Fresh and Saline Ground-Water Zones in the Punjab Region West Pakistan

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1608-I

Prepared in cooperation with the West Pakistan Water and Power Development Authority under the auspices of the U.S. Agency for International Development

Fresh and Saline Ground-Water Zones in the Punjab Region West Pakistan

By WOLFGANG V. SWARZENSKI

CONTRIBUTIONS TO THE HYDROLOGY OF ASIA AND OCEANIA

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1608-I

Prepared in cooperation with the West Pakistan Water and Power Development Authority under the auspices of the U.S. Agency for International Development

Delineation of fresh and saline ground-water zones from data collected during a program of test drilling and water sampling in the Punjab region of West Pakistan

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1968

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

ILLUSTRATIONS

TABLE

FRESH AND SALINE GROUND-WATER ZONES IN THE PUNJAB REGION, WEST PAKISTAN

By WOLFGANG V. SWARZENSKI

ABSTRACT

An extensive program of test drilling and water sampling, undertaken by the Water and Soils Investigation Division (WASID) of the West Pakistan Water and Power Development Authority (WAPDA) to evaluate hydrologic problems related to waterlogging and soil salinity, has furnished data for the delineation of fresh and saline ground-water zones in the Punjab region of West Pakistan. Fresh ground water containing generally less than 500 ppm (parts per million) of total dissolved solids is found in wide belts paralleling the major rivers and in other areas of ground-water recharge. The fresh ground-water zone of upper (northeastern) Rechna Doāb, where annual precipitation in places exceeds 30 inches, is the most extensive of the Punjab region and attains a depth of 1,700 feet or more below land surface near Gujrānwāla. Fresh ground water adjacent to the Indus River extends locally to depths of about 1,500 feet.

Saline ground water occurs downgradient from sources of recharge, particularly in the central parts of the interfluvial areas. Also, available data indicate a gradual increase in mineralization with depth and distance from sources of fresh-water recharge. Thus, even extensive fresh-water zones appear to be underlain, at variable depths, by saline ground water in most of the Punjab region. The saline ground waters of the Punjab region do not constitute, however, a distinct salt-water body that can be defined in terms of stratigraphic position, sea-level datum, particular lithology, or by chemical character.

The ground waters of the Punjab region are characterized by a gradation from calcium magnesium bicarbonate types, near the sources of recharge, to waters containing a dominant proportion of sodium. Water containing from 500 to 1,000 ppm is commonly of the sodium bicarbonate type, or it may be of the mixed type, having about equal proportions of the common anions (bicarbonate, chloride, and sulfate). With increasing mineralization from about 1,000 to 3,000 ppm, the relative proportion of chloride and sulfate increases, and these waters are generally of the sodium chloride or sodium sulfate type. The highly mineralized waters of the Punjab region are generally of the sodium chloride type, whereas in Dera Ismāīl (D.I.) Khān District sodium sulfate waters predominate. The ground waters from more than 900 sampling sites have been classified into eight types, according to dominant cations and anions. These types have been further subdivided into groups containing different amounts of total dissolved solids.

The pattern of distribution of saline ground-water zones in the Punjab region and the observed gradual increase in mineral content, downgradient from sources of fresh-water recharge, can be explained best by the processes of evaporation from the water table and solution of minerals within the alluvial aquifier.

INTRODUCTION

Detailed ground-water investigations in progress since 1954 in the Punjab region, are currently (1965) being conducted by the Water and Soils Investigation Division (WASID) of the West Pakistan Water and Power Development Authority (WAPDA). The investigations, undertaken with the advisory assistance of the U.S. Geological Survey under a basic agreement between the Government of Pakistan and the U.S. Agency for International Development (AID), have been directed toward the formulation of reclamation measures to combat waterlogging and salinization and the assessment of the ground-water potential of the Punjab region and other areas of West Pakistan. A report on the hydrology of the Punjab, based on the results of the first 10 years of these investigations, was published by WASID (Greenman and others, 1963). Other WASID publications describe the geology, water quality, and aquifer characteristics or give basic hydrologic data on a regional or areal basis (see "Selected references"). The area of investigation is shown in figure 1.

Because of the nature and urgency of primary reclamation objectives, the exploration in the earlier stages of the investigations was limited generally to the upper part of the alluvial aquifer. About 1,030 test holes drilled in 47,000 square miles of the Punjab region during the 1950's defined the nature of the alluvium to depths of about 600 feet and yielded water-quality data to depths of 400 to 500 feet. Wells used for aquifer tests generally tapped alluvial sands between 80 and 300 feet. Since 1962, however, WASID has drilled about 95 deep test holes in the Punjab and the adjacent areas of Bahāwalpur and Dera Ismāīl (D. I.) Khān District; and these holes have permitted water sampling to depths of 600 to 1,500 feet. The present report is concerned chiefly with the vertical extent of fresh and saline ground-water zones, as revealed by sampling of deep water since 1962, but also considers areal or spatial water-quality relationships in the ground-water reservoir of the Punjab region.

The agencies concerned with Pakistan's water resources eventually will be obliged to consider development of all available ground water, including the deeper part of the alluvial aquifer which today (1966) appears to be beyond the limit of economic exploitation. Accordingly,

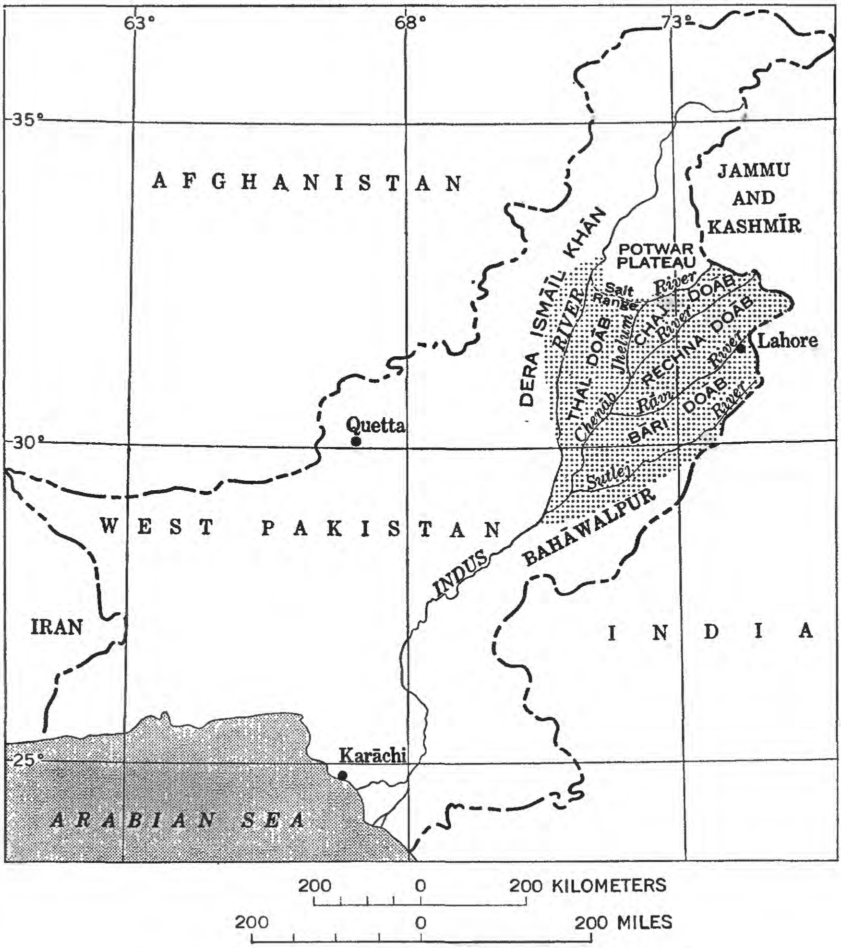

FIGURE 1.—Location of the Punjab region (stippled pattern).

and although there are substantial gaps in present (1966) knowledge of the vertical distribution of fresh and saline ground water in the Punjab region, it seems appropriate at this time to make pertinent data and their interpretation available to the agencies concerned with ground-water development.

This report has been prepared under the administrative direction of Mr. S. M. Said, Chief Engineer, Water and Soils Investigation Division of WAPDA. The writer thankfully acknowledges the help received from his colleagues in discussion of the problem and review of this report. Special thanks are due to Mr. Abdul Hamid, chemist, WASID, and Messrs. M. J. Mundorff and G. D. Bennett, of the U.S. Geological Survey.

ALLUVIAL AQUIFER

Ground water is contained in interbedded deposits of alluvial sand and silt which are present almost everywhere to depths of 1,000 feet and more in the Punjab region. These deposits have been laid down since late Tertiary time by the Indus River and its tributaries in a vast alluvial plain that extends from the foothills of the Himalaya to the Arabian Sea. Gradients of the land surface of the plain are generally very low and range from about 1½ feet per mile in the upper northern and northeastern part of the region to less than 1 foot per mile to the south and southwest.

The monotony of the alluvial plain is broken by scattered hills and bedrock outcrops south of Sargodha in Chaj Doāb, and near Chiniot, Sāngla Hill, and Shāh Kot in Rechna Doāb. The bedrock hills are projections of the northwest-trending Delhi-Shāhpur Ridge that is largely buried by alluvium. The rocks of this buried ridge, presumably of Precambrian age, are essentially impermeable and define the lower limit of the alluvial aquifer in parts of Chaj, Rechna, and Bāri Doābs. Elsewhere in the Punjab there are no outcrops of consolidated rocks and their presence below the alluvium is conjectural. Rocks of the Siwalik Series, however, were penetrated by an oil test well near Karampur and may also be present below the alluvial deposits in northwestern Bāri Doāb, at depths of about 1,000 feet (Kidwai and Alam, 1964).

The water-bearing characteristics of the upper part of the alluvial aquifer have been evaluated by about 140 pumping tests in the Punjab region. Horizontal permeabilities of the material in the screened zones range from 0.001 to 0.008 cfs (cubic feet per second) per square foot and are commonly between 0.0025 and 0.004. In areas where the alluvium is less permeable, permeabilities generally range from less than 0.001 to about 0.002. Although the alluvium may locally contain large proportions of silt and silty clay, the occurrence of these deposits is generally in the form of thin lenticular beds. Ground water in the alluvial aquifer is generally unconfined; however, because of the random distribution of clayey strata, the aquifer is anisotropic and lateral permeabilities are generally much greater than vertical permeabilities. Specific capacities of tubewells range from about 50 to more than 120 gpm (U.S. gallons per minute) per foot of drawdown. The results of pumping tests and aquifer characteristics in the Punjab region are described in some detail by Bennett and others (1964).

DISTRIBUTION OF FRESH AND SALINE GROUND-WATER ZONES

The areal distribution of fresh and saline ground-water zones in the alluvial aquifer of the Punjab region is shown on plate 1. The lines represent average conditions at depths of about 100 to 450 feet, as revealed by water samples collected between 1957 and 1965. The quality of water in shallower wells, that is, those at depths of less than about 100 feet, is commonly influenced by seepage from the canal systems. Therefore, data obtained from shallow open wells were not considered in the preparation of plate 1, which is believed to portray essentially preirrigation conditions. As shown on plate 1, fresh ground water, defined by the 1,000-ppm line, occurs in the upper (northeastern) parts of Chaj, Rechna, and Bāri Doābs. In these areas, precipitation is relatively high, ranging from 15 to more than 30 inches per year. Fresh ground water is also found in belts paralleling the major rivers of the Punjab region where infiltration from rivers crossing the present and recently abandoned flood plains provided recharge. The width of these belts, from about 4 to more than 20 miles, is largely dependent on the width of the flood plain, which is commonly bounded by interfluvial terraces (bar uplands). In many places, particularly in parts of Bāri and Chaj Doābs, the scarps bordering the terraces demarcate the transition zone from fresh ground water to the highly mineralized ground water of the interfluves.

Zones of saline ground water, containing from 4,000 to more than 20,000 ppm (parts per million) of total dissolved solids, are found in the central and lower (southwestern) parts of the doabs and in the Bahāwalpur area to the southeast of the Sutlej River (pl. 1). Moreover, saline ground water is found in the upper (northern) part of Thal Doāb and in the piedmont areas of the Sulaimān Range, west of the Indus River. All these saline ground-water zones are in areas that receive less than about 14 inches of rain per year. Annual precipitation in the southwestern part of the Punjab region is between 5 and 10 inches.

Study of profiles through the aquifer (pl. 2) indicates a gradual increase in mineralization with depth and distance from sources of fresh-water recharge throughout most of the alluvial aquifer. There is, however, no distinct salt-water body that can be defined in terms of stratigraphic position, sea-level datum, or any particular lithology nor is there a well-defined zone of diffusion between fresh and saline ground water. Thus, the saline ground-water zones of the Punjab region can only be defined by the limits of the lines of equal total dissolved solids. The degree of salinity, however, appears to be related to the total water budget peculiar to any one hydrologic unit.

290-850—68——2

Some of the factors affecting the distribution and concentration of highly mineralized ground water have been discussed by Greenman, Swarzenski, and Bennett (1963). These include not only variations in the magnitude of seepage from the streams bounding the doabs and areal patterns of precipitation and evaporation but also such physiographic features as direction and degree of slope, symmetry and width of the doabs, and the relative width and position of the terraces (bar uplands) and recently abandoned flood plains within each doab.

Locally, the recharging effect of canals or former stream channels may be manifest by the presence of 200 to 300 feet of relatively fresh water in a generally saline environment. On the other hand, in areas of predominantly fine-textured material, there may be local increases in the degree of salinity, as much as 1,000 or 2,000 ppm, in a fresh-water environment. These local increases are due to reduced ground-water flow and the solution of minerals.

THAL DOĀB

Because of relatively small precipitation in Thal Doāb (5 to 14 in. per yr), ground-water recharge is limited to seepage from the bordering streams, inundation canals in the lower (southern) part of the doab, and, since 1947, from the Thal Canal System. Of these, recharge from the Indus River is dominant in Thal Doāb. Ground water containing generally less than 500 ppm extends eastward from the Indus River in a broad zone parallel to the Indus. Except in the lower part of the doab, the thickness of this zone is generally 1,500 feet or more. Test hole T10 near Kalūr Kot revealed fresh water (320 ppm) at a depth of 1,042 feet. Near the town of Dera Ismāīl (D.I.) Khān a water sample from 1,320 feet contained 240 ppm of dissolved solids, and similar conditions were observed in the northern part of D.I. Khān District. In preirrigation time ground-water gradients were southeasterly, from the Indus River toward the interior of Thal Doāb, and it can be assumed that the fresh-water zone paralleling the Indus extends to depths of 1,500 feet or more in most of western Thal Doāb, except in the extreme southern part. Locally, the fresh-water zone is overlain by more saline water, to depths of 300 or 400 feet. These conditions are illustrated on plate 2, *A–A′*, in which the curvature of the 1,000-ppm line indicates the deterioration in the quality of water in the upper part of the aquifer. At Kalūr Kot, near the Indus River, the shallow ground water has concentrations of 2,000 and 3,000 ppm. Elsewhere, concentrations rarely exceed 1,000 or 1,500 ppm and ground water becomes increasingly fresher with depth in this zone.

The fresh-water zone attains its greatest width in the vicinity of Mankera and may actually extend across Thal Doāb to the Jhelum River near latitude 31°30′ N. (pl. 1). No test holes were drilled in this inaccessible part of the doab, but water samples taken at T5, near Mankera, indicate fresh water to a depth of 1,042 feet with total dissolved solids ranging from about 500 to 800 ppm.

The fresh-water zone adjacent to the Jhelum and Chenāb Rivers in Thal Doāb is considerably narrower than that near the Indus (pl. 1). This fact may be explained by the larger flow of the Indus River, steep escarpments close to the Jhelum River, and by the concentration of fine-textured alluvium in the upper and lower parts of the doab, near Khushāb, Girot, and Muzaffargarh. As shown on plate 2, *A–A′*, near Girot fresh water extends only about 5 miles westward from the Jhelum River. The depth of fresh water along the flood plains of the Jhelum and Chenāb Rivers probably exceeds 1,000 feet. For example, in test hole T4, 20 miles north of Athārān Hazāri, fresh water containing 620 ppm was found at a depth of 1,073 feet.

Saline ground-water zones found in the lower central part of Thal Doāb, as shown on plate 1, are located within the low-lying area of the abandoned flood plains of the Indus and Chenāb Rivers. This fact may explain the generally lower salinities (4,000 to 6,000 ppm) in the lower part of Thal Doāb as compared with those in other doabs and the apparent displacement of the saline zones to the east of the central axis of the lower part of Thal. The vertical extent of these saline zones has not been explored below a depth of 500 feet. There are, however, indications of increasing salinity with depth in some of the test holes.

The most highly saline ground water (10,000 to 13,000 ppm) in Thal Doāb was found in an isolated zone, between Girot and Ādhi Kot, in the northern part of the doab (pls. 1 and 2, *A–A′*). This zone, like other saline zones in Thal, is in the eastern part of the doab; also, it may be contiguous with the area of generally poor-quality ground water near Khushāb, to the northeast. To the north, however, water quality improves markedly, and total solids rarely exceed 1,000 to 1,500 ppm. Most deep samples taken along the road from Khushāb to Miānwāli contained less than 1,000 ppm. In two deep test holes (T1, T20), drilled near the base of the Salt Range north of Bandiāl and Khushāb, the water contained 1,400 to 1,500 ppm at depths of 515 to 773 feet. Thus, ground water directly south of the Salt Range is of good or fair quality to considerable depth. Individual shallow wells in the piedmont area, however, may yield more or less saline water, according to their location with respect to present drainage channels from the Salt Range.

CHAJ DOĀB

The vertical extent of fresh and saline ground-water zones in Chaj Doāb is shown by two axial profiles (pl. 2, *B–B'*, *F–F'*) and three transverse profiles (pl. 2, *A–A'*, *G–G'*, and *H–H'*).

Extensive fresh-water zones are found in the upper (northeastern) part of the doab and along the present and abandoned flood plains of the Chenāb River. In test hole C52, 8 miles north of Phālia, fresh water was logged to a depth of 1,000 feet or more. At that site, located on the terrace, a water sample from 760 feet contained 450 ppm. Ground water in the upper part of the doab, which receives 18 inches of rain or more, is generally of good quality. To the northwest of Gujrāt, however, the water locally contains as much as 1,500 to 2,000 ppm, as shown by the closed 1,000-ppm line (pl. 1). This area, south and southwest of the Pabbi Hills, is characterized by generally fine deposits.

In the flood plain of the Chenāb River, about 12 miles upstream from Chiniot, fresh water of 160 to 300 ppm was found to a depth of 720 feet (test hole C44). At the same site, at a depth of 905 feet (125 ft above the consolidated basement rocks) the water contains 2,260 ppm. The extent of the fresh-water zone at that site, about 20 miles wide, is shown on plate 2, *H–H'*. Downstream from Lālīan, the fresh-water zone adjacent to the Chenāb River in Chaj Doāb is generally narrower, being 6 miles wide or less.

Extensive fresh-water zones along the Jhelum River are restricted to the area between Malakwāl and Rasūl, in the upper part of Chaj, and to the area north and south of Sāhiwāl, in the lower part of Chaj. The extent of the zone in the latter area is shown on plate 2, *A–A'*, which indicates a maximum fresh-water thickness of about 900 feet (test hole C48). In the central part of the doab, particularly near Shāhpur, relatively impermeable deposits in the vicinity of the Jhelum River have restricted recharge by the river to shallow depths or have virtually confined it to the present flood plain (pl. 2, *G–G'*). Locally, along former courses of the Jhelum there are fresh-water zones to depths of 100 to 250 feet in a generally saline environment. One such channel is located between Shāhpur and Sargodha (test hole C25, pl. 2, *G–G'*). It extends northward to C103 (pl. 2, *H–H'*), where fresh water was found to a depth of 242 feet. Former courses of the Jhelum and Chenāb rivers apparently have also modified that part of the saline zone in the lower part of Chaj Doāb that is located on the abandoned flood plains of these rivers. Thus, water containing less than 1,000 ppm was found at depths of 150 to 340 feet at test holes G2, Z52, and C46 (pl. 2, *B–B'*).

Seepage from the major canals also has locally improved the quality of shallow ground water in the saline zone of Chaj Doāb. The distribution of such fresh-water zones is highly erratic, in accord with varying permeability of the material underlying the canals. Fresh-water zones of this nature are of limited extent and available data indicate that their thickness ranges generally from a few tens to about 150 feet.

The areal distribution of saline ground water in Chaj Doāb is shown on plate 1. The transverse and axial sections (pl. 2, *A–A′*, *B–B′*, *F–F′*, *G–G′*, *H–H′*) reveal that salinity increases with depth and exceeds 30,000 ppm near the base of the aquifer, in the vicinity of the buried ridge and also in the lower (southwestern) part of Chaj Doāb, near the confluence of the Chenāb and Jhelum Rivers, where bedrock has not been encountered in test drilling (pl. 2, *A–A′*, *B–B′*). The spacing of the lines on plate 2 (*A–A′*, *B–B′*, *F–F′*, *G–G′*, *H–H′*) indicates a gradual increase in mineralization with depth and distance from sources of fresh-water recharge throughout most of the aquifer. It is interesting to note that highly saline ground water is found in the upper part of the aquifer that was unsaturated prior to the general rise of water levels. Although no data on the quality of water in pre-irrigation time are available, it appears that much of the saline ground water found today at shallow depth is continuous with deeper saline zones. It apparently has been displaced upward and its upper surface is but slightly modified by the downward percolation of fresh water from canal seepage (pl. 2, *F–F′*, *H–H′*).

RECHNA DOĀB

Extensive fresh-water zones, 15 to 20 miles wide, occur along the flood plains of the Chenāb and Rāvi Rivers. Their depth is believed to be about 1,000 feet or more throughout the doab. In the lower part of Rechna Doāb, however, the width of these zones is considerably reduced, as shown on plate 1. A test well drilled near the confluence of the Chenāb and Rāvi Rivers (R4, pl. 2, *C–C′*) revealed fresh water to a depth of about 1,000 feet. A sample from 1,255 feet contained 4,700 ppm of dissolved solids.

The largest area of fresh ground water in the Punjab region is found in the upper part of Rechna Doāb, extending northeastrely from Shekhūpura and Khāngāh Dogrān toward the border of Jammu and, Kashmīr, and extending laterally toward the Chenāb and Rāvi Rivers (pl. 1). In most of this area, the ground water contains less than 500 ppm (R37, 71, 72, pl. 2, *C–C′*. A test well near Gujrānwāla (R72) yielded water of 230 ppm from a depth of 1,700 feet. Similar to conditions in the upper part of Chaj Doāb, ground water in areas of predominately fine-grained alluvial deposits is locally more mineralized. One such area, having concentrations of 1,000 to 2,000 ppm, is found to the southwest of Pasrūr, in the upper part of Rechna Doāb.

Saline ground-water zones are found in the central lower part of Rechna Doāb (pls. 1 and 2, *C–C′*). Salt concentrations increase gradually downdoab to 3,000 to 5,000 ppm near Lyallpur, where seepage from the Rakh Branch has locally improved the quality of shallow water. The most highly mineralized ground water is restricted to a comparatively narrow zone in the center of the doab, containing 10,000 to 12,000 ppm in the vicinity of Toba Tek Singh and 15,000 to 18,000 ppm near Shorkot Road. In the latter area the degree of mineralization is remarkably uniform from about 100 feet to 1,100 feet, as shown by the near-vertical position of the 15,000-ppm line (R1, 73, pl. 2, *C–C′*).

BĀRI DOĀB

Because of less favorable recharge conditions in Bāri Doāb, fresh-water zones are generally less extensive than in Rechna. Within about 20 miles southwest of Lahore, the average annual rainfall is less than 14 inches and diminishes to less than 10 inches in the lower third of the doab. Moreover, the steep scarps of the terrace prevented the transgression of meandering streams in that direction and thus restricted the recharge potential of the Rāvi and former Beas Rivers. The terrace in Bāri Doāb is relatively narrow, extending southwesterly to the vicinity of Khānewāl. Traces of former stream channels, common on all other interfluves, are generally absent on the terrace of Bāri Doāb. The scarps bordering the terrace coincide with the limit of fresh-water zones to a remarkable extent, and the water underlying the terrace is generally of inferior quality.

Thus, fresh ground water in the upper part of Bāri Doāb, within Pakistan, is restricted to a relatively small area extending easterly and southeasterly from Lahore to the border (pl. 1). A test hole drilled near Wāgha (BR144) revealed fresh water to a depth of 1,070 feet. Downdoab, this fresh-water zone is reduced in thickness and extends to the vicinity of Pattoki. It is overlain by a zone of increasing thickness of more or less mineralized water, commonly containing from 1,500 to 4,000 ppm (pl. 2, *D–D′*).

Major fresh-water zones in Bāri Doāb are located along the flood plains of the Sutlej, lower Chenāb, and Rāvi Rivers, as shown on plate 1. Of these, the zone adjacent to the Sutlej is generally 15 to 20 miles wide throughout the doab, whereas the zone adjacent to the Rāvi River, between Lahore and Montgomery, is generally narrower. However, a wide belt of fresh water is found along the abandoned flood plains of the lower Rāvi and Chenāb Rivers between Miān Channū and Multān (pl. 1). The thickness of these zones is believed to be generally 1,000 feet or more. Near Lodhrān the fresh-water zone adjacent to the Sutlej River is about 1,100 feet thick (BR99, pl. 2, *E–E′*). At test hole BR76, near Mailsi, a water sample from 1,166 feet contained 520 ppm.

The saline ground-water zone in the upper part of Bāri Doāb, already referred to, is found in the area of the terrace between Rāiwind and Montgomery. Near Okāra, maximum concentrations of 10,000 ppm were determined within the explored depth limit of about 600 feet. Throughout most of this zone concentrations range from about 5,000 to 8,000 ppm (pls. 1 and 2, *D–D′*). As is the case in the other doabs ground water in the lower central part of Bāri Doāb is also generally saline. The deepest water samples (450 to 500 feet) taken in the center of the saline zone, between Dunyāpur and Jalālpur Pīrwāla, contain between 8,000 and 10,000 ppm (pls. 1 and 2, *E–E′*). Available data indicate that salinity increases with depth in this area. Between the saline zones of the upper and extreme lower parts of Bāri Doāb, ground water is mineralized to a variable degree, as shown on plate 2, *D–D′*. This zone, located in the center of the doab, is characterized by rapid changes in water quality within a short distance. There are areas where fresh ground water extends to depths of 400 feet or more, whereas the water in adjacent areas is mineralized to 5,000 to 7,000 ppm. All these local fresh-water zones can be attributed to long periods of recharge by rivers, particularly the Beas, which formerly flowed through the center of the doab. At least one zone of locally improved ground water, south of Chīchāwatni, may be attributed to a former course of the Rāvi River that traversed the terrace (pl. 1). Throughout the lower (southwestern) part of Bāri Doāb there is evidence of former stream channels and junctions, which permitted fresh-water recharge at places now distant from present sources. Some of the changes in the position of river courses took place in historic times and explain the complex distribution pattern of fresh and saline ground water in Bāri Doāb.

BAHĀWALPUR AREA

The only extensive fresh-water zone in the Bahāwalpur area occurs to the southeast of the Sutlej, parallel to the river. It is generally 5 to 8 miles wide; locally, near Ahmadpur East and Khānpur (Rangpur), in the southwestern part of the area, the width of the fresh-water zone increases to 15 to 20 miles (pl. 1). A deep test hole near Khairpur (BWP62) revealed fresh water (240 ppm) at a depth of 985 feet. In the area south and southeast of Bahāwalpur where water in the upper part of the aquifer is of poor quality, fresh water is found below 300 to 400 feet and extends to depths of about 800 feet at BWP77A.

Because of low precipitation, generally between 5 and 10 inches, the chief source of fresh-water recharge in the Bahāwalpur area is the Sutlej River. Ground water moves generally southward from the river toward the desert area of Cholistan and is commonly highly mineralized; maximum concentrations of 20,000 to 25,000 ppm have been measured in test holes at or near the southern boundary of the canal-irrigated area, at a distance of 25 to 35 miles from the Sutlej River (pl. 1). Seepage from irrigation canals has locally improved the water quality in the upper part of the aquifer and water containing less than 1,000 ppm has been noted to depths of 100 to 200 feet in some test holes located within the saline zone.

In the southern part of the Bahāwalpur area, between Fort Abbās and Derawār Fort, there is a zone of reduced salinity as indicated by the reentrant of the 5,000 ppm line shown on plate 1. This relatively low-lying area corresponds to the Ghaggar (Hakra) channelway, which was occupied in historic times by a major stream. This stream, also known as the Hakra, appears to have joined the Indus-Nara south of Panjnad River. Although the Ghagger (Hakra) channelway is now generally dry, flood waters occasionally flow through it from the east, near Fort Abbās, in periods of uncommonly high rainfall. Available data indicate that the upper part of the aquifer along the channelway contains water of about 4,000 ppm, but that locally it may be fresh. At depth, however, ground water is highly saline, as indicated on plate 2, *E–E′*. At Derawār Fort (BWP93A), a water sample from 1,360 feet contained 25,400 ppm.

QUALITY OF WATER IN THE PUNJAB REGION

The river waters of the Punjab region, the ultimate source of most of the ground-water recharge, commonly contain from about 90 to 350 ppm of total dissolved solids. Although dissolved solids concentrations vary seasonally with discharge and increase generally downstream, the average concentration is of the order of 150 to 180 ppm. All river waters are of the calcium bicarbonate type, in which each of these ions accounts for more than 60 percent of the total cations and anions (table 1). Upon entering ground-water circulation, these waters, which initially contain only about 13 percent sodium, commonly increase in sodium content by twofold or threefold but with little increase in the amount of total dissolved solids. Thus, in ground water containing less than 300 ppm, the calcium content is generally reduced to about 40 percent or less of the total cations largely as the result of base exchange in clays and the precipitation of calcium carbonate. The magnesium content of these ground waters is generally similar to that in river water (about 25 percent of the total cations) and therefore there is generally an excess of calcium and magnesium over sodium in ground water containing less than 300 ppm.

Average ionic concentration of the major constituents of river water and ground water, from shallow and deep sources containing less than 2,000 ppm, are compared in table 1. The data given in this table for Rechna Doāb, within each group of total dissolved solids, are in close agreement with similar data for other doabs and may illustrate the chemical character of slightly mineralized ground water in the Punjab region. It is interesting to note that the average calcium content of 40 percent in waters from shallow wells (300 to 500 ppm total solids) is considerably higher than the calcium percentage in samples from deeper sources (table 1).

The ground waters of the Punjab region are characterized by their evolution from fresher calcium magnesium bicarbonate waters, near sources of recharge, to more mineralized waters containing a dominant proportion of sodium. Ground water containing from 500 to 1,000 ppm is commonly of the sodium bicarbonate type or it may be of the mixed type, in which the common anions (bicarbonate, chloride, and sulfate) are present in about equal proportions. With increasing mineralization, from 1,000 to 3,000 ppm, the relative proportion of chloride and sulfate increases over the bicarbonate, and these waters are generally of the sodium chloride or sodium sulfate type. The highly mineralized waters of the Punjab region are generally of the sodium chloride type, whereas in D. I. Khān District they are pre-

TABLE 1.—*Chemical composition of river water and ground water from shallow and deep sources, Rechna Doāb*

Total dissolved solids (ppm)	Cations												Anions											
	Calcium (Ca)				Magnesium (Mg)				Sodium (Na) and potassium (K)				Carbonate (CO_3) and bicarbonate (HCO_3)				Chloride (Cl)				Sulfate (SO_4)			
	Percent of total milliequivalents per liter																							
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
<300	62	42	42	41	25	29	24	26	13	29	34	33	72	71	66	73	11	11	10	5	17	18	24	22
300-500	---	40	25	29	---	25	26	20	---	35	49	51	---	64	66	74	---	8	12	7	---	28	22	19
500-1000	---	18	15	15	---	21	17	14	---	61	68	71	---	57	50	56	---	15	17	16	---	28	33	28
1000-2000	---	11	9	---	---	12	13	---	---	77	78	---	---	51	38	---	---	18	27	---	---	31	35	---

A. Average, Indus, Jhelum, and Chenāb Rivers, 1960-64 (153 ppm).
B. Average, 192 samples from shallow wells, Rechna Doāb, 1956-59.
C. Average, 190 samples from deep test holes, WASID, 1956-63.
D. Average, 89 samples from tubewells, Shadman Reclamation Scheme, 1963.

dominantly of the sodium sulfate type. Calcium and magnesium chloride waters are not common anywhere in the area; however, a small number of water samples of this type, containing from 3,000 to 10,000 ppm, have been noted in all saline ground-water zones.

The classification of ground water in the Punjab region is shown by bar graphs in figure 2 that summarize analytical data for 953 water samples taken, during WASID's test drilling operations between 1956 and 1963, from Bāri, Chaj, Rechna, and Thal Doābs and the Bahāwalpur area. In general, only one water sample from each test site was included in the compilation of chemical data. Thus, figure 2 presents a synopsis of the chemical quality of ground water between depths of about 200 to 400 feet at more than 900 test sites.

ORIGIN OF SALINE GROUND-WATER ZONES

SOLUTION-EVAPORATION HYPOTHESIS

Data concerning the distribution of saline ground-water zones and their chemical character, when examined in the context of preirrigation ground-water flow patterns and the Punjab region's geologic history, indicate that there is neither a single source for the saline waters of the Punjab region nor a single theory that would adequately explain their origin.

With respect to water quality, significant features in the hydrologic regimen of the Punjab region are the semiarid or arid climate, areal distribution of recharge, and extremely low ground-water gradients, which are generally 1½ feet per mile or less. Also, as has been stressed by Greenman, Swarzenski, and Bennett (1963), evaporation from the water table and solution of minerals by slowly percolating ground water must have been important factors affecting the chemical quality of ground water. A hypothesis combining the processes of solution and evaporation appears best to explain the observed gradual mineralization of ground water downgradient and away from sources of recharge and the distribution pattern of saline ground-water zones in the Punjab. The term "solution-evaporation hypothesis" is proposed here.

Accordingly, the reaction of ground water with clay minerals and any soluble secondary salts within the alluvial aquifer resulted in a moderate progressive increase, downgradient, in the salt content of the percolating waters. A factor contributing to the initial mineralization of ground water was evaporation from the shallow water table adjacent to the rivers and particularly along the wide belt of abandoned flood plains. The intermittent flooding of some of these areas in the past, followed by long periods of evaporation from a free-water surface or a shallow water table, may have created local sources of moderately mineralized ground water close to the rivers.

With increasing distance from sources of fresh-water recharge, the character of ground water changed from a predominantly sodium bicarbonate type to sodium sulfate and chloride waters. Mineralization proceeded according to relatively simple laws of physical chemistry, in which the solvent action of the water varied chiefly with the concentration of total dissolved solids, the relative proportions of different salts in solution, and the concentrations of dissolved gases, particularly carbon dioxide. With increasing mineralization, the least soluble salts were precipitated, such as the carbonates of calcium, magnesium, and iron and also iron hydroxide. The presence of calcium carbonate nodules (kankar) and ferruginous concretions throughout the alluvium bears witness to conditions favoring precipitation of these compounds in the alluvial deposits. Changes in the physical environment, particularly in the position of the water table, subsidence, or the introduction of new sources of recharge, would tend to reverse the conditions favoring precipitation. Local variations in the content of total dissolved solids or in the chemical composition of ground water may be explained by the retention of, or incomplete flushing of, saline water from clay strata or by variations in the nature of soluble minerals within the alluvial deposits. It may be assumed that local salt concentrations are present within the alluvial deposits that have been derived from salt-bearing sedimentary rocks of the Tertiary and older formations bordering the Punjab region to the north and west or that they have resulted from surficial salt accumulations on the alluvial plain during the geologic past. Local salt accumulations of this type, which may have passed through several cycles of erosion and deposition, would involve chiefly the salts of relatively low solubility including calcium sulfate. Calcium sulfate predominates in many of the moderately mineralized ground waters of D. I. Khān District. In this case the origin of the calcium sulfate may be sought in secondary gypsum that is within the piedmont and alluvial deposits and is derived from gypsum beds of Tertiary age exposed in the Sulaimān Range (Hood and others, 1964).

As total dissolved solids increase beyond 3,000 or 4,000 ppm, there is a progressive trend toward ground water of the sodium chloride type; and, as shown in figure 2, the majority of samples in the ranges of 5,000 to 10,000 ppm and greater are sodium chloride waters. Locally, however, waters of the calcium chloride type are present, particularly in the lower part of Rechna and Bāri Doābs and in the Bahāwalpur area; sodium sulfate waters are common in D. I. Khān District and are also present in the Bahāwalpur area. Calcium chloride and sodium sulfate waters commonly contain from 3,000 to 10,000 ppm of total

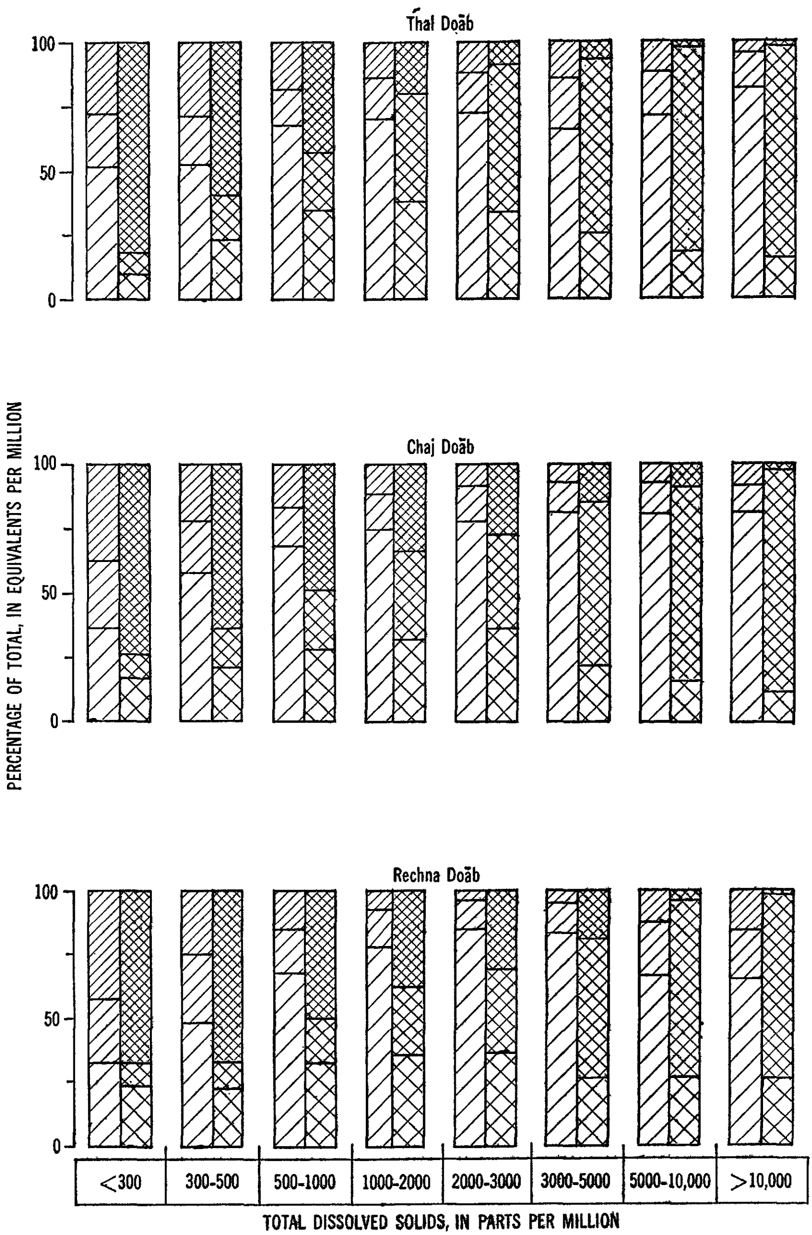

FIGURE 2.—Average ionic concentrations in 953 water samples, 1956–63.

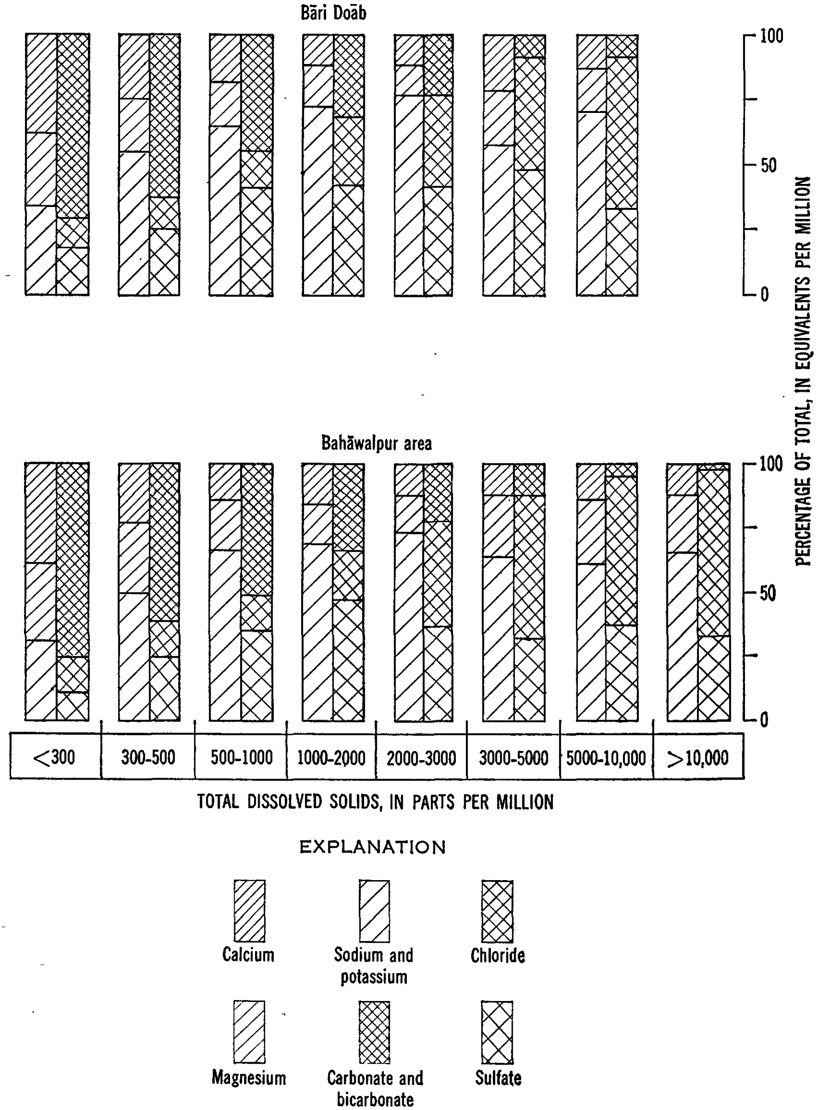

FIGURE 2.—Average ionic concentrations in 953 water samples, 1956–63—Continued

dissolved solids and their occurrence is probably related to variations in the lithologic environment.

In the lower downgradient parts of the doabs, particularly in the large areas of abandoned flood plains, evaporation from the water table must have contributed in substantial measure to the mineralization of ground water. In the preirrigation period, these areas were characterized by a flattening of the hydraulic gradients, convergence of ground-water flow, and the probable reversal of flow directions near the confluence of rivers. Thus, long-continued evaporation from shallow, nearly stagnant ground water was most certainly an important process in the building up of the salinity in the water in these areas. Although the rate of effective evaporation decreases appreciably below a water-table depth of about 8 feet, it is likely that significant evaporation losses occur from much greater depths. As suggested by Greenman, Swarzenski, and Bennett (1963) they may extend to depths of 60 feet or more under the climatic conditions prevailing in the lower part of the Punjab region.

OTHER THEORIES

Other theories seeking to explain the origin of the saline ground waters of the Punjab region emphasize the importance of evaporite deposits of the Salt Range and other areas, cyclic windborne salt accumulations, or connate sea water as sources of salts in the saline ground water. In general, these theories fail to account for the observed pattern of salinity distribution in the alluvial aquifer. If halite and gypsum deposits in the Salt Range were primary sources of salts in the ground water of the Punjab region, increasing mineral concentrations toward the source, reaching maxima near the base of the Salt Range, might be expected; this however, is not the case. Similarly, observed ground-water salinities do not point to any other source of surficial salt accumulation.

In regions of low relief and strong prevailing winds, salt and saline silt may be transported by winds from coastal or inland salt flats and deposited over extensive areas. In the Punjab region windborne salts have no doubt contributed to the mineralization of ground water; however, it cannot be established that the regional pattern of ground-water salinity in the Punjab is primarily related to windborne sources of salt.

In the Punjab region there is no evidence of a marine transgression younger than the Eocene. Limestone and other marine strata of Eocene age are found in the mountain ranges to the north and west of the alluvial aquifer in the Salt Range, in the Potwar Plateau, and they probably underlie a part of the alluvial plain. The first Himalayan orogeny, at the close of the Eocene, appears to have been accompanied by a general withdrawal of the sea in the northern part of West Pakistan. In the Sind region, however, marine conditions prevailed throughout the Oligocene and early Miocene, up to the second Himalayan upheaval. In the north, including the Punjab region, small residual basins or lagoons and brackish-water conditions may have persisted in early post-Eocene time. Thus, the lowermost rocks of the Murree Series, of Oligocene age, may include strata of brackish-water origin. All subsequent deposition, however, from early Miocene to Pliocene, Pleistocene, and Recent time, indicates a fresh-water, terrestrial environment of deposition. The rocks of predominantly fluviatile origin include those of the upper Murree, the Siwalik, and the Pleistocene and Recent alluvium, which were deposited during a time span of about 25 million years or more. During part of this time, climatic conditions were probably similar to those of the present, but moister climates presumably prevailed during the Pliocene and the pluvial stages of the Pleistocene. In view of the time span involved and the abundance of river water flowing from the Himalayan region into the alluvial plain, it is probable that an interface between fresh and saline water was always maintained in the coastal zone and that it migrated southward somewhat contemporaneously with the seaward growth of the alluvial plain. In part of the Punjab, alluvial deposits directly overlie the Precambrian(?) basement rocks; elsewhere, they may rest on several thousand feet of rocks of the Murree and Siwalik Series, which are of fresh-water origin. No brackish-water or evaporite deposits are known from the early Miocene and younger rocks that would suggest the presence of an isolated shallow marine basin in which saline waters may have remained trapped since middle Tertiary time. Thus, any theory ascribing the origin of saline ground water in the Punjab region to residual marine waters is inadequate, largely on geologic grounds. Asghar and Hamid (1960) have speculated that the saline ground water of the Punjab may be a mixture of residual sea water and surface waters. It is generally not possible, however, to identify the marine origin of saline ground waters by chemical character alone. On the other hand, age determinations by radioisotope methods of samples of saline water from different depths may shed light on this controversial question.

MOVEMENT OF FRESH AND SALINE GROUND WATER

The movement of ground water through the alluvial aquifer of the Punjab region, as deduced from preirrigation and more recent water-table maps, is described by Greenman, Swarzenski, and Bennett (1963). In Chaj, Rechna, and Bāri Doābs, the preirrigation water table generally sloped from the rivers downstream and toward the central axes of the doabs and indicated that the rivers were sources of ground-water recharge. In upper Rechna and Bāri Doābs, the water-table contours were nearly normal to the rivers, or their curvature indicated a water table slightly above the level of the adjacent rivers, as the result of recharge from precipitation in these areas. In Thal Doāb, the contours suggest that ground-water flow was predominantly southeasterly from the Indus River, toward the Chenāb River and lower Bāri Doāb. The Indus River was also the principal source of ground-water recharge in D. I. Khān District, where ground water moved southwesterly from the river (Hood and others, 1964). In the preirrigation period, ground-water flow in the Bahāwalpur area was generally southward from the Sutlej River toward the desert areas. Since the introduction of intensive canal irrigation, water levels have been rising and the water table in much of Chaj and Rechna Doābs, in part of Bāri Doāb, and in the upstream areas of Thal Doāb and Bahāwalpur is now above the average level of the bordering streams and within 5 to 15 feet of the land surface. Thus, there is a component of ground-water flow toward the rivers, as shown by Greenman, Swarzenski, and Bennett (1963, fig. 18).

Available water-table maps depict ground-water gradients only in two dimensions. Although the major component gradients of ground-water flow in the vast alluvial aquifer were probably in a horizontal plane in the preirrigation period, it can be assumed that significant vertical gradients were present in the flow system of the past, as they are today. Little or no information is available, however, with respect to the vertical distribution of pressure heads in the aquifer, either present or past.

In the preirrigation period, recharging fresh water moved downward from the line sources of the river channels, and subsequent ground-water flow was essentially downgradient, with upward components probably present throughout much of the flow system. The upward components were presumably most pronounced in the discharge areas of high evapotranspiration losses, that is, the flood plains and particularly the zones of flattened gradients and stagnation in the lower parts of the doabs. These conditions are depicted in two hypothetical flow sections, plate 3. Plate 3, X–X' is a profile along the flow path from the vicinity of Chiniot on the Chenāb River, toward the confluence of the Rāvi and Chenāb in the lower part of the Rechna Doāb, and is based on preirrigation water levels. Areas of maximum evapotranspiration losses and presumably of upward ground-water flow are found adjacent to the Chenāb River and centering near Shorkot Road (pl. 3, X–X') in the large area in the lower part of Rechna Doāb. The area in the lower part of Rechna Doāb is a zone of ground-water stagnation, characterized by flattened hydraulic gradients, and probably includes a small area of reversed ground-water flow updoab from the confluence of the Chenāb and Rāvi Rivers. As indicated on plate 3, X–X', the water table in a large part of this area, coinciding with the zone of highly mineralized ground water, was at depths of 25 feet or less below land surface in the preirrigation period.

Plate 3, *Y–Y′* shows ground-water flow in the preirrigation period from the Indus River southwestward into D.I. Khān District, and southeastward into Thal Doāb. It is assumed that water levels in the lower part of D.I. Khān District have not changed substantially since preirrigation time. In this illustration, areas of ground-water recharge and downward components of flow are indicated along the Indus River and along the front of the Sulaimān Range. In the intervening area, including D.I. Khān City, upward components of ground-water flow were noted throughout the deeper part of the aquifer. In D.I. Khān District, ground water moves from the sources of recharge toward a hydraulic sink or zone of discharge sink, located a few miles downgradient from test hole DIK19 (pl. 3, *Y–Y′*). Under conditions analogous to those of the lower parts of the doabs, the water becomes increasingly mineralized toward this zone of discharge or stagnation, where, moreover, the water table is as deep as 90 feet (Hood and other, 1964) below the land surface. As shown also on plate 3, *Y–Y′*, ground water moved from the Indus River southeastward, into Thal Doāb, toward a relatively small zone of mineralized ground water near Chaubāra.

In general, figure 2 and plate 3, *X–X′* support the hypothesis of progressive ground-water mineralization by the processes of evaporation and solution. Evaporation from the water table tends to create a zone of maximum mineralization just below the water table. Indications of such high mineral concentrations just below the water table are found in many areas beneath the terraces, where neither irrigation canals nor former river channels are present, particularly in western Thal Doāb (pl. 2, *A–A′*), Bāri and Rechna Doābs, and parts of D.I. Khān District. The periodic shifting of rivers, however, and the construction of major canals in the Punjab region have masked these conditions by introducting new sources of fresh-water recharge.

Within the saline ground-water zone of the lower part of Rechna Doāb there is a central area, about 10 to 15 miles wide, in which mineral concentrations of 15,000 to 18,000 ppm are remarkably uniform within the explored depth of about 1,100 feet (pl. 3, *X–X′*). The degree of mineralization is probably the net result of all factors affecting the hydrologic budget of lower Rechna Doāb and is specific for that area. The saline ground water of this zone is believed to be nearly stagnant; however, there are no data available at present (1965) to substantiate this conclusion. Downward components of flow, perhaps related to increased densities of the saline ground water, may be present in most or part of this zone. It is a matter of further speculation whether a fraction of the saline ground water of the lower part of Rechna Doāb becomes part of the regional system of deep ground-water circulation, with gradients toward the Arabian Sea, if, indeed, such a system exists.

The question whether and to what extent upward gradients in the alluvial aquifier have persisted since preirrigation time is of practical interest, but it cannot be answered adequately on the basis of available data. To shed some light on this problem a small number of paired, shallow and deep observation wells have been put down since 1961 in Rechna and Chaj Doābs, and in D.I. Khān District. Downward components of groundwater flow were noted only in the upper (northeastern) parts of Chaj and Rechna Doābs, north of Phālia and near Gujrānwala. Most of the paired observation wells indicated upward components of flow from depths of 800 feet or more and some of the deep wells produced artesian flow. Thus, a temporary piezometer installed in Khāngāh Dogrān produced flow from a depth of 1,445 feet, which indicated a pressure head of about 15 feet above the water table in 1962. This test site (R71) is located close to the central axis of Rechna Doāb, in an area where the water table has risen about 50 feet since preirrigation time.

Because of the fact that water levels have risen 50 to 90 feet throughout a large part of the doabs one might expect downward components of ground-water flow in most of the area, except where the rivers are line sinks for effluent ground-water seepage. Presently available information, however, indicates that upward components of flow, at least from the deeper part of the aquifier, are rather common. They may have persisted from preirrigation time and probably were enhanced in the central parts of the doabs including some of the saline ground-water zones, by disproportionately large seepage losses of the canal systems in the upper part of the doabs.

In order to evaluate three-dimensional ground-water flow in any of the Punjab region's hydrologic units, it will be necessary to install temporary or permanent piezometers, screened at two or three different depths. Probably 50 to 75 groups of piezometers would be required to provide adequate coverage for each doab.

CONCLUSIONS

West Pakistan's principal natural resource is the ground-water reservoir underlying the Punjab Plain. By conservative estimates, about 2 billion acre-feet of fresh ground water is stored in the alluvial deposits of the Punjab region. The aquifer, which is generally unconfined, is being replenished by the infiltration of water from rivers, canals, and precipitation. Extensive zones of fresh ground water, containing from less than 500 to 1,000 ppm of total dissolved solids, are found in the northeastern parts of Chaj and Rechna Doābs, where increased precipitation in the vicinity of the foothill ranges of the Himalaya and seepage from canals in the upper doabs provide above-average recharge. Moreover, fresh ground water extending to depths of 800 to more than 1,500 feet is found in wide belts paralleling the major rivers. The largest area of fresh ground water is found in the upper part of Rechna Doāb, extending northeasterly from Shekhūpura toward the border of Jammu. In this area ground water generally contains less than 500 ppm of total dissolved solids. A test well near Gujrānwāla yielded water of 230 ppm from a depth of 1,700 feet.

Saline ground water, containing from 4,000 to more than 30,000 ppm, occurs downgradient from sources of fresh-water recharge, particularly in the lower central parts of the interfluvial areas and, presumably, underlies most of the Punjab Plain. Saline ground water is also found in the northern part of Thal Doāb; in the piedmont area of the Sulaimān Range, west of the Indus River; and in a large part of the Bahāwalpur area, southeast of the Sutlej River.

The distribution of fresh and saline ground-water zones and the observed gradual mineralization of ground water with increasing distance from sources of recharge are related to the total water budget operative in each of the hydrologic subunits of the Punjab region. With respect to water quality, the significant factors in the hydrologic regimen are areal distribution of sources of recharge, including present and abandoned river courses, precipitation patterns, and extremely low ground-water gradients, which are generally 1½ feet per mile or less. Water-quality data, examined in the context of preirrigation flow patterns, indicate that there is neither a single source of the saline ground waters of the Punjab region, nor a single theory that would adequately explain their origin. The solution of minerals contained in the alluvial deposits by slowly circulating, nearly stagnant ground water and evaporation from the water table, apparently effective to depths of 90 feet or more, are two processes that seem adequate to explain the origin of the saline ground waters in the Punjab Plain. Ground water in the former province of Sind, downgradient and to the south, locally contains 100,000 ppm or more of total dissolved solids. It may be assumed that the areal distribution of saline zones and the degree of mineralization of ground water in that area are also controlled by the combined processes of solution and evaporation, operating in an environment comparable with, but more arid than, that of the Punjab region.

SELECTED REFERENCES

Asghar, A. G., and Hamid, Abdul, 1960, Saline characteristics of waters in old canal colonies of West Pakistan: West Pakistan Eng. Cong. Proc. Paper 342, p. 48.

Auden, J. B., 1951, Some geological and chemical aspects of the Rajasthan salt problem: India Natl. Inst. Sci. Bull. 1, p. 53.

Bennett, G. D., Ata-ur-Rahman, Sheikh, Ijaz Ahmed, and Ali, Sabir, 1964, Analysis of aquifer tests in the Punjab region of West Pakistan: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div., Tech. Paper 6, 94 p., 24 figs.

Ghosh, P. K., 1952, Western Rajputana—its tectonics and minerals, including evaporites: India Natl. Inst. Sci. Bull. 1, p. 101.

Gilani, Maqsood Ali Shah, and Hamid, Abdul, 1960, Quality of ground water, Chaj Doāb: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div., Basic Data Release 2, 90 p., 4 figs.

Greenman, D. W., Swarzenski, W. V., and Bennett, G. D., 1963, The ground-water hydrology of the Punjab, West Pakistan: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div., Bull. 6, 98 p., 29 figs.

Hood, J. W., Khan, L. A. and Jawaid, K., 1964, Preliminary report on ground water in the Dera Ismāīl Khān District, West Pakistan: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div., Prelim. Rept. 4, 32 p., 16 figs.

Hussain, M. A., and Hamid, Abdul, 1964, Quality of ground water, Bāri Doāb: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div., Basic Data Release 10, 95 p., 4 figs.

Kidwai, Z. U., 1962, The geology of Rechna and Chaj Doābs, West Pakistan: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div., Bull. 5, 27 p., 14 figs.

Kidwai, Z. U., and Alam, S., 1964, The geology of Bāri Doāb, West Pakistan: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div., Bull. 8.

Shamsi, R. A., 1960, Quality of ground water, Bahāwalpur area: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div., Basic Data Release 4, 10 p., 2 figs.

Shamsi, R. A., and Hamid, Abdul, 1960, Quality of ground water, Rechna Doāb: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div., Basic Data Release 1, 85 p., 4 figs.

——— 1961, Quality of ground water, Thal Doāb: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div., Basic Data Release 7, 75 p., 4 figs.

Siddiqi, Rauf, and Kazmi, S.A.T., 1964, The geology of Thal Doāb, West Pakistan: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div., Bull. 7.

U.S. GOVERNMENT PRINTING OFFICE: 1968