4.36	15.44	1:1.40	5.63	20.48	1:0.84
2.89	10.00	1:6.00	4.18	15.13	1:3.50	5.46	20.08	1:2.30
2.65	9.85	1:3.50	3.69	14.50	1:2.00	4.98	20.11	1:1.10
2.84	10.22	1:5.00	4.08	15.10	1:2.90	5.25	19.95	1:1.90
2.84	10.06	1:7.00	4.13	15.29	1:4.10	5.31	20.17	1:2.80
2.67	9.76	1:6.30	3.94	14.98	1:3.50	5.13	19.90	1:2.28
2.70	9.56	1:8.70	4.06	14.94	1:5.00	5.35	20.21	1:3.36

$Ca+Mg=2.38$ meq/lt $Na=0.46$ meq/lt; $CO_3+HCO_3=1.96$ meq/lt.
in meq/lt.

TABLE 11

Case Studies by Hrvard of Ground Water Salinization

	Case 1	Case 2		Case 3	Case 4
1. Tubewell Spacing	—	6000	or	2000 ft.	
2. Tubewell depth	—	250	or	50 ft.	
3. Good or bad land	—	0	or	60 Tons per Acre Salt on Surface.	
4. Percent drainage of tubewell water.	—	0	or	10 percent	
5. Initial ground water concentration.		1000	or	2000 ppm.	
6. Pumping rate* (equals recharge rate)	0.881	1.674		0.881	1.674
7. Drainage rate*	—	—		0.088	0.17
8. Surface water rate *	1.586	2.248		1.674	2.418
9. Consumptive use*	1.586	2.248		1.586	2.248

Notes: * in cu. ft./sq. ft./yr.

Within limits, five of the above parameters can be controlled by choice: well spacing, well depth, percentage drainage of tubewell effluent, pumping rate, and surface water rate.

The pumping rate is kept equal to the recharge rate to retain a steady state flow problem for study.

It was found that the spacing of wells has no influence on salt build-up characteristics of irrigation water.

For 10 percent drainage it was assumed that the canal inflow was increased by 0.088 and 0.17, respectively, to keep system comparable and in hydraulic steady state.

The studies show clearly the adverse effects of no drainage of some tubewell effluent. No drainage at all leads to an ultimate theoretical concentration approaching infinity.

TABLE 12

Additional Case Studies Required for Analysis of Ground Water Salinization

1. Tubewell depth	50,	150,	250,	or	350 ft.	
2. Good or bad land	0,	60,		or	120 tons per acre salt on surface.	
3. Percent drainage of tubewell water.	10,	20,	50,	or	100	
4. Anisotrophy ratio	10 or 100					
5. Initial ground water concentration.	4000,	10,000		or	20,000 ppm.	
6. Ground Water mining rate*	0,		0.5,	or	1.00	
	Case I	Case II		Case III	Case IV	Case V
7. Pumping rate (=recharge rate)	0.681	1.674		2.0	2.0	3.0
8. Surface Water rate*	1.586	2.248		4.0	5.0	6.0
9. Consumptive use*	1.586	2.248		2.0	3.0	3.0

*All in cubic feet per square foot per year.

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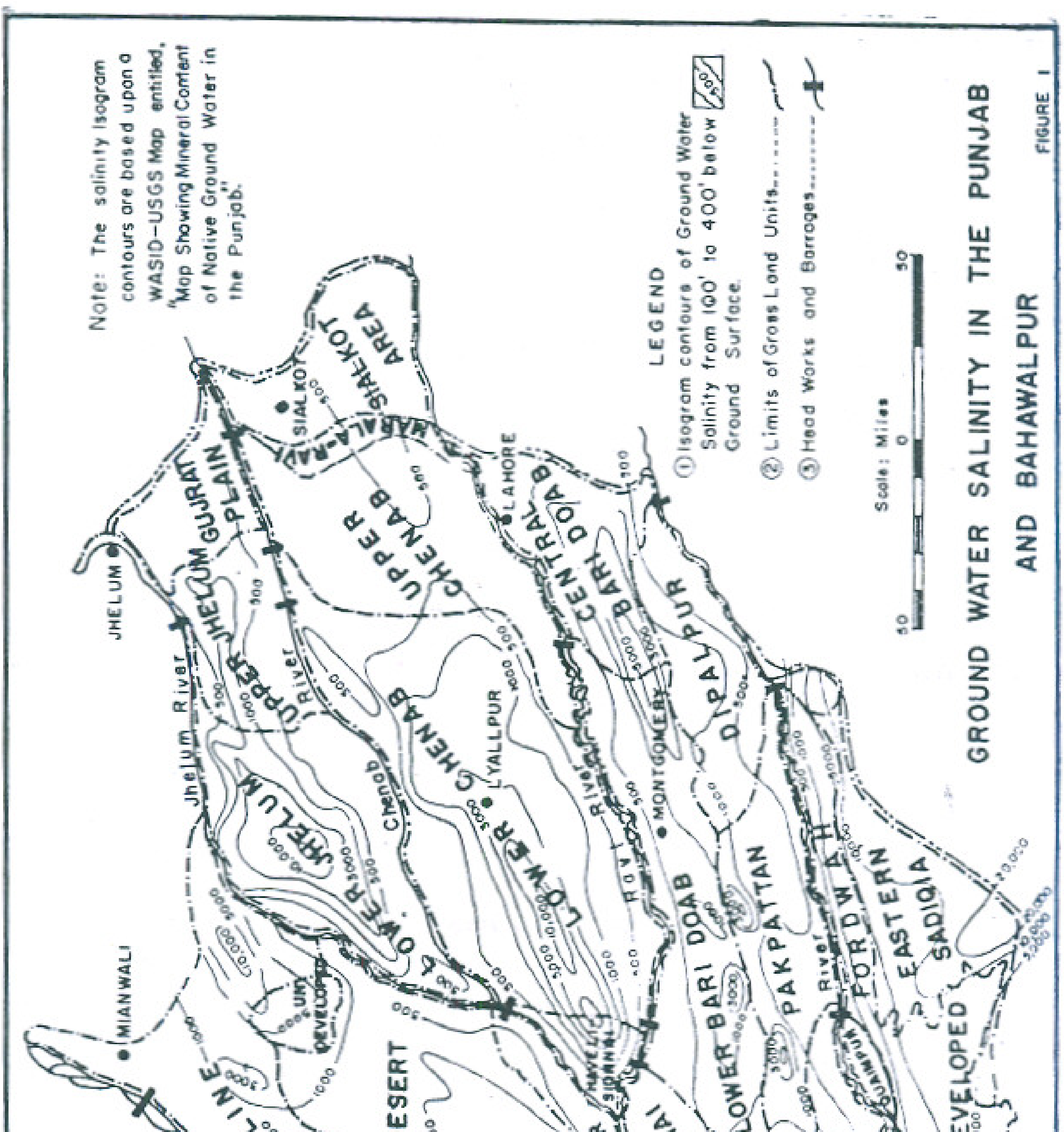
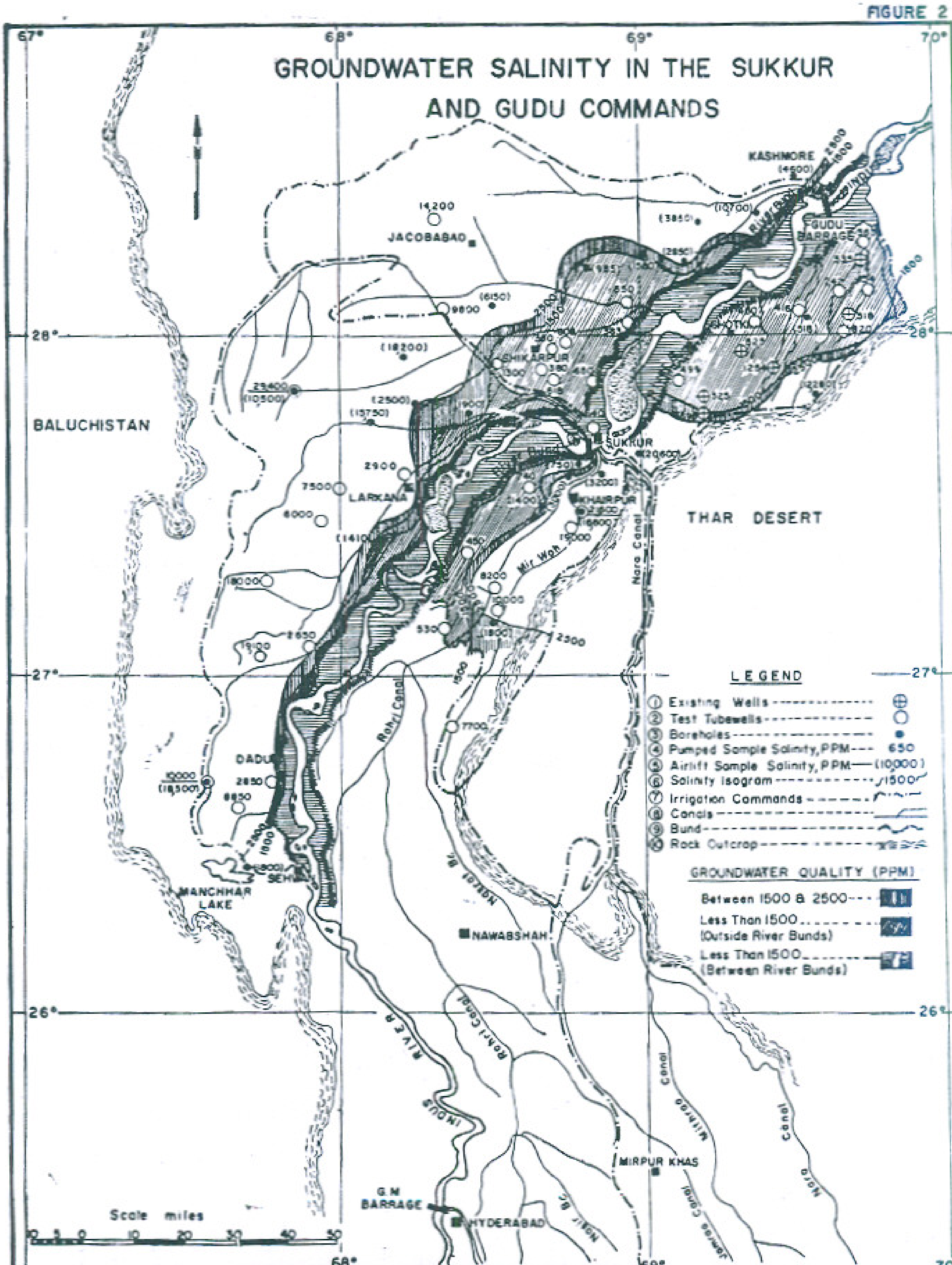

Note: The salinity Isogram contours are based upon a WASID–USGS Map entitled, "Map Showing Mineral Content of Native Ground Water in the Punjab."
LEGEND
① Isogram contours of Ground Water Salinity from 100' to 400' below Ground Surface.
② Limits of Gross Land Units
③ Head Works and Barrages
Scale: Miles
50 0 50
GROUND WATER SALINITY IN THE PUNJAB AND BAHAWALPUR
FIGURE I
MIANWALI
JHELUM
SIALKOT
LAHORE
LYALLPUR
MONTGOMERY
MULTAN
LEIAH
DERA ISMAIL KHAN
DERA GHAZI KHAN
Jhelum River
Chenab River
Ravi River
Sutlej
Indus River
THAL MAIN LINE
DESERT
UPPER JHELUM
JHELUM GUJRAT PLAIN
MARALA-RAVI
SIALKOT AREA
UPPER CHENAB
LOWER CHENAB
LOWER JHELUM
CENTRAL BARI DOAB
DIPALPUR
LOWER BARI DOAB
PAKPATTAN
FORDWAH
EASTERN SADIQIA
MAILSI
SIDHNAI
RANGPUR
MUZAFFARGARH
PANJNAD
BAHAWAL
UNDEVELOPED

FIGURE 2


GROUNDWATER SALINITY IN THE SUKKUR
AND GUDU COMMANDS
BALUCHISTAN
THAR DESERT
KASHMORE
GUDU BARRAGE
JACOBABAD
SHIKARPUR
GHOTKI
SUKKUR
LARKANA
KHAIRPUR
DADU
SEHWAN
MANCHHAR LAKE
NAWABSHAH
MIRPUR KHAS
G.M. BARRAGE
HYDERABAD
RIVER INDUS
Rohri Canal
Nara Canal
Mir Wah
LEGEND
① Existing Wells
② Test Tubewells
③ Boreholes
④ Pumped Sample Salinity, PPM 650
⑤ Airlift Sample Salinity, PPM (10,000)
⑥ Salinity Isogram 1500
⑦ Irrigation Commands
⑧ Canals
⑨ Bund
⑩ Rock Outcrop
GROUNDWATER QUALITY (PPM)
Between 1500 & 2500
Less Than 1500 (Outside River Bunds)
Less Than 1500 (Between River Bunds)
Scale miles
10 5 0 10 20 30 40 50

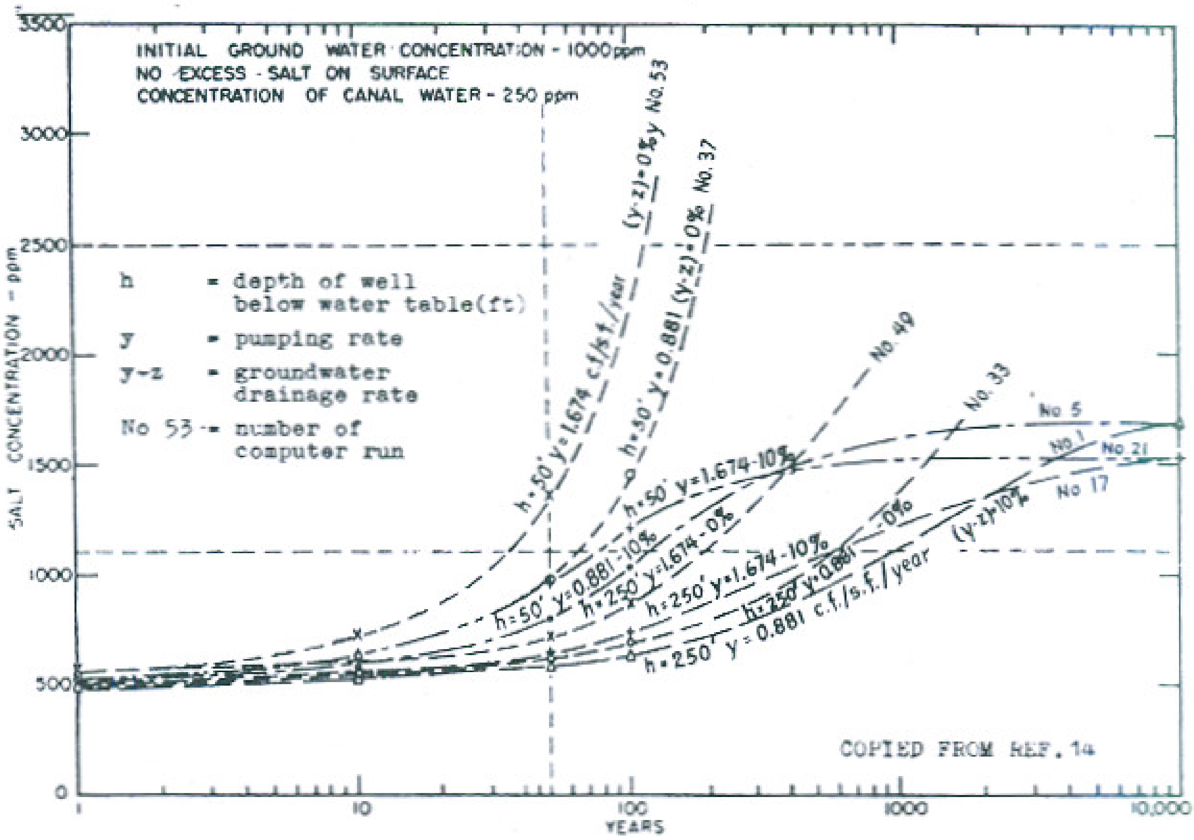


FIG. 3 SALT CONCENTRATION OF APPLIED IRRIGATION WATER

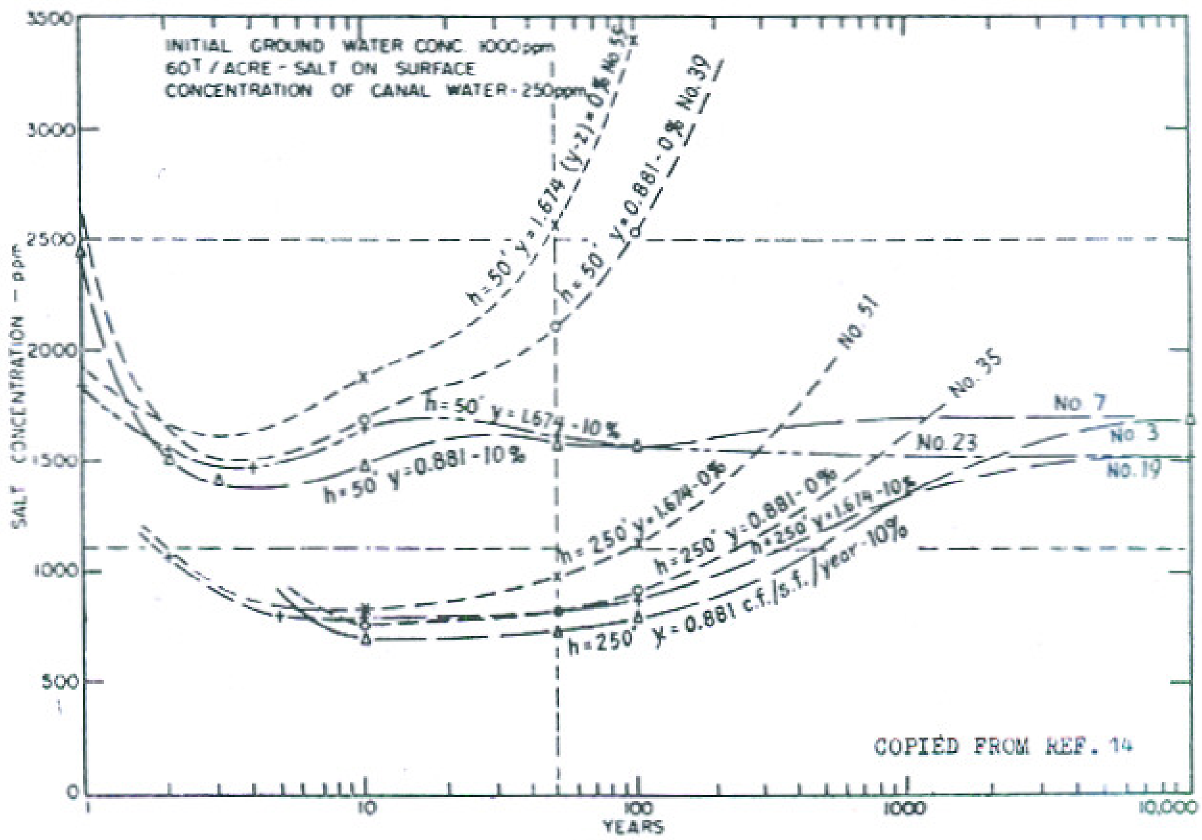


FIG. 4 SALT CONCENTRATION OF APPLIED IRRIGATION WATER