Ground-Water Hydrology of the Punjab, West Pakistan With Emphasis on Problems Caused by Canal Irrigation

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1608–H

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

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By D. W. GREENMAN, W. V. SWARZENSKI, *and* G. D. BENNETT

CONTRIBUTIONS TO THE HYDROLOGY OF ASIA AND OCEANIA

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CONTENTS

ILLUSTRATIONS

[Plates are in plate volume]

TABLES

CONTRIBUTIONS TO THE HYDROLOGY OF ASIA AND OCEANIA

GROUND-WATER HYDROLOGY OF THE PUNJAB, WEST PAKISTAN, WITH EMPHASIS ON PROBLEMS CAUSED BY CANAL IRRIGATIONS

By D. W. GREENMAN, W. V. SWARZENSKI, and G. D. BENNETT

ABSTRACT

Rising water tables and the salinization of land as the result of canal irrigation threaten the agricultural economy of the Punjab. Since 1954 the Water and Soils Investigation Division of the West Pakistan Water and Power Development Authority has inventoried the water and soils resources of the Punjab and investigated the relations between irrigation activities, the natural hydrologic factors, and the incidence of waterlogging and subsurface-drainage problems. This report summarizes the findings of the investigation, which was carried out under a cooperative agreement between the Government of Pakistan and the U.S. Agency for International Development, and its predecessor, the U.S. International Cooperation Administration.

Leakage from the canal systems, some of which have been in operation for more than 100 years, is the principal cause of rising water levels and constitutes the major component of ground-water recharge in the Punjab. Geologic studies have shown that virtually the entire Punjab is underlain to depths of 1,000 feet or more by unconsolidated alluvium, which is saturated to within a few feet of land surface. The alluvium varies in texture from medium sand to silty clay, but sandy sediments predominate. Large capacity wells, yielding 4 cfs or more, can be developed almost everywhere. Ground water occurring within a depth of 500 feet below the surface averages less than 1,000 ppm of dissolved solids throughout approximately two-thirds of the Punjab. It is estimated that the volume of usable ground water in storage in this part of the alluvial aquifer is on the order of 2 billion acre-feet. In the other one-third of the Punjab, total dissolved solids range from 1,000 to about 20,000 ppm. In about one-half of this area (one-sixth of the area of the Punjab) some ground water can be utilized by diluting with surface water from canals.

The ground-water reservoir underlying the Punjab is an unexploited resource of enormous economic value. It is recognized that the scientific management of this ground-water reservoir is the key to permanent irrigation agriculture in the Punjab. The West Pakistan Water and Power Development Authority has prepared a long-range program for reclaiming the irrigated lands of the Punjab. The essential feature of this program is a proposed network of tubewells (drilled wells) located with an average density of about one per square mile. Ground-water withdrawals will serve the dual purpose of helping to supply irrigation requirements and of providing subsurface drainage. Despite the feasibility

and inherent advantages of tubewell reclamation methods, it is inevitable that just as the superposition of the canal system on the native environment caused undesirable side effects, large-scale ground-water withdrawals again will disturb the hydrologic regimen. The distribution of withdrawals and maintenance of a favorable salt balance are two distinct but related aspects of the ground-water budget that present potential hazards that must be considered in the design and management of the tubewell projects. The availability of ground water for irrigation diminishes from northeast to southwest, or downgradient along the doab (an area lying between two rivers) and is negligible in the centers of the lower parts of the doabs, where the ground water is too highly mineralized for use. Ground-water supplies must be developed in areas where they are available and it might become necessary, under a program of maximum exploitation of ground-water resources, to transfer supplies from outside sources to points of use in the lower parts of the doabs.

Several factors inherent in the tubewell system will tend to depreciate the quality of ground water with time. Among these are the addition of salts leached from the soils, increased concentration of salts due to repeated cycles of recirculation, and the possible lateral and upward encroachment of saline water in response to pumping. It is reasonably certain that the rate of change in quality will be slow and that it will not present serious problems in the near future—probably not within the 40- to 50-year economic lifetime of the contemplated group of projects.

INTRODUCTION

LOCATION AND GENERAL FEATURES OF THE AREA

The Punjab—Land of Five Rivers—consists of the vast alluvial plain traversed by the Indus River and its tributaries, the Chenāb, Sutlej, Jhelum, and Rāvi Rivers, in the northern part of West Pakistan. Toward the north the Punjab is bordered by the Himalayan Foothills, the Salt Range, and the Potwar Plateau. The Indus and Sutlej Rivers are, respectively, the western and southeastern boundaries of the area. The alluvial plain extends southward, beyond the Punjab, to the Arabian Sea.

The investigation covered by this report comprises Thal, Chaj, Rechna, and Bāri Doābs, an area of about 40,000 square miles (fig. 1). Each doab is a large interfluvial area bounded by two of the principal streams of the Punjab. Rechna, Bāri, and Thal Doābs are similar in size, having a length of about 250 miles and a maximum width of about 70 miles between the rivers. Chaj Doāb is about one-half as large as the others. The total area comprises about 25.3 million acres, as follows:

Doāb	*Million acres*
Thal	7.9
Bari	7.2
Rechna	7.0
Chaj	3.2
Total	25.3

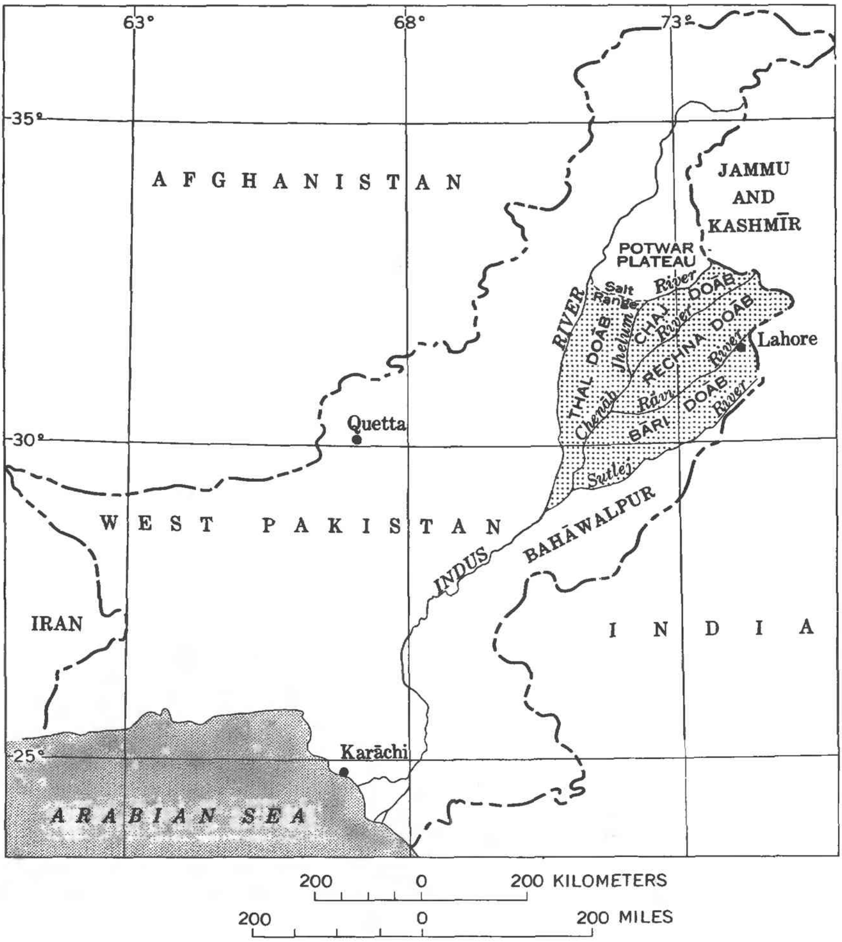

FIGURE 1.—Index map of West Pakistan showing the Punjab (stipple pattern) area.

Lahore, capital of the province of West Pakistan, is the largest city and the principal center of trade, industry, and education. Other major cities are Multan and Montgomery in Bāri Doāb; Jhang, Lyallpur, Gujrānwāla, and Sialkot in Rechna Doāb; Sargodha, Gujrāt, and Shāhpur in Chaj Doāb; and Mianwali and Muzaffargarh in Thal Doāb. All the cities and most of the major towns are located on surfaced roads and are served by main lines or branch lines of the Pakistan Western Railways.

The economy of the Punjab is largely agricultural and is based on an extensive system of canal irrigation introduced more than one hundred years ago. There are two crop seasons, the "Kharif" (April–

October), which includes the monsoon (wet) season, and the "Rabi" or dry season (October–April). The principal Kharif crops are cotton, sugar cane, rice, and maize. Wheat is the chief crop during the relatively dry winter season.

Rural population density is high, averaging about 500 persons per square mile and exceeding 800 persons per square mile in some areas.

TOPOGRAPHY AND DRAINAGE

The slope of the land in most of the Punjab is to the southwest and ranges from about 2 feet per mile in the northern part of the area to less than 1 foot per mile at the southern end. Thal Doāb, however, slopes generally to the south at similar gradients. Average slopes are about 1½ feet per mile. In the center of the doabs, terraces or bars rise as much as 50 feet above the level of the adjacent flood plains. The low relief of the plains and terraces is broken by a few scattered bedrock hills in Rechna and Chaj Doābs and by extensive dune areas in the central desert of Thal Doāb.

The area is drained by the five prominent rivers, the Indus, Jhelum, Chenāb, Rāvi, and Sutlej. The rivers are subject to extreme variations of flow; the mean monthly discharge during the summer months is about 15–20 times that of the winter months. There is generally a period of low-water flow from the middle of December to the middle of March, chiefly derived from ground-water seepage in the upstream areas. The main rise of the rivers usually begins by the middle of March, with the melting of the Himalayan snows, and reaches a maximum during July or August as the result of the monsoon rains. About 60 percent of the total annual discharge of the rivers is concentrated in the 3-month period June–August.

Before the introduction of canal irrigation, drainage of the monsoon runoff occurred through natural channels, called "nalas," leading into the rivers. In general, however, natural drainage features are poorly defined in the flat terrane.

CLIMATE

The climate of the Punjab, typical of the low-lying interior of the Indo-Pakistan subcontinent, is characterized by large seasonal fluctuations in temperature and rainfall. It is continental, ranging from semihumid in the northeast to arid in the southwest. Day-time temperatures in the sixties and seventies and night-time temperatures in the low forties are common from December to February. Frost is rare in the plains. Maximum temperatures of more than 105°F are common from May to August, although the warmest months are May and June, prior to the monsoon rains. The mean annual temperature at Lahore is 75.1°F; it increases to about 85°F toward the southwest. The Punjab is on the fringe of the monsoon belt, and about 70 percent of the average annual rainfall occurs from June to September (table 1).

TABLE 1.—*Average monthly and annual precipitation, in inches, at selected stations in the Punjab, 1916–57*

[From records of Irrigation Branch and Land Records Department, Government of Pakistan]

Station	Annual	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Sialkot	32.20	1.52	1.62	1.50	0.92	0.85	2.06	8.27	9.57	3.91	0.67	0.35	0.96
Gujrānwāla	23.50	1.06	1.09	1.43	.73	.66	1.49	6.92	6.40	2.50	0.42	.15	.65
Lahore	18.98	1.04	.82	.82	.63	.41	1.50	5.09	5.15	2.55	.36	.12	.49
Chunian	12.19	.53	.39	.49	.22	.32	1.13	3.34	3.67	1.68	.09	.04	.29
Montgomery	10.30	.45	.52	.53	.30	.35	.73	2.80	2.85	1.35	.08	.08	.26
Pākpattan	8.62	.46	.31	.33	.28	.29	.91	2.34	2.15	1.27	.03	.05	.20
Mūltan	7.60	.24	.32	.44	.27	.52	.41	2.44	1.66	.89	.10	.08	.23
Shujāābād	5.10	.19	.23	.31	.24	.26	.42	1.39	1.37	.50	.03	.00	.16

Rainfall is generally scant and sporadic and, therefore, not a dependable source of crop moisture. Annual precipitation at different locations varies considerably over the period of observation. Mean annual precipitation in the Punjab is shown in figure 2, an isohyetal map expanded from Sheikh and Hussain (1960). This map is based upon data from rain-gaging stations throughout the Punjab. For most of these stations, the period of record used in constructing the map extended from 1916 to 1957.

As shown in figure 2, precipitation ranges from 24 to more than 30 inches per year in the upper reaches of Rechna and Chaj Doābs, in proximity to the Himalayan Foothills. Precipitation diminishes to the southwest; the lower half of Rechna and Chaj, and nearly the entire area of Thal and Bāri Doābs, receive less than 14 inches of rain per year. The least rainfall, about 6 inches annually, occurs in the lower reaches of Thal and Bāri Doābs. The significance of areal variations in precipitation in the hydrologic budget of the Punjab is discussed in a subsequent section of this report.

SOILS

The soils of the Punjab are composed of alluvial material which was carried from the Himalayan ranges by tributaries of the vast Indus River system. Frequent changes in the rate of flow of the streams, recurrent floods, and ponding of the sediment-laden waters have created a varied and mixed soil pattern throughout the area. Although the magnitude of reworking of the alluvium by wind action cannot be ascertained everywhere, it is generally believed that the soils in much of the area have been modified by deflation and redeposition. Moreover, extensive areas of sand dunes are found in the central desert of Thal Doāb, and, locally, in the lower reaches of the other doabs.

257-729 O—67——2

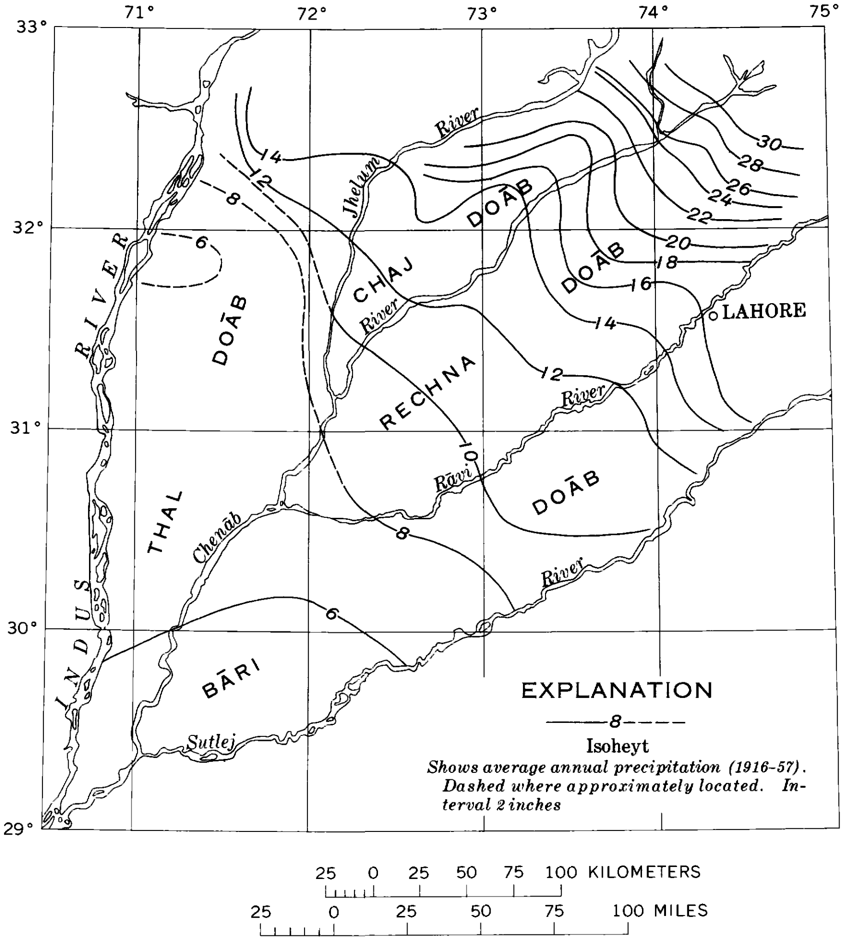

FIGURE 2.—Isohyetal map of the Punjab.

The soils of the Punjab are of recent origin and nearly everywhere azonal. Generally, the soils cannot be classified by genetic characteristics, and therefore they have been grouped into five basic series according to subsoil texture. Semidetailed soil surveys have been completed in most of the area. Detailed descriptions of the soils in Rechna and Chaj Doābs have been published by Asghar and Zaidi (1960) and by Zaidi and Rehman (1961), respectively.

In many respects the soils show a high degree of similarity throughout the area. They are reddish-brown to grayish-brown, mostly moderately coarse and medium-textured soils, containing high percentages of fine to very fine sand and silt. The clay part consists largely of nonswelling minerals, which may account for the generally favorable permeability characteristics of the soils. Most soils in the Punjab are moderately to highly permeable; only a small percentage displays low coefficients of permeability. The lime content of the soils is high, which is normal for areas of low rainfall.

The soils of the area, in general, are intrinsically fertile and have high potential productivity. In many areas, however, organic matter and plant nutrients, such as nitrogen and phosphorus, have been greatly depleted. When adequate water supply and the requisite manures or chemical fertilizers are provided, the soils of the Punjab normally attain a high level of productivity.

Preliminary land-classification data for Rechna and Chaj Doābs indicated that 55–60 percent of the area was unsuitable for irrigation farming in 1962, mainly as the result of waterlogging and salinity. Reclamation measures can rehabilitate most of these lands. If the salinity were eliminated, more than 90 percent of the lands would be classified as suitable for irrigation farming. The productivity of most lands affected by waterlogging and salinity in Bāri and Thal Doābs can also be restored by suitable reclamation procedures.

HISTORY AND PROBLEMS OF IRRIGATION

The climate of the Punjab makes irrigation a prerequisite to intensive agriculture. The favorable combination of other natural factors, such as abundant surface water and inherently fertile and permeable soils, makes irrigation feasible. Thus, throughout the recorded history of the Punjab, man has contrived ways to divert water to cultivated fields.

The oldest method of irrigation in the Punjab is flood irrigation, locally known as "sailab." In this method, which is restricted to the active flood plains, crops (mainly wheat) are planted after the recession of the summer flood waters. Lands under sailab irrigation retain their productive capacity indefinitely, and the method is still employed on the active flood plains, most of which are not served by canals.

Canal irrigation in the Punjab began at about the end of the 17th century with the construction of inundation canals which drew water from the rivers during periods of high stage for distribution to upland areas bordering the flood plains. The original purpose of the inundation canals was to furnish water for Moghul parks and gardens. Some diversions for agriculture were permitted, however, and the results were so successful that subsequent canals were constructed primarily for agricultural purposes. By the middle of the 19th century a rather extensive network of inundation canals was in operation with the maximum development concentrated along the Sutlej and Chenab Rivers.

The inundation canals represented an advance over sailab methods because they could convey water to more remote areas and draw water through a greater range of river stage. Thus, irrigation deliveries were maintained for a longer period of the year. The canals, however, could function only during periods of relatively high flow; irrigation, therefore, was limited to the summer season and to a relatively narrow belt along the rivers.

The final step in the evolution of the irrigation system in the Punjab came in about the middle of the 19th century with the introduction of so-called perennial canals. Permanent diversion works known as barrages, or headworks, were constructed at strategic sites on the rivers to place the inundation canals under weir control. These facilities allowed larger diversions from the rivers than were possible with the inundation canals, especially during the winter season. Thus, irrigation was extended into the central parts of the doabs, and in many areas the canals operated throughout the year; hence the term "perennial."

The first perennial canal system in the Punjab was the Upper Bāri Doāb Canal which was opened in 1859. This was followed by the Lower Chenab Canal in Rechna Doāb in 1896 and the Lower Jhelum Canal in 1901. In 1915 the Upper Chenāb, Upper Jhelum, and Lower Bāri canals were completed as parts of the Triple Canal Project, which also included an extensive system of link canals to transfer water from the Jhelum and Chenāb Rivers to the Rāvi River. Between 1915 and 1930 the inundation canals fed by the Sutlej River were converted to perennial canals; and with the completion of the headworks at Kālābagh in 1946 and Taunsa in 1958, all the canals serving the Punjab had been converted to weir control.

Total diversions at the headworks in the Punjab and Bahāwalpur areas during the period 1950–59 were at the average rate of 51.4 million acre-feet per year. This amount includes 7.2 million acre-feet per year transferred from the Jhelum and Chenāb Rivérs to the Rāvi. The remaining 44.2 million acre-feet per year served to irrigate the summer and winter crops on 18.6 million acres of agricultural land in the Punjab and adjacent areas, as follows:

	Million acre-feet per year (average 1950–59)	*Culturable area served by canals (million acres)*
Thal, Chaj, Rechna, and Bāri Doābs	33. 9	14. 9
Dera Ghazi Khan	1. 6	. 5
Bahāwalpur	8. 7	3. 2
Total	44. 2	18. 6

The locations, average annual diversions, and irrigated acreage for each of the canal systems in the Punjab are shown on plate 1. The agricultural area of the Punjab constitutes about 7 percent of the world's irrigated land, which is probably the largest area of virtually contiguous irrigation development in the world.

Because canal irrigation always involves diversion and redistribution of surface runoff, disruption of the hydrologic regimen is inevitable. In the Punjab the hydrologic effects of perennial canal irrigation were especially marked because the same natural factors that made irrigation attractive and feasible were also the sources of serious hydrologic problems in the modified environment. Thus, the permeable soils favored canal leakage which dissipated about 50 percent of canal diversions within the distribution system. Apart from depleting the supply available for irrigation, the seepage losses formed a new increment of ground-water recharge which, under the flat hydraulic gradients that prevail in the Punjab, could not be discharged through subsurface drainage. Hence, throughout the Punjab the inception of canal irrigation was followed by a period of rising ground-water levels. This trend persisted until the water table rose sufficiently near land surface to establish a new equilibrium in which evaporation loss was the dominant discharge factor. The trend of rising water levels and generally poor drainage conditions led to progressive salinization and waterlogging of the soil; these hazards were amplified by certain management practices.

In the Punjab, with the pressure of a growing population on the land, the tendency has been to expand the irrigated acreage and adjust irrigation application accordingly, rather than adjusting the irrigated acreage according to the availability of irrigation supplies. As a result, irrigation applications generally are inadequate to satisfy the consumptive uses of the crops, not to mention the leaching requirement of the soils. Moreover, the river regimen and the terrane are not conducive to extensive additional development of surface water to make up the deficiency in the irrigation supplies. About 80 percent of the runoff occurs in the summer months, but most of the water is wasted to the sea because the flat plains do not offer favorable reservoir sites.

In this environment, characterized by deficient irrigation supplies and inadequate subsurface drainage, the economic utility of the irrigated lands has steadily depreciated. By 1960 more than 8 of 13.7 million acres under irrigation in the Punjab were to some degree affected by salinity. Of this amount, about 3.5 million acres were out of production. Salinity is encroaching upon new lands at the rate of about 100,000 acres per year, of which about half goes out of production. Furthermore, crop yields from unaffected lands are only a fraction of world averages, owing in considerable part to the inadequate supply of irrigation water.

PREVIOUS STUDIES

The potential hazards of inadequate subsurface drainage in the Punjab were recognized soon after the perennial canals went into operation. Beginning about 1870, observation wells were established in the irrigated areas, and a schedule of semiannual water-level measurements was adopted to monitor the effects of irrigation activities on the water table. The network of observation wells was extended as new areas were brought under irrigation and now comprises several thousand wells.

Since about 1915, when salinity and waterlogging began to rank as major problems, the data of observation wells have been subjected to virtually continuous study of various commissions, government officers, and scientists. Most of the studies were too limited in scope to evaluate all pertinent factors; hence the findings were generally inconclusive and often misleading. Thus, Wilsdon and Sarathy (1928), and Taylor, Malhotra and Mehta (1933) related the rise in groundwater levels in irrigated areas to the effects of monsoon rain. Mehta (1940) found that rice and cotton irrigation was responsible for significant local recharge to the water table. Wilsdon and Bose (1934) cited the bedrock ridge beneath the alluvium as a possible cause of drainage problems in upstream areas. The work of Midha, Luthra, and Vaidhianathan (1937) showed that canal seepage losses must be an important factor of ground-water recharge. Other investigators related local water logging to the disruption of surface drainage by road embankments, canals, and the like.

On the basis of these studies, various remedial measures were employed, including closure of canals during the monsoon season; construction of open-ditch drains in waterlogged areas; and planting of phreatophytes along canals. The most ambitious effort was the installation of 1,600 wells along major canals in Rechna and Chaj Doābs. The wells were located so as to intercept canal leakage and pump it back to the canal. None of these measures provided more than local or temporary relief, and the regional problems of salinity and waterlogging continued to increase in severity.

The first comprehensive study of the problem of subsurface drainage was made by Carlston (1953). He examined all available hydrologic and geologic data for Rechna Doāb and concluded that canal leakage was the major factor involved. He recommended that further detailed studies should be made to determine which methods of reclamation were most appropriate for the Punjab.

PURPOSE AND SCOPE OF THIS INVESTIGATION

A comprehensive program of water and soils investigations was begun in 1954 under a cooperative agreement between the Government of Pakistan and the U.S. International Cooperation Administration (USICA), the predecessor agency of the U.S. Agency for International Development (USAID). Under the terms of the agreement the Provincial Government of West Pakistan furnished personnel for the project and field and office facilities. USAID provided a team of technical advisors on loan from the U.S. Geological Survey, and supplied vehicles, field and laboratory equipment, and other commodities required for the execution of the project.

In brief, the objectives of the investigations were to inventory the water and soils resources of the Punjab and to describe the relationships between irrigation activities, natural hydrologic factors, and the incidence of waterlogging and subsurface-drainage problems. The ultimate purpose for obtaining the information is to provide a scientific basis for the planning of regional reclamation and development programs and for the designing of individual projects under those programs.

Most of the basic data on the geology and on the occurrence and quality of ground water used in the preparation of this report have been published in a series of more than 20 descriptive preliminary reports on the investigation. The purpose of this report is to consolidate and correlate the results of the basic investigations into a regional interpretation of the hydrology. Subsequent reports will explore in greater detail certain critical aspects of the hydrology, such as the geochemistry of ground water, until the requirements of the reclamation and development programs are satisfied.

ACKNOWLEDGMENTS

The field studies upon which this report is based were made under the direction of Mr. Sayyid Hamid, Project Director of the Ground Water Development Organization, and his successor, Mr. S. M. Said, Chief Engineer, Water and Soils Investigation Division (WASID), Water and Power Development Authority (WAPDA). Technical guidance for the studies was furnished by a team of USAID advisors under the supervision of G. A. LaRocque, Jr., and his successor David W. Greenman, of the U.S. Geological Survey.

The writers are indebted to many members of WASID's staff who assisted in the compilation and analysis of data and the preparation of illustrations. Special acknowledgment is due to Abdul Hamid, Maqsood Ali Shah Gilani, and R. A. Shamsi for quality-of-water studies; M. A. Lateef, Abdul Shakur, and Amjad Hussain Shah for

compilation of water-level data; and Z. U. Kidwai and Rauf Siddiqi for the compilation of geologic data.

GROUND-WATER GEOLOGY

Under the auspices of the Colombo Plan, the Government of Canada has published a report on a reconnaissance survey of the landforms, soils, and land use of the Indus Plains, which contains descriptions of physiographic units (Fraser, 1958). The character and distribution of the alluvium underlying the Punjab have been investigated in considerable detail by the Water and Soils Investigation Division of WAPDA. Since 1955 about 800 exploratory holes have been drilled to depths ranging from 600 to 1,500 feet. Geologic data for Rechna and Chaj Doābs have been published by Kidwai (1962). The geology of Thal and Bari Doābs is described by Siddiqi and Kazmi (1963) and by Kidwai and S. Alam (1963), respectively. The following summary is based largely on the reports of these writers.

PHYSIOGRAPHY

The Punjab has been divided into four physiographic units and three subdivisions (pl. 2) as follows:

1. Kirana Hills
2. Pabbi Hills
3. Piedmont areas
4. Alluvial plain:
    - Active flood plains
    - Abandoned flood plains
    - Bar uplands

KIRANA HILLS

The inclusive term "Kirana Hills" has been given to a series of isolated bedrock hills near the villages of Kirana, in southern Chaj Doāb, and Chiniot, Sangla, and Shāh Kot, in central Rechna Doāb (pl. 2). The bedrock hills, rising as much as 1,000 feet above the surrounding ground, are prominent locally, but are minor features in the vast alluvial plain of the project area. The northwesterly alinement of the Kirana Hills and associated outcrops expresses the trend of a bedrock ridge that is largely buried by alluvium.

PABBI HILLS

The Pabbi Hills, which are part of the Himalayan Foothills, occupy a small area in the northernmost part of Chaj Doāb (pl. 2) and rise 400–500 feet above the surrounding alluvial and piedmont deposits. These hills are formed by an anticline in the Siwalik Group, which is composed of interbedded sandstone, siltstone, and conglomerate. Widespread development of gullies and vertical erosion of both the Siwalik rocks and overlying loess deposits have imparted a typical badland topography to the area, particularly on the northern flank of the anticline.

PIEDMONT AREAS

The transitional areas betwen the alluvial plains and the mountainous areas of the Salt Range and Himalayan Foothills are shown as piedmont areas on plate 2. These consist largely of alluvial fans which have been dissected by hill torrents and small perennial streams; much of the detrital material has been reworked repeatedly by sheetflooding. The width of the piedmont zone ranges from about 3 to 15 miles, and gradients vary from about 10 to more than 50 feet per mile. Generally, the lower slopes of the piedmont merge with the alluvial plains without a distinct boundary.

ALLUVIAL PLAIN

As shown on plate 2, the dominant physiographic units is the alluvial plain of the Punjab, a part of the Indo-Gangetic Plain. The alluvium consists of sand and silt and minor amounts of gravel and clay, deposited by the Indus River and its present and ancestral tributaries. In accordance with their mode of deposition by large constantly shifting rivers, the alluvial deposits are heterogeneous, and individual strata have limited horizontal and vertical continuity. The three physiographic subdivisions of the alluvial plain (pl. 2) are based on the present relationship of the surface features to the rivers.

Active flood plains

This subdivision includes the meander belt and present flood plain of the principal rivers of the area. During low-water stage, the rivers flow in braided or meandering channels, as much as 5 miles wide. Meander scars, sandbars, natural levees, and backwater swamps are conspicuous features of the active flood plains.

Abandoned flood plains

These areas, paralleling the rivers in a belt as much as 20 miles wide, are a few feet higher than the active flood plains. They represent flood plains that have been abandoned in comparatively recent times by the major rivers. However, the low-lying parts of the abandoned flood plains are subject to inundation by exceptionally high floods, which at places may extend to the bar uplands. Within the abandoned flood plains are areas of higher ground rising to elevations approaching those of the bar uplands. These features

257-729 O—67——3

surrounded by channel scars are isolated remnants of the bar, or in some places they may represent depositional features of the streams.

The abandoned flood plains are of hydrologic significance in that they provided the site of recharge by the rivers in the recent past (p H32). As shown on plate 2, the bar upland to the north and west of Sheikhūpura, in Rechna Doāb, apparently has been breached by incursions of the Chenāb and Rāvi Rivers during high floods. This low-lying area, mapped as part of the abandoned flood plains, contains ground water of excellent quality to depths of more than 1,500 feet, probably largely as the result of infiltrating flood waters (pl. 9). In Bāri Doāb the meandering courses of the former Beas and Sutlej Rivers have practically obliterated the interfluvial bar upland. The coalescing flood plains of these rivers, in most of southern Bāri Doāb, have created an uncommonly wide zone that received ground-water recharge from the rivers until recent times (pls. 2, 9).

Bar uplands

Large areas of relatively older alluvium are found in the central parts of the four doabs. Because of their elevation above the bordering flood plains, generally beyond the reach of flood waters of the five rivers, these areas, termed "bar uplands," are the most significant physiographic features of the alluvial plain. They coincide to a large extent with zones of highly mineralized ground water within the doabs (p. H32). Typically, the bar uplands rise abruptly from the abandoned flood plains and are bordered by steep scarps, 5–25 feet high. In upper Thal and the southwestern part of Rechna Doābs, where the bar uplands are being actively eroded by the rivers, the scarps are especially pronounced and are locally as high as 50 feet above the rivers. Elsewhere, however, the boundary between flood plains and bar upland is not distinct. The width and position of the bar in each doab, as shown on plate 2, has been determined by the lateral shifting of the rivers in comparatively recent times.

In Rechna, Chaj, and Bāri Doābs ancient river channels may be identified on the bar. These channels are more appropriately called systems, as each channel may be several miles wide and contain several scars showing successive positions of the ancestral rivers. The principal channels on the bar upland are indicated on plate 2. They commonly trend in the same direction as the present rivers and contain typical channel and flood-plain deposits. Generally, the traces of the channels become lost in the upstream part of the bar, where sheetflooding has obliterated them. An exception to this, and to the general orientation of the channels, is the small belt of meander scars and flood-plain deposits in Chaj Doāb north of Phalia (pl. 2). These sediments have a north-south orientation and may represent a former channel of the Jhelum River. It should be emphasized that the traces of these old channels do not represent a continuous riverbed or flood plain; rather, they represent many meander scars, natural levees, and channels that are individually discontinuous, but whose alinement may be conveniently mapped as a single unit.

GEOLOGIC UNITS

In the Punjab Plains, Quaternary alluvium has been deposited on semiconsolidated Tertiary rocks or on a basement of metamorphic and igneous rocks of Precambrian age. The distribution of Tertiary rocks in the project area is unknown, except in the Pabbi Hills area, in northeastern Chaj Doāb (pl. 2), where rocks of the Siwalik system are exposed. In the area of the buried bedrock ridge, in Chaj, Rechna, and Bāri Doābs, exploratory drilling has revealed that the Precambrian basement rocks are overlain directly by Quaternary alluvium. The the northeast and southwest of the bedrock ridge, test holes drilled to a maximum depth of about 1,500 feet bottomed in alluvium. Hence, no information is available concerning the total thickness of the alluvial deposits, the southward extension of Tertiary or older sedimentary rocks from the Salt Range and the Pabbi Hills, and the depth to the basement complex in most of the area.

The detailed descriptions of the geologic units, given by Kidwai (1962) in his report on the geology of Rechna and Chaj Doābs, are also applicable to the entire Punjab. Three of the geologic units are of subordinate regional significance: the Potwar loess, piedmont deposits, and aeolian deposits. The occurrence of the Potwar loess is restricted to the northern flank of the Pabbi Hills (pl. 2). Piedmont deposits are confined to a narrow belt, generally less than 15 miles wide, adjacent to the Himalayan Foothills and the Salt Range. The piedmont deposits consist of poorly sorted sand and gravel near the hills, grading into clayey sand and silt. The material, derived from the erosion of adjacent bedrock hills and loess, has been deposited as fans at the foot of the mountains. It has been reworked nearly everywhere by sheetflooding and is severely gullied by hill torrents. The aeolian deposits are found mostly in the nonirrigated parts of Thal Doāb, whose extensive desert areas are characterized by sand dunes or rolling sand plains. However, scattered sand dunes are prominent features in small local areas in the lower reaches of Bāri, Rechna, and Chaj Doābs, near Lodhrān, Shorkot, and Jhang (pl. 2). Windborne silt and fine sand, originating from the flood plains of the rivers, are found locally within the alluvial complex. These aeolian deposits, blanketing small areas or filling local depressions, are intimately associated with the alluvium; their separation from the alluvium is generally impracticable.

As the ground-water reservoir of the area is contained almost exclusively in the alluvial deposits, only the alluvial complex and its water-bearing properties and the buried bedrock ridge will be discussed in detail.

ALLUVIAL COMPLEX AND ITS WATER-BEARING CHARACTERISTICS

The alluvium of the Punjab Plains, derived from the mountain ranges to the north, has been deposited by the present and ancestral tributaries of the Indus River. The alluvial complex of Pleistocene and Recent age represents the latest phase of sedimentation in an environment that had its beginnings in mid-Tertiary time: the deposition of predominantly fluviatile sediments in a subsiding trough—a foredeep adjacent to the rising Himalayan ranges.

The alluvial complex consists principally of fine to medium sand, silt, and clay. Beds of gravel or very coarse sand are uncommon. Pebbles of siltstone or mudstone, however, may be found embedded in silty or clayey sand in many places. Also associated with fine-grained strata are concretionary zones or nodules of kankar, a calcium carbonate deposit of secondary origin. The study of drill cuttings and electric logs has shown the absence of thick horizons of pure clay within the alluvium. Except for local clay lenses, a few feet thick, the finer parts of the alluvium consist generally of sandy, gravelly, or silty clay. Although there are local concentrations of fine-grained sediments of considerable thickness, individual strata are generally lenticular and have little horizontal or vertical continuity. The random distribution of coarse- and fine-grained sediment within the alluvial complex is entirely consonant with its mode of deposition by large constantly shifting streams.

The lithology of the alluvium, as inferred from the study of well samples and electric logs, is shown by the series of geologic sections in each doab (pls. 3–6). These illustrations show the heterogenous character of the uppermost 600 feet of the alluvium in downstream and transverse directions and the random distribution of clay zones within the alluvium. Local accumulations of relatively fine-grained material are found in the upper parts of all doabs and in the vicinity of the bedrock ridge. A comparison of plates 3–6 shows that, in general, the alluvial deposits of Chaj Doāb contain a larger porportion of fine-grained material than those of the other doabs. Sandy and relatively permeable alluvial deposits are predominant in most of Thal Doāb (pl. 3), and in the lower part of Bāri Doāb (pl. 6).

The alluvial deposits of the Punjab, in spite of their heterogenous composition, form a unified highly transmissive aquifer, in which ground water occurs for the most part under water-table conditions.

Tubewells[1] yield 2–4 cfs (cubic feet per second) of water almost anywhere in the area. The uppermost 300 feet of the aquifer, which is but slightly compacted, is the most productive zone.

Specific capacity is, of course, only a rough measure of the potential of the aquifer, since it depends upon many factors other than the characteristics of the sediments. The specific capacity of a well in a thick unconfined aquifer depends upon the permeability and specific yield of the aquifer, but also upon the degree of penetration of the aquifer by the screen, the duration of pumping, the availability of recharge, the radius of the well and the head loss occurring in the screen and gravel pack. Most of the tubewells presently being constructed in the Punjab employ from 100–200 feet of screen, of 6- to 12-inch diameter. Experience throughout the Punjab indicates that wells of this design will usually yield from 0.1 to 0.25 cfs per ft of drawdown for pumping times of a few days or weeks.

The water-bearing properties of the alluvium were determined by field and laboratory methods. The laboratory studies involved the determination of porosity from repacked drill cuttings. From these studies, the average porosity of the alluvial sands is estimated to be about 0.35; it must be considerably less for the aquifer as a whole.

To determine the characteristics of the alluvial aquifer, about 170 pumping tests were run throughout the four doabs. The field procedures, techniques of analyses, and results of this test series are summarized in a U.S. Geological Survey Water-Supply Paper (Bennett and others, 1967). Most of the wells used in the pumping tests were similar in design to those being installed in the various reclamation projects in the Punjab. The screened or perforated interval usually was between 100 and 200 feet in length; the top of the screen usually was located between 50 and 150 feet below land surface. From 4–10 observation wells were generally used. The detailed results of these tests are available in the files of WASID. Originally, the tests were analyzed by the conventional time-drawdown methods of Theis and Jacob. The results of these original analyses seemed to contradict the obvious geologic evidence that the aquifer was unconfined, and frequently indicated a transmissibility that seemed questionably high for the type of sediment. Reexamination of the test data and review of the test-well designs indicated that in most cases the assumptions underlying the conventional methods of analysis could not have been satisfied by the field conditions. Numerous special pumping tests, involving extensive networks of piezometers, were then conducted in order to study in detail the flow system around a tubewell of the design

[1] "Tubewell" is a term used in India and Pakistan for a conventional drilled and screened well.

used in the test series. These tests established conclusively that the aquifer is in effect an unconfined system, and that the discharge of tubewells of the design in question generally is derived from water-table storage or, in a few cases, partly from water-table storage and partly from surface recharge sources. Using the results of the special tests, new methods were developed by which the earlier pumping tests could be adequately analysed. These methods were then applied to the data of the earlier tests to obtain values for lateral transmissibility, specific yield, and, in a few instances, vertical permeability. Generally, the results were reasonable and in agreement with the geologic evidence, and are therefore believed to be reliable. The lateral transmissibility figures were divided by the length of screen used in the tubewell to obtain average lateral-permeability values.

Certain facts should be kept in mind in connection with the interpretation of these permeability data. In most of the test wells, unperforated casing was installed through the low-permeability silts and clays; drilling was generally continued until one to two hundred feet of relatively permeable silt or sand had been penetrated, and screen was then installed opposite this material. Thus, the average permeability obtained by dividing the transmissibility figure by the screened interval does not represent the average for all the materials that may be present in the geologic section penetrated by the tubewell; it should be regarded, rather, as a rough average for those materials in the section exclusive of the fine silts and clays. As such, it will generally be somewhat higher than the average for the entire section penetrated by the tubewell. The figures may in fact be slightly high even when interpreted as the average permeability of the silts and sands, owing to the effects of partial penetration of the aquifer by the test wells. The method used in obtaining these figures is based upon the assumption that, at least within a few hundred feet of the well, the flow is confined largely to the screened interval. If this assumption is not satisfied, as is often true in partially penetrating wells, the method yields permeability figures that are too high. For anisotropic sediments, however, in which the vertical permeability is appreciably less than the lateral permeability, the assumption that flow is confined to the screened interval is usually acceptable. The few calculations of vertical permeability which could be made indicate that the average vertical permeability is considerably less than the average lateral permeability throughout the Punjab. This conclusion is strongly supported by the weight of geologic evidence. The effects of partial penetration upon the lateral-permeability figures are therefore probably not severe.

The locations of test wells in the four doabs, together with the average lateral-permeability figures, are shown on plate 2. Very high and also relatively low values of permeability can be observed at scattered locations throughout the area. This simply reflects the fact that sections of predominantly coarse sand as well as sections of predominantly fine silt can be located in all parts of the Punjab. Certain general differences between areas can nevertheless be noted by taking averages of the permeability figures for the tests conducted in the areas in question. Thus, in Thal Doāb permeabilities are generally high, indicating a somewhat higher proportion of coarse sediment than is present in the other doabs; in Chaj Doāb permeabilities are low, indicating a higher proportion of fine sediment.

Whereas the lateral-permeability figures refer to the screened intervals of the test wells, the specific-yield figures obtained in the tests actually apply to the material at water-table depth in the vicinity of the test well. This interpretation is made on the basis of the special pumping tests mentioned above, which verified that well discharge is generally supplied from water-table storage or local surface recharge, and which indicated a method by which approximate specific-yield figures could be obtained from the earlier tests. Most of the specific-yield figures determined by this method fell between 0.07 and 0.25, although a few figures as low as 0.01 and as high as 0.40 were obtained. The average value, for all tests for which calculations were attempted, was 0.14. In a number of tests, in which there were obvious indications of recharge or in which an insufficient number of observation wells were used, the method of calculation proved inapplicable. The accuracy of the method is insufficient to warrant any attempt to define geographic variations in specific yield. The results should simply be taken as an indication of the range through which specific yield can be expected to vary in the Punjab Plains.

Whereas the aquifer is in effect unconfined, the anisotropy of the sediments frequently causes well-drawdown records to resemble those normally observed in artesian aquifers. This is especially true in wells where the top of the screen is located at a considerable depth below the water table. Despite these effects, however, the evidence is indisputable that the aquifer is unconfined, and that well discharge on any scale results in drainage from the water table.

PRECAMBRIAN ROCKS

The bedrock hills at Chiniot, Sangla, Shāh Kot, and Kirana represent the peaks of a buried or suballuvial ridge which underlies the central part of Rechna and Chaj Doābs. The ridge, which is composed of indurated metamorphic and igneous rocks of Precambrian age, has also been referred to as the Shāhpur-Delhi Buried Ridge, from the inference that it represents the northwesterly extension of the ancient Aravalli Mountain system in India. The locations of outcrops and the approximate depth to bedrock in the area of the buried ridge are shown on plate 7. The ridge trends to the northwest and scattered outcrops are located along the strike between Shāh Kot and Charnali (pl. 7). As shown by the contours, the northeastern flank of the ridge dips steeply beneath the alluvium, and only a few miles away from the outcrops the alluvial material has a thickness of more than 1,500 feet. Available data indicate that slopes to the southwest are less steep. The contours also indicate that the average thickness of the alluvium over the crest of the ridge is on the order of 400–500 feet. Test wells drilled close to the outcrops penetrate bedrock at shallower depths; this, however, is offset by the presence of deep gorges or channels between the outcrops (pl. 7). Undoubtedly, many other deep bedrock channels and also high points exist in the relief of the buried ridge, which can only be detected by additional test drilling.

The influence of the buried ridge on the movement of ground water has been the subject of much discussion, and the estimates of its effect have ranged from negligible to that of a total barrier. On the basis of geologic information the following comments can be made.

The blocking or damming effects of the bedrock outcrops on the regional movement of ground water are probably negligible, as only a very small part of the total area of Rechna and Chaj Doābs is occupied by the bedrock hills. More important is the average or effective depth of the ridge; or, in other words, the relationship between the transmissive thickness of the alluvium over the crest of the ridge and the transmissive thickness of the alluvium upstream from it. Although this relationship is not known with certainty, it is obvious that the alluvium is considerably thinner over the ridge than it is either upstream or downstream. However, the peaks of the ridge are not continuous across the doabs, and the average elevation of the ridge is not sufficiently great to affect seriously the movement of water in the upper several hundred feet of the alluvium, where the bulk of ground-water flow takes place.

As significant as the suballuvial ridge itself are the extensive clay deposits associated with it. As discussed above, fine sediments predominate along the axis of the ridge in Chaj, Rechna, and Bāri Doābs. The combination of relatively impermeable alluvium and high bedrock may locally impede the movement of ground water. In particular, the presence of bedrock outcrops and clay bodies in proximity to the rivers are factors that locally control or restrict the circulation of fresh ground water. However, because of the large gaps between bedrock outcrops and the occurrence of sandy zones intercalated everywhere in the alluvium, the buried ridge cannot be considered a barrier to the movement of ground water on a regional scale.

OCCURRENCE OF GROUND WATER BEFORE IRRIGATION

RECHARGE, MOVEMENT, AND DISCHARGE

In the natural environment that existed before the inception of perennial canal irrigation, the ground-water hydraulic system in the Punjab was in a state of dynamic equilibrium—that is, considered over moderately long periods of time, recharge to the ground-water reservoir balanced discharge and there was no long-term rise or decline of the water table. This concept is basic to an understanding of the hydrology of the area. It is supported on several grounds. First, it can be argued on the basis of logic. Natural processes always tend to adjust toward equilibrium, and in view of the geologic time involved since the development of the Indus Plain, it is almost beyond the realm of probability that this generation could be witness to a natural hydrologic environment that was out of balance. Second, historical records provide no evidence of changes in the environment. Third, analysis of recent precipitation data for the Punjab (Sheikh and Hussain, 1960) shows no significant trend of rising or declining precipitation, without which it is unlikely that the natural ground-water regimen would be subject to long-term change.

The equilibrium condition of the hydraulic system before irrigation began is depicted on plate 8, which shows, respectively, the elevation of the water table above mean sea level and the depth to the water table below land surface. These maps are based on miscellaneous data which were found in various files of the Irrigation Branch, Public Works Department of West Pakistan. The data represent the earliest available measurements in each area; for most of the areas shown, most of these measurements were made before the installation of any barrage irrigation systems. An exception to this is in upper Bāri Doāb, where the Upper Bāri Doāb Canal System went into operation in 1859, whereas the period of measurement was from 1895 to 1910. In lower Bāri Doāb the period of measurement extended from 1909 to 1920; in Rechna Doāb it extended from 1872 to 1900; in Chaj Doāb it extended from 1880 to 1907; and in Thal Doāb it extended from 1935 to 1940. The methods used to collect these data were crude by present-day standards, and individual items of data may be greatly in error. But the water-level maps which have been synethesized from these data

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show a persistent pattern which probably is reasonably representative of the average conditions in the preirrigation period.

The equilibrium condition of the ground-water regimen reflected the compound effects of many factors—including geology, climate, and topography and drainage—on both the local and regional occurrence of ground water. The effects of these factors cannot be equated quantitatively into a water budget because of inadequate data, but the gross effects can be described qualitatively by relating them to appropriate features of the water-level maps. An understanding of the influence of the natural factors in the virgin environment is important, because these factors continue to influence the occurrence of ground water under the irrigation regimen. Of particular importance in the hydrologic budget of the Punjab is the distribution of precipitation, which decreases from about 30 inches in the northeast to about 5 inches annually in the southwest (fig. 2). If precipitation rates are below a certain threshold value, probably on the order of about 10–14 inches under the prevailing temperature conditions and seasonal distribution of precipitation, percolating rains will tend to fill soil-moisture deficiencies, without, however, providing appreciable recharge to the water table. Precipitation rates are apparently below these threshold values in most of the Thal Doāb and in the central and lower parts of the other doabs. Therefore, in these areas recharge derived from precipitation ceases to be a significant factor in the ground-water budget, and the infiltration of river water becomes the sole source of ground-water replenishment.

The most obvious features of the water-level contour map (pl. 8) are the troughs formed by the water table beneath Chaj, Rechna, and Bāri Doābs and the marked flattening of the hydraulic gradient in the lower reaches of the doabs, especially along the axes of the troughs. The axes of the troughs are in almost perfect alinement with the axes of the doabs. On the map showing the depth to the water table (pl. 8) the troughs are reflected by the closed pattern of the contours which show increasing depth to the water table from the margins toward the centers of the doabs. Thus, the general direction of ground-water movement was diagonally away from the rivers and downstream toward the axes of the doabs. However, it should be noted that the preirrigation flow is difficult to describe in terms of the two-dimensional map alone; as the discussion of preirrigation conditions is developed, it will become apparent that the flowlines were three dimensional generally terminating at the water table where evaporative losses occurred. In approximately the upper halves of the doabs, the hydraulic gradient was steeper than the topographic gradient; the water table was at depths of more than 100 feet below land surface near the center of Rechna Doāb, more than 70 feet near the center of Chaj Doāb, and more than 70 feet near the center of Bāri Doab. In the lower halves of the doabs the hydraulic gradient was less than the topographic gradient, and the depth to water diminished downstream until the water table merged with the rivers.

The troughs evidently were related to the climate and the surface-drainage pattern. Near the northeastern border of Rechna Doāb the water-level contours were nearly normal to the rivers. Thus, the water table was at about the same elevation as the river levels, and there was apparently no appreciable movement of water between the rivers and the ground-water reservoir. Ground water was derived from underflow from the upstream areas and from local precipitation which ranged from about 22 inches per year at Gujranwala to more than 30 inches at Sialkot (fig. 2). The quantity available from these sources balanced underflow to downstream areas and local losses to evapotranspiration. Some 15–20 miles from the northeastern limit of the doab the contours curve upstream, so that a trough in the water table appears between the rivers; this trough becomes much more pronounced downgradient along the doab, indicating that leakage from the rivers to the ground-water system became progressively more important.

About the same conditions prevailed in the northeastern end of Chaj Doāb, except that the contours curved slightly upgradient along the doab and described a shallow depression in the water table between the rivers even in the uppermost part of the doab. Evidently, underflow from upstream areas plus recharge from local precipitation did not quite balance underflow downstream and evapotranspiration losses; equilibrium was maintained by a small component of recharge from the rivers to the ground-water reservoir. The differences in the ground-water regimen between the doabs are probably due to the geology of the upstream areas. Chaj Doāb abuts bedrock terrane which presumably yields less ground-water underflow than the alluvial sediments abutting the northeastern end of Rechna Doāb.

The data available for Bāri Doāb do not strictly apply to the preirrigation period. The Upper Bāri Doāb Canal was opened in 1859, whereas systematic measurements of water levels were not undertaken until a much later date. The contours for upper Bāri Doāb actually represent data for the period from 1890 to 1910. For the southern and central parts of the doab, the contours probably closely approximate preirrigation conditions; in the northern part of the doab, however, they reflect the influence of the Upper Bāri Doāb Canal System. Thus, the downgradient curvature of the contours in the northern part of the doab, indicating a water-table ridge between the rivers, probably can be attributed to seepage from the canal system during the period from 1859 to about 1900. Within a short distance down the doab, the curvature of the contours reverses, indicating a water-table trough similar to that in Rechna and Chaj Doābs. Thus, the effect of the canal system diminishes within the northern quarter of the doab, and a pattern of flow similar to that in Rechna and Chaj Doābs prevails throughout the rest of the doab.

In Rechna, Chaj, and Bāri Doābs the upgradient convexity of the water-level contours increased progressively downgradient along the doab more or less in proportion to the decline in the average annual precipitation (fig. 2) and the increase in the mean annual air temperature. Thus, with diminishing recharge from precipitation the depth of the water-table trough below river level increased, which, in turn, resulted in increased recharge from the rivers. The hydraulic gradient remained relatively uniform, evidently because the progressive decrease in the rate of recharge from precipitation was balanced by an increase in recharge from the rivers and by decreased losses to evapotranspiration as the depth to the water table increased. This trend continued downstream to about the center of Rechna and Chaj Doābs, and to somewhat beyond the center of Bāri Doāb, where the hydraulic gradient along the axes of the troughs began a progressive flattening which persisted downstream toward the tips of the doabs. With the flattening of gradient the depth of the ground-water troughs diminished, and this was accompanied by decreased recharge from the rivers to the water table.

The flattening of the hydraulic gradient in Rechna, Chaj and Bāri Doābs apparently was related to evapotranspiration losses from the flow system. The data for Bāri Doāb suggest very strongly that a reversal of gradient occurred near the western end of the doab—that is, that the water table reached its lowest elevation some 20–30 miles from the end of the doab and from that point rose to merge with the rivers at the extremity of the doab. The data for Rechna Doāb suggest a similar situation but on a smaller scale; the reversal in gradient, if present, occurred very close to the confluence and involved a very slight rise in the water table. These presumed reversals are significant in that they indicate closed regions of evapotranspiration loss—that is, regions that show inflow on all sides, which must be balanced by outflow—which can be only evapotranspiration losses from the ground-water system within the region. Even if the reversals were not present, loss of flow by evapotranspiration seems to be the only plausible explanation for the flattening of the gradient. The alternative interpretation—that the transmissibility of the sediments gradually increases down the doab—contradicts the available evidence. The geology of the region indicates no appreciable difference in the character of the sediments from northeast to southwest through the area. Futhermore, aquifer tests performed throughout the four doabs indicate no general increase in permeability in a downgradient direction.

Although the flattening of the hydraulic gradient was brought about primarily by losses of flow, the form of the water table was strongly influenced by several other factors. Among these was the geometry of the doabs, or the courses of the rivers bounding the doabs. In Rechna and Bāri Doābs, assuming that the reversals in gradient were actually present, the rivers constituted continuous recharging boundaries enclosing the lower ends of the doabs. In adjusting to equilibrium, the water table in each doab stabilized in the particular position in which flow from the rivers and from upgradient balanced the evapotranspiration loss from the doab. This equilibrium position would of course depend upon the geometry of the rivers bounding the doab. In Chaj Doāb, where there is little evidence of a direct reversal of gradient, the confluence area marked a boundary along which the head was relatively high and across which little outflow could occur. The equilibrium position of the water table must have been influenced by the geometry of this boundary.

The form of the preirrigation water table was of course also related to the nature of the flow system in three dimensions. Although the vast area of the Indus Plain, as compared to the thickness of the sediments, suggests a flow pattern that is virtually two dimensional, some vertical components of flow must nevertheless have been present. The rivers, which acted as sources of recharge throughout much of the area, extend only to a shallow depth in the sediments, and seepage from the rivers therefore involved some downward movement. Similarly, loss due to evapotranspiration implies some upward movement within the ground-water system. Although there is practically no data in existence today relating to vertical-head differences in the preirrigation period, the general form of the three-dimensional flow pattern can be reconstructed from the known conditions of recharge and discharge and from information on the quality of water at depth in the aquifer.

In an aquifer in which circulating fresh water directly overlies saline water which is static or nearly static, the zone of transition between the two fluids is always observed to rise in the general direction of flow of the fresh water. Thus, if a fresh water-brackish water transition can be traced in an aquifer, the direction of fresh-water flow at depth can be taken as upward along this transition zone. Data on quality of water collected in recent years suggest that such a zone of transition occurred in the Punjab during the preirrigation period. The zone seems to have been set in motion and partly disrupted by changes in the flow pattern brought about by irrigation. However, because of the slow rates of movement of ground water, the gross features of the preirrigation transition zone can still be recognized at present. The directions of movement which can be inferred from this transition zone support the theory of recharge from the rivers and discharge by evapotranspiration.

Figure 3 shows a generalized hydrologic cross section along line *A–A′* in Rechna Doāb (inset on figure 3 shows location of section). In viewing this cross section one should bear in mind that a vertical exaggeration of 169 times has been employed. The lithology shown in the figure represents the general nature of conditions in the doab, but it is not necessarily an accurate representation of conditions along the line of section. Similarly, the hydrologic information is not presumed to be an accurate portrayal of the preirrigation conditions along the line of section, but rather is a general representation of conditions in the lower doab. The dashed line represents the preirrigation water table. The dotted lines are lines of equal head; each of these lines represents the trace of a three-dimensional surface of equal head on the vertical plane of the section. The arrows indicate directions of flow. Although the cross section illustrates the vertical

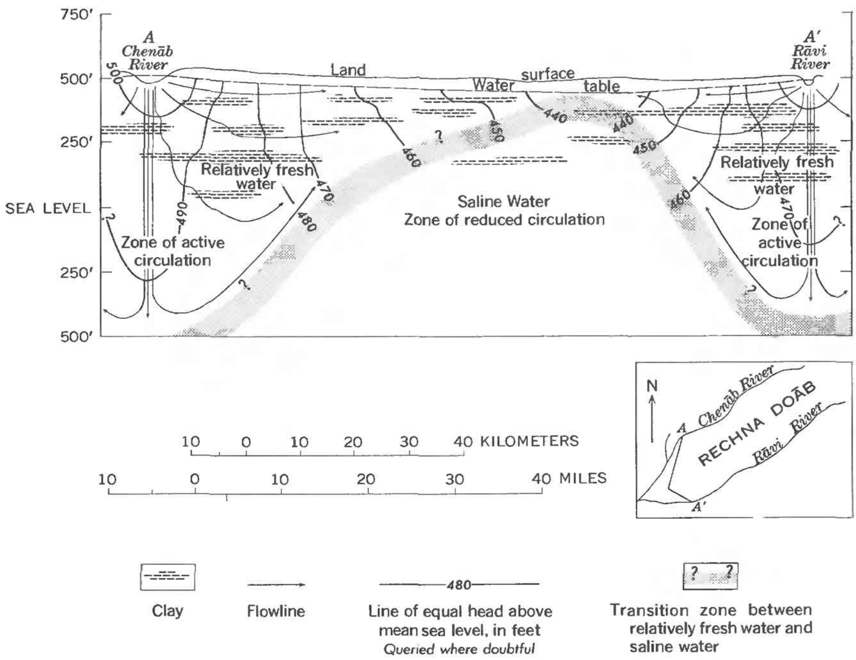

FIGURE 3.—Hydraulic profile for Rechna Doāb for preirrigation period.

flow pattern in lower Rechna Doāb, the same general pattern must also have existed in lower Chaj and lower Bāri Doābs.

It can be seen from the cross section that the thickness of the zone of fresh-water flow decreases along the flow path, from a maximum of about a thousand feet beneath the rivers to a minimum of less than a hundred feet at the low point of the water table. In the vicinity of the rivers the flow was largely downward and outward from the channel beds. Within a relatively short distance of the rivers, however, the flow must have become nearly horizontal in the sands, though with a slight upward component, and almost vertical through the fine silts and clays. This behavior is commonly observed in sections of alternating sand and clay; the flow lines tend to cross materials of low permeability (clay) in the shortest possible distance—that is, vertically. This, in turn, requires that the surface of equal head be "refracted" sharply at the contacts between sand and clay, becoming nearly horizontal in the clay and nearly vertical in the sand.

The water-table contours on the map of plate 8 may be thought of as the lines of intersection of the water table and the three-dimensional surfaces of equal head. The general form of these surfaces of equal head can be visualized by combining the pictures given in the cross section and in the map. The lines of flow in three dimensions may then be visualized as lines that are orthogonal to the surfaces of equal head.

The theory of preirrigation flow presented here implies that evapotranspiration losses from the water table have occurred from considerable depths and raises the question as to whether evapotranspiration on the scale required is possible from such depths. To investigate this question, trial computations of flow losses were made for lower Chaj Doāb, taking into account the flattening of the hydraulic gradient, the convergence of flow paths which must have occurred toward the axis of the doab, and the decrease in thickness of the fresh-water system in the direction of flow. These computations must be regarded as crude estimates, owing to the approximate nature of the data upon which they are based. They nevertheless provide a reasonable indication of the order of magnitude of the flow losses that must have occurred. The calculations indicate that the losses were heaviest adjacent to the rivers, where the water table was closest to the surface, and that they decreased rapidly toward the axis of the doab. The losses ranged from more than 1 foot per year near the river to less than 1.5 inches per year at a distance of 20 miles from the river, where the depth to water was about 60 feet. Thus, the calculations indicate that the required flow losses are not excessive, and that the pattern of loss coincides with that which could be expected from considerations of evapotranspiration as a function of depth to water.

In summary, the occurrence of the native ground waters were generally similar in Rechna, Chaj, and Bāri Doābs because the environment was similar. The configuration of the water table in each doab was controlled by the pattern of evapotranspiration loss, by the geometry of the doab, and by the nature of the three-dimensional flow system in the doab. The boundary conditions imposed by the rivers separated the doabs into virtually discrete hydrologic units, in each of which hydraulic equilibrium was maintained largely by local factors operating within the doab.

The conditions in Thal Doāb obviously differ somewhat from those in Rechna, Chaj, and Bāri Doābs. The water-table contours begin to space out to some extent in lower Thal, but they do not show the pronounced upgradient curvature shown in the other doabs. The contours indicate that the regional ground-water flow was southeasterly away from the Indus through most of the doab and suggest that, although some of the flow was lost by evaporation in crossing the doab, a part of it left the doab as underflow beneath the Chenāb or possibly as discharge into the Chenāb. There are many possible configurations of the three-dimensional surfaces of equal head that are compatible both with the water-table contours and these hypotheses of outflow. The topography and surface hydrology of the region also tend to suggest outflow into or under the Chenāb. The bed of the Indus is generally somewhat higher than that of the Chenāb, and the discharge of the Indus is by far the largest of any of the rivers of the Punjab. It is logical to suppose, therefore, that seepage losses from the Indus were high during the preirrigation period. As lower Thal Doāb is relatively narrow in width, it seems equally logical to suppose that these seepage losses were not completely evaporated within the doab, and that at least some of the seepage left the doab as underflow or as discharge into the Chenāb River.

Although there is thus a certain amount of evidence in favor of the theory of outflow from Thal Doāb in the preirrigation period, the available data on quality of water give only partial support to this theory. Ground-water flow across the doab should be indicated by a zone of relatively fresh water extending across the doab, with perhaps a gradual deterioration in quality in the direction of flow. The water-quality data indicate that such a pattern could be present in certain sections of the doab. In other areas, however, highly mineralized ground water is found along the axis of the doab, with transitions to fresher water toward the rivers. This somewhat limited correlation between the water-level data and the quality-of-water data makes it impossible to arrive at a firm conclusion regarding the pattern of flow in Thal Doāb during the preirrigation period. The difficulty may arise in part from the fact that there was extensive inundation canal irrigation along the Indus before the earliest organized effort at data collection. These inundation operations must have had some effect on the water table, so that the map plate 8 does not represent strictly undisturbed natural conditions. In any event, further study and perhaps some additional data on quality of water will be needed before a final analysis of preirrigation flow in Thal Doāb is possible.

CHEMICAL QUALITY OF THE NATIVE GROUND WATER

DISTRIBUTION OF FRESH AND SALINE GROUND-WATER ZONES

The term "native ground water" is defined here as ground water that existed in the aquifer in the preirrigation period and whose quality has not been substantially altered by the admixture of seepage water from the canal systems. Although no clear dividing line can be drawn, the quality of water at depths below 100 feet is believed to represent preirrigation conditions in most places. The evaluation of the quality of the native (preirrigation) ground water is based on about 2,600 complete chemical analyses of water samples from about 800 test holes drilled from 1955 to 1962. Water samples were collected from all major water-bearing beds penetrated by the boreholes to a depth of about 450 feet, which generally was the maximum effective depth of the water-sampling device. However, a few water samples from deep observation wells, from depths as much as 1,300 feet, were obtained. The principal cations and anions (Ca, Mg, Na+K and HCO_3,SO_4,Cl) of the samples were determined in the Quality-of-Water Laboratory of WASID. Routine analysis included also the determination of pH, electrical conductivity, and total dissolved solids. The boron and nitrate content of a relatively small number of water samples was also determined in the laboratory. Inasmuch as these constituents may affect the suitability of ground water for irrigation, it may become necessary to determine the concentration of these and possibly other constituents in the future. With few exceptions, the nitrate content of about 450 water samples from test holes in Thal, Rechna, and Chaj was found to be less than 3 ppm (parts per million); commonly it ranged from a trace to 1 ppm. Boron was analysed in 179 samples from shallow and deep sources in Rechna Doāb. The boron content in these samples ranged from 0.05 to more than 3 ppm, and 128 samples had less than 1 ppm.

Many analyses from the Bahāwalpur area and Rechna, Chaj, and Thal Doābs have been published by WASID (Shamsi, 1960; Shamsi and Hamid, 1960, 1961; Gilani and Hamid, 1960). Unpublished data

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for parts of the project area in which investigations are continuing are available in the files of WASID.

Plate 9 shows the areal variation in the dissolved-mineral content of the native ground water in the Punjab. The values of total dissolved solids used in the construction of the map commonly represent the average of all samples collected from each borehole from depths between 100 and 450 feet. For the interpretation of the quality of the native ground water, data for samples from depths of less than 100 feet were ignored because of the possibility of contamination by shallow ground-water supplies, which are not native to the aquifer, but were derived from leakage from the irrigation system. At most sites there were only moderate differences in the mineral concentration of the samples collected from various depths between 100 and 450 feet below land surface. Anomalies were relatively rare and were probably often due to sampling and analytical errors which are inevitable in a sampling program of this magnitude. In some areas, however, there are significant differences in the quality of the native ground water at different depths, as discussed below.

On a regional basis, the differences in mineralization of the ground water are largely the result of the pattern of circulation that existed in the preirrigation environment (pl. 8). Under that environment, ground water moved from the rivers, and from upstream areas where precipitation was a factor of recharge, downstream into areas of progressively diminishing precipitation towards the southwestern parts of the doabs where stagnation and discharge through evaporation were the dominant factors in the regimen. With increasing distance from areas of recharge and active circulation, ground water in transient storage became progressively more mineralized.

It should be emphasized that the isogram lines shown on plate 9 depict conditions in the upper part of the reservoir only. At depth the entire area of the Punjab is generally believed to be underlain by saline ground water, and the position of the interface between fresh and saline waters, as it is found today, for the most part represents equilibrium conditions that existed before irrigation. The maximum thickness of any fresh-water zone is found nearest to the principal sources of recharge—along the river courses and in areas of relatively high precipitation. From available data it appears that the maximum thickness of fresh water in the area generally does not exceed 1,000–1,200 feet. Fresh water up to these depths was found in some observation wells and test holes along the lower courses of the Chenāb, Rāvi, and Sutlej Rivers, and also in the upper part of Chaj Doāb. However, in the upper part of Rechna Doāb, the area of maximum precipitation in the Punjab, a continuous fresh-water zone, at least 1,700 feet thick, was logged in a test hole near Gujrānwāla. It is possible that similarly extensive fresh-water zones exist also in the lands adjacent to the Indus River, where the full thickness of the aquifer has not been explored as yet.

The regional evolution of the chemical quality of the ground water involved virtually two stages. In the areas of largely active recharge and circulation, the mineral content increases gradually down the hydraulic gradient to about 2,000 ppm, chiefly as a result of solution of materials from the sediments. This trend gives way in the central and lower reaches of the doabs to a rather abrupt transition into zones of highly mineralized ground water where the mineral concentration of the ground water is enhanced by the effects of stagnation and evaporation from the water table. The concentration of dissolved solids in the native ground water increases to about 20,000 ppm in Bahāwalpur and in Chaj and Rechna Doābs and to about 10,000 ppm in Bāri and Thal Doābs.

The distribution and concentration of the highly mineralized ground water express the balance between total ground-water recharge and discharge. This balance is influenced by local variations in the factors affecting the hydrologic budget. These include not only variations in the magnitude of seepage from each of the bounding streams and in the rates of precipitation and evaporation, but also such physiographic features as direction of slope, symmetry and width of the doabs, and the relative width and position of the bar uplands and abandoned flood plains within each doab. The pattern of mineralization of the native ground water is also modified by other factors. For example, the mineral content of the ground water commonly increases in areas where the alluvium is predominantly clay. On the other hand, the residual effects of antecedent surface drainage may result in the occurrence of relatively fresh ground water in a generally saline environment. It is not possible on the basis of available data to correlate all cause and effect relationships, but the principal features of the quality of the native ground water can be related to pertinent factors in the regional hydrologic environment.

Thus, the occurrence in Rechna and Chaj Doābs of the most highly mineralized native ground water is related to the relatively contiguous and prominent development of the interfluvial bar uplands in those doabs. The saline zones in Rechna and Chaj Doābs coincide to a large degree with the boundaries of the bar uplands (pl. 2). The flood plains adjoining the bar uplands are locally low enough to be subjected to periodic inundation by flood water, some of which infiltrates to the water table. But the height of the interfluves above the reach of the most severe floods prevented direct recharge from the flood waters;

moreover, climatic factors virtually precluded recharge from precipitation. These conditions resulted in the relative stagnation of ground water under flattened hydraulic gradients beneath the bar uplands and increasing mineralization in the direction of flow.

The relatively moderate mineralization of the saline ground water in Bāri Doāb probably is related to the narrow width of the bar upland and to the more widespread distribution of recharge in the flood-plain terrane, which is the most significant physiographic feature of the doab.

The abandoned flood plains (pl. 2) are characterized by numerous flood-water channels and river courses abandoned in comparatively recent time, which provide temporary or intermittent long-term recharge to the water table. Although the position of the principal streams of the area in the past generally is a matter of conjecture, two known major shifts in the courses of the Rāvi and Beas Rivers, about 200 years ago, have significantly influenced the quality of ground water. The lower Ravi formerly occupied a more southerly channel that apparently is responsible for a relatively wide belt of water containing less than 1,000 ppm of total dissolved solids. The belt, 20–25 miles wide, extends from Mian Channu to Khānewāl and Mūltan, in lower Bāri Doāb (pl. 9). The Beas River, whose present course and juncture with the Sutlej River now lie within Indian territory, to the northeast, fomerly traversed the entire length of Bāri Doāb and joined the Chenāb River south of Shujaabad. The abandoned course of the Beas River in Bāri Doāb, shown on plate 9, is only the latest of a series which joined the Sutlej River in the central and upper parts of the doab. The river, however, must have maintained its course through lower Bāri Doāb, toward the Chenāb River, for considerable time, as evidenced by the data on the quality of water. The infiltration of river water has resulted in widespread dilution, to depths of 300–400 feet, of the saline ground-water zone in lower Bāri Doāb. Conditions are exemplified in table 2.

The coincidence of saline ground-water zones with the bar uplands also is evident in upper Bāri Doāb (pls. 2, 9). In that part of the doab, the bar upland generally is less than 15 miles wide and is bordered by steep scarps toward the Ravi in the north and toward the flood plain of the former Beas to the south. Ground water beneath the bar contains generally more than 4,000 ppm of total solids in a narrow, elongated zone extending from Rāiwind to Okāra (pl. 9), whereas fresh water occurs beneath the adjacent flood plains. The lower part of the bar upland, from Montgomery to its termination near Khānewāl, is generally less distinct and rises but slightly above the flood plains. This area is traversed by many stream channels,

TABLE 2.—*Quality of ground water in test holes 106, 107, 111, and 112, lower Bari Doāb, 1962*

Test hole [1]	Depth of sample (feet)	Total dissolved solids (parts per million)
106	108	1, 350
	240	2, 190
	328	3, 250
107	108	970
	218	1, 750
	328	3, 600
	438	8, 500
111	130	2, 240
	218	3, 270
	328	9, 100
	456	9, 110
112	108	320
	174	418
	262	3, 770
	350	3, 835
	460	7, 050

[1] Location of test holes shown on pl. 2.

possibly including a former course of the Rāvi River, which drain southward toward the flood plain of the Beas River. Owing to the breaching of the bar and local recharge through relatively permeable zones in the alluvium, the mineral content of ground water in this area is variable, but generally less than beneath the bar in upper Bāri Doāb.

The distribution and mineral concentration of the saline ground water in central and lower Thal Doāb are markedly different from conditions in the other doabs. The narrow width of lower Thal Doāb and periodic flooding of the entire area by the bordering Indus and Chenab Rivers are factors that may explain the relatively moderate mineralization of ground water in that area (pl. 9). The relatively higher elevation and greater recharge potential of the Indus River, in comparison with the Jhelum River, probably are responsible for the dominantly southeasterly direction of ground-water flow in the upper and central parts of Thal Doāb and the apparent displacement of zones of highly mineralized water to the east of the doab's axis (pl. 9). But the occurrence of ground water containing generally less than 1,000 ppm of total solids in a large area extending from northeastern Thal through the central part of the doab to the Chenab River is difficult to explain from available information. That area is characterized by deficient precipitation (fig. 2) and a prominent and extensive bar upland—a combination of factors that invariably is associated with saline ground water in other parts of the Punjab. These apparently anomalous conditions may be due to the recharging effect of a former course of the Indus River, which traversed the central part of Thal Doāb in comparatively recent time; or the conditions may be due to the generally coarse texture of the sediments. It was pointed out in the discussion of geology that the alluvium underlying Thal Doāb, compared with other parts of the Punjab, generally contains less clay, which is a major source of soluble minerals in ground water. Conditions in Thal Doāb also may be due to subtle features of, or changes in, the hydrologic environment that are unrecognized from available data. Further studies of all factors involved in the regimen will be necessary to describe adequately the occurrence and quality of ground water in Thal Doāb.

The regional pattern of mineralization of the native ground water in each doab also is influenced to a variable degree by local factors. Thus, the presence of fresh water to depths as much as 250 feet in test holes 25 and 103 (pl. 2) in a generally saline ground-water environment, to the north and west of Sargodha (Chaj), may be attributed to a former course of the Jhelum River. Evidence of fresh-water recharge from recently abandoned stream courses can also be found in western Chaj, near Sahiwal, and in Rechna Doāb near Sheikhūpura and Hafizabad (pl. 9). Undoubtedly, similar conditions prevail in other areas, but they are not revealed by existing information.

In some areas the occurrence of fresh-water zones, bounded by more mineralized water above and below, may also be attributed to the position of former stream courses. Under special conditions, many cycles of seasonal flooding, followed by long periods of evaporation may have been responsible for the infiltration of mineralized water to the water table, particularly in parts of the abandoned flood plains that are underlain by relatively impermeable material. This process would explain the "stratification" of ground water in the upper part of the aquifer, observed in several test holes in north-central Chaj and southwestern Bāri Doābs. Variations in the mineral content of ground water sampled at different depths in these areas is illustrated in table 3.

In some areas, however, the isolated occurrence of relatively fresh water also may be due to local semiconfined conditions. Thus, in northeastern Bāri Doāb, near Rāiwind and Kasur, ground water containing less than 500 ppm of total dissolved solids is found at depths of about 600 feet, whereas highly mineralized water containing as much as 9,000 ppm is found above. Although fresh water under semiconfined conditions may occur locally in other parts of the Punjab, such areas cannot be delineated by present (1962) available information.

TABLE 3.—*Variations in quality of ground water from different depths, Chaj and Bāri Doābs, 1962*

Test hole [1]	Depth of sample (feet)	Total dissolved solids (parts per million)
Chaj 57	100	840
	230	2, 210
	370	705
	460	1, 500
	648	7, 350
Bari 101	108	2, 800
	174	3, 510
	306	1, 120
	478	3, 270

[1] Location of test holes shown on pl. 2.

The distribution of fresh and saline ground-water zones is locally controlled by the presence of clay deposits within the alluvium. If these are situated in proximity to the river, they may effectively reduce recharge and restrict the circulation of fresh water. The presence of saline ground-water zones, to about 12,000 ppm of total dissolved solids, in contiguous areas of northeastern Thal and Chaj Doāb, near Kushāb and Shāhpur, appears to be due to the widespread occurrence of clays (pl. 9). The inferior quality of ground water in that area can be adequately explained by the lack of recharge from the Jhelum River and by increased mineralization of ground water in contact with clay strata. Although this area is only 20 miles from the Salt Range, the solution of halite and gypsum beds of that mountain range appears to be a minor, probably insignificant, factor contributing to the formation of these, or any other, saline ground-water zones in the area. Available information indicates that there is no general increase of ground-water salinity toward the Salt Range.

CHEMICAL COMPOSITION OF GROUND WATER

The native ground water can be grouped into at least three distinct and one transitional categories, according to the relative concentration of cations and anions in waters of different degree of mineralization.

1. Calcium magnesium bicarbonate water commonly has a total dissolved solids content of 200–500 ppm.
2. Sodium bicarbonate waters range from 300 to more than 1,000 ppm in total solids and predominate in the 500 to 1,000 ppm range.
3. With mineralization increasing to 2,000–3,000 ppm, there generally is an increase in sulfate and chloride content, with little

or no corresponding increase in bicarbonate. Any one of the anions may be dominant, but very commonly these waters are of the mixed type, in which bicarbonates, sulfates, and chlorides account for 20–40 percent each of the total anions. The sodium concentration, however, maintains its dominant position also in these waters and commonly exceeds 50 percent of the total cations present.

4. Highly mineralized ground water containing 4,000 ppm or more total dissolved solids is generally a sodium chloride water, in which the relative concentration of chloride ions commonly increases with total dissolved solids. Locally, however, some of the saline waters contain relatively high percentages of magnesium, calcium, and sulfate.

The common ranges of ionic concentrations of ground water in each of the doabs is given in table 4, and the relationship between the relative concentration of chloride and total dissolved solids is shown in figure 4.

TABLE 4.—*Common ranges of the principal cation and anion concentrations in the native ground water*

Area	Total dissolved (parts per million)	Cations (percent)			Anions (percent)		
		Calcium	Magnesium	Sodium and potassium	Carbonate and bicarbonate	Sulfate	Chloride
Thal	500	30–45	15–30	40–50	40–70	10–25	15–25
	1,000–3,000	11–20	10–25	65–85	5–20	25–50	40–70
	4,000	10–20	10–30	50–85	3–5	10–28	60–80
Chaj	500	25–40	20–45	50–75	60–70	5–15	10–20
	1,000–3,000	3–20	10–26	60–80	30–55	20–50	25–40
	4,000	5–10	10–20	70–85	6–10	5–25	75–90
Rechna	500	20–50	20–40	40–70	50–70	10–25	10–20
	1,000–3,000	4–20	6–25	60–85	20–56	25–40	20–60
	4,000	2–25	2–35	45–95	1–3	18–35	65–80
Bâri	500	16–35	15–30	45–65	50–65	25–40	6–15
	1,000–3,000	5–20	10–25	70–90	20–35	35–60	22–40
	4,000	10–25	15–25	50–80	6–10	20–40	50–75
Bahāwalpur	500	20–35	30–40	30–40	50–65	20–35	8–15
	1,000–3,000	8–20	11–25	65–80	15–30	35–65	15–40
	4,000	12–15	20–30	50–70	1–5	16–35	60–80

Variations in the composition of the native ground water are largely due to chemical changes in the course of progressive mineralization of ground water. These changes are universal under similar conditions of climate and localized recharge. They reflect the geochemical evolution of the ground water in the hydrologic environment. In areas of recharge along the rivers and in the upper reaches of the doabs where precipitation is relatively high, ground water generally contains between 200 and 500 ppm of total dissolved solids (pl. 9).

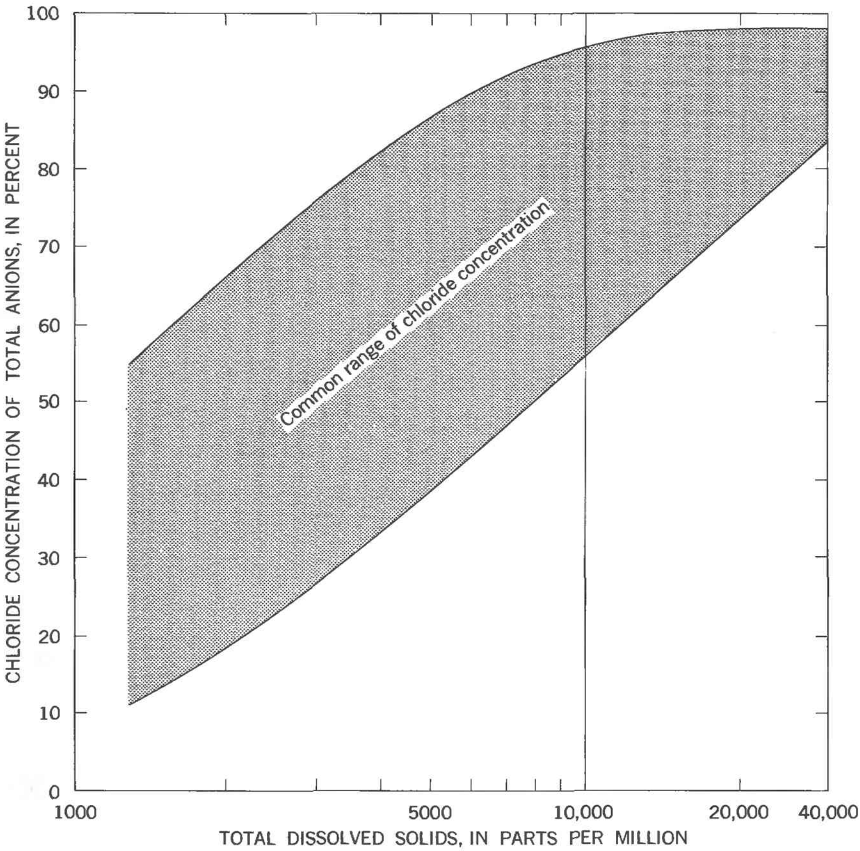

FIGURE 4—Range of chloride concentration in the native ground water.

Water from the five major rivers of the area, providing the bulk of ground-water recharge, has an average mineral content of about 150–170 ppm. River water is wholly of the calcium bicarbonate type, having relative Ca and HCO_3 concentrations in excess of 65 percent each of the total cations and anions. The infiltrating river waters, upon entering ground-water circulations, gradually, become more mineralized and may be modified to the sodium bicarbonate type within a few miles from the rivers. An increase in sodium content is also common in progressively deeper water samples. The relative increase in sodium at the expense of calcium appears to be the result of base exchange in clays of the alluvial deposits.

The moderate transition in chemical quality downgradient to a concentration of about 2,000 ppm total dissolved solids is largely the result of chemical reaction between the ground water and the sediments. The increased concentration chiefly involved the accretion of the more soluble constituents of the rocks—sodium of the cations and chloride and sulfate of the anions. Thus, ground water in the range of concentration of dissolved solids between about 500 and 2,000 ppm is commonly a sodium bicarbonate water, or it may be of the mixed type; sodium generally is the dominant cation, but the anions may be relatively evenly distributed among bicarbonate, chloride, and sulfate.

Evaporation appears to be an important factor in the more abrupt increase in mineral content above a concentration of about 2,000 ppm dissolved solids. Sodium and chloride account for much of the increase, and in the range of concentration between about 2,000 and 4,000 ppm dissolved solids, the character of the ground water evolves from a mixed type to a sodium chloride type, in which these ions comprise about 50 percent or more of their respective groups. Increasing concentration of dissolved solids above 4,000 ppm is marked by an increase in the relative concentrations of sodium and chloride, and in many of the highly mineralized waters these ions acount for 75 percent or more of their groups. The transition in the character of the highly mineralized water reflects the differential solubilities of the various ions. With increasing concentration of dissolved solids, the least soluble constituents, the alkaline earths, are precipitated as carbonates and, to a lesser extent, as sulfates. Therefore the relative concentration of these ions in ground water diminishes with increasing total mineral content. Geologic studies have shown that the precipitation of calcium carbonate, as kankar, is most common in the zones of highly mineralized ground water.

There are some slight differences in the chemical character of the ground water in different doabs. For example, the relative concentration of sulfate is characteristically high in Bāri Doāb and Bahāwalpur and low in Chaj Doāb, as compared to Rechna and Thal Doābs (table 4). These differences cannot be correlated with any obvious features, but they are probably related to the local geologic environment.

Thus, the mineralization of the ground water in the Punjab generally supports the thesis that the doabs function for the most part as discrete hydrologic units. In that connection the salient features are first, the progressive deterioration of the quality of water with distance from the rivers, and second, the differences in the composition of the ground water between the doabs. If underflow were a major factor in the water balance, it would be expressed by continuation of the highly mineralized zones beneath the river accompanied by gradual changes in the chemical character. These effects are not evident within depths of several hundred feet below land surface, and at greater depths ground-water movement probably is insignificant.

EFFECTS OF IRRIGATION ON THE GROUND WATER REGIMEN

HISTORY OF RISE OF WATER LEVELS

The natural hydrologic environment in the Punjab as described in the previous sections of this report was changed by the introduction of irrigation. The superposition of the canal system introduced additional factors of recharge which resulted in a rise of the water table in and around the irrigated areas. The introduction of irrigation in Rechna and Chaj Doābs occurred at about the same time, and the effects of irrigation on the water table followed similar paterns in these doabs.

The Lower Chenāb Canal was opened in 1892 and the Lower Jhelum Canal, in 1901. The map on plate 7 shows the position of the regional water table in 1910. By that time there had been a general rise in water level throughout the irrigated regions, ranging from less than 10 feet near the tail ends of the systems to more than 40 feet near the bifurcation points in the upper parts of the doabs. Seepage losses were greatest near the bifurcations because of the greater density of canals and the larger discharges in these areas; also, irrigation was generally more intense in the upper parts of the systems. Near the rivers there was relatively little rise in water level because the water table was already close to the surface.

A rise ranging from 10 to 20 feet also occurred upstream from the Lower Chenāb and Lower Jhelum Canals in areas that received no irrigation supplies. This rise was caused primarily by leakage from the main-line canals, which cross the doabs transversely to the direction of preirrigation ground-water movement. The areas upstream from these canals thus received ground-water inflow from all sides, and water levels rose accordingly.

The Upper Jhelum Canal was opened in 1915 and the Upper Chenab Canal, in 1912. The maps on plate 7 show the effects of these and the older canals on the water table from 1910–20. Plate 10 shows the water table in 1960. The total effect from preirrigation to 1960 is illustrated on plate 1, which shows the change in water level, and on plate 10, which shows the depth to water in 1960.

Hydrographs of observation wells depict the local history of water-table rise in different areas. In general, the hydrographs for Rechna and Chaj Doābs, where data since the advent of irrigation are available, begin with a slow rate of rise, on the order of 0.3–0.5 feet per year, and subsequently show a considerably steeper rise (figs. 5, 6). The cause of the change in slope is not fully understood; it may be due to the fact that in many areas the canal systems did not attain full capacity until they had been in operation for a number of years. The more rapid rise following the initial mild rise is characterized by a straight-line slope which is steeper in the central areas of the doabs as compared to areas near the tail ends of the system and along the rivers. Following this period of linear rise there is an interval of progressive flattening of the hydrographs, indicating an increasing evapotranspiration loss as the water table approached land surface. The depth of the water table below land surface at which this flattening begins differs from one area to another; it is commonly about 10–15 feet in the upper parts of the doab, about 20–30 feet in the central zones, and from 35–45 feet in the lower parts of the doab. Along the rivers, however, the flattening began soon after the start of irrigation, at water-table depths ranging from 15 to 22 feet below land surface. The hydrographs eventually stabilized at depths below land surface which vary from 5 to 20 feet, depending on local topographic and climatic conditions and on the proximity to the rivers.

The change in the original ground-water-flow pattern due to the superposition of the irrigation system in Rechna and Chaj Doābs is shown by the successive water-table contour maps, plates 8, 7, and 10. The ground-water trough in the center of each doab gradually dis-

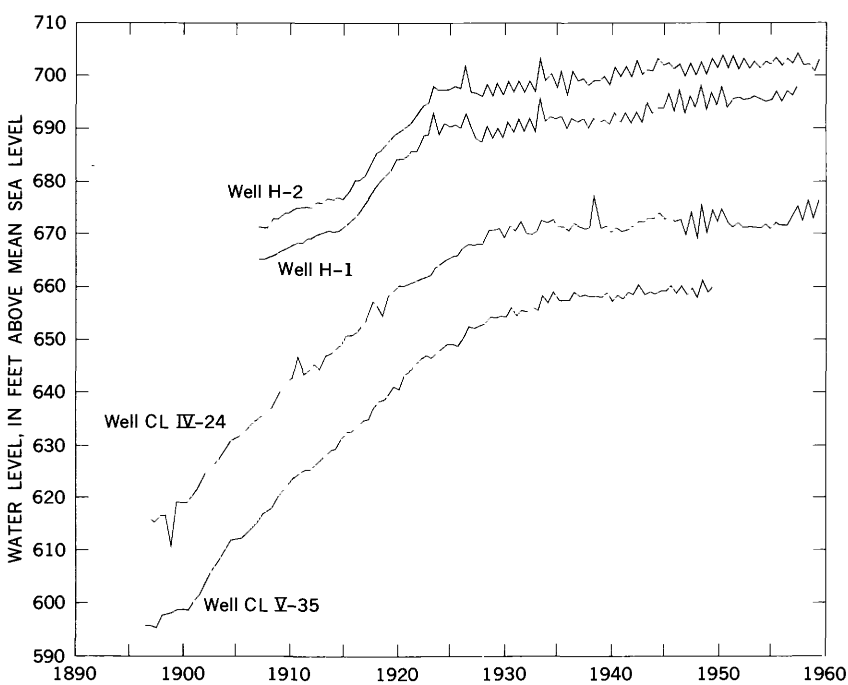

FIGURE 5.—Hydrographs for four wells in Rechna Doāb.

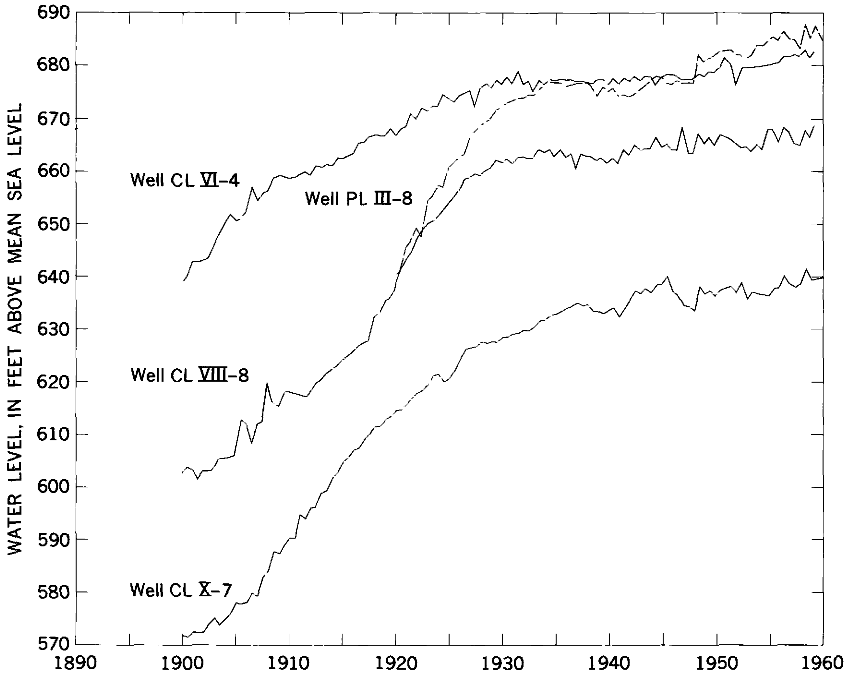

FIGURE 6.—Hydrographs for four wells in Chaj Doāb.

appeared during the course of irrigation. Four cross sections along the line *B–B′*, representing the water table in the preirrigation period and in the years 1910, 1920, and 1960, respectively, are shown in figure 7.

The final flow pattern under the irrigation regime is considerably different from that which prevailed in the preirrigation period. The pattern of flow from the rivers toward the ground-water troughs in the lower doabs, with gradually diminishing loss along the flow path due to evapotranspiration, has been superseded by a pattern of seepage from the canals, with more or less evenly distributed evapotranspiration over the area. Thus, both the discharge and the sources of seepage are now distributed more evenly over the doab than in the preirrigation period. As a result of this change in the pattern of recharge and discharge, the hydraulic gradient is now nearly uniform throughout the doab; the pronounced flattening of the gradient in the lower parts of the doabs no longer is in evidence.

The Upper Bāri Doāb Canal was opened in 1859 sometime before the earliest efforts at systematic water-level data collection. Continuous and reliable records for northern Bāri Doāb extend back to about 1890 or 1895. Thus, many of the effects of the canal system

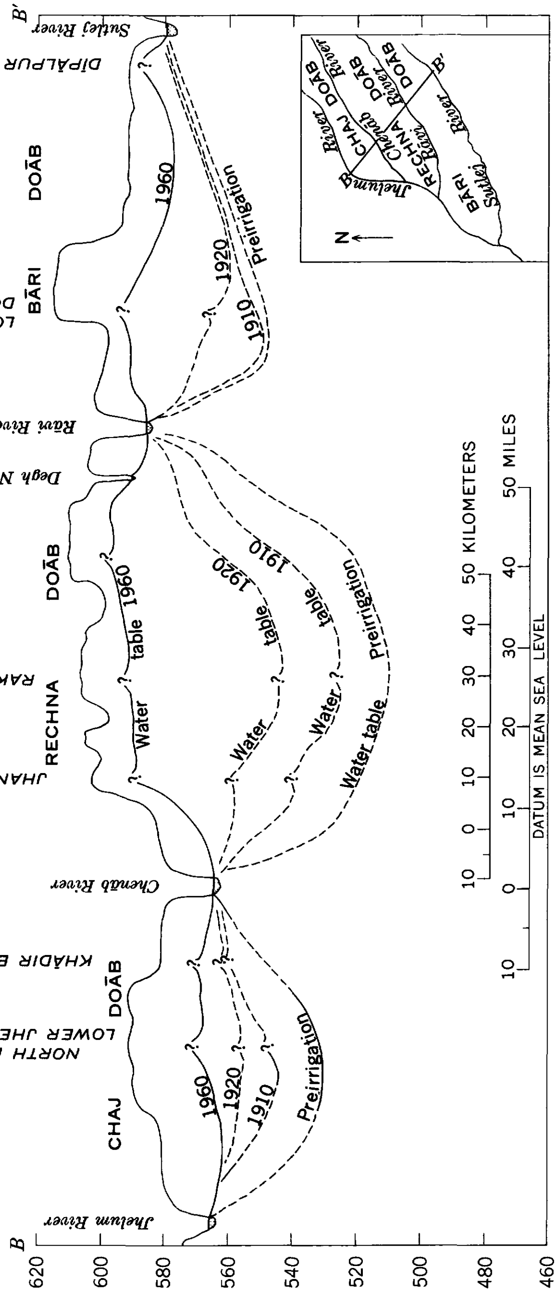

FIGURE 7.—Water-table profiles along line *B–B′*, Chaj, Rechna, and Bāri Doābs.

occurred before the period of record; however, certain observation wells which were affected relatively late in the history of the system provide a partial record of the effects. The hydrographs of two such wells, CL XXI–2 and CL XXI–5, are shown in figure 8. Both of these hydrographs exhibit a linear rise at the beginning of the record. The flattening of the hydrograph as the water table approached land surface is clearly evident on both hydrographs.

The lower Bāri Doāb Canal was opened in 1913, and continuous records of the effect of this system on water levels are available. Hydrographs of two observation wells, CL VII–4 and CL VIII–4, in the area irrigated by this system are shown in figure 8. These hydrographs differ from those in Rechna and Chaj in that the initial period of slow rise is absent. The rise begins on a linear trend and maintains the same slope until the flattening sets in as the water table approaches land surface. The behavior is observed in most of the hydrographs for Bāri Doāb; at present there is no adequate explanation for this

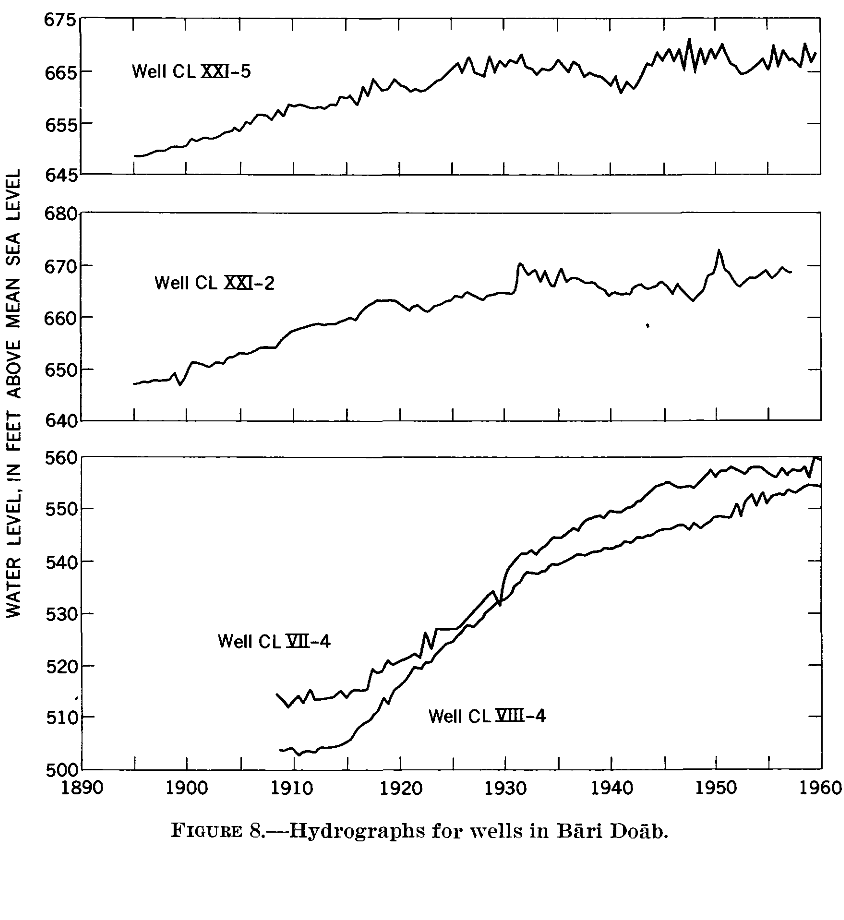

FIGURE 8.—Hydrographs for wells in Bāri Doāb.

difference between the hydrographs for Bāri and those for the other doabs.

Three major canal systems fed by the Sutlej were completed between 1926 and 1928; these were the Pakpattan, Dipalpur, and Mailsi systems. The effects of these systems are shown in the hydrographs of wells NPL XIV–29, VII–2 (Ferozepur Circle), and CL XXIII–13, respectively, in figure 9. The Sidnai system, utilizing water from the Ravi, was connected to the Sidnai Headworks in 1939, although it had functioned as an inundation system since 1885. The hydrograph of well CL VI–3 (fig. 9) illustrates the effect of this system. Some of the

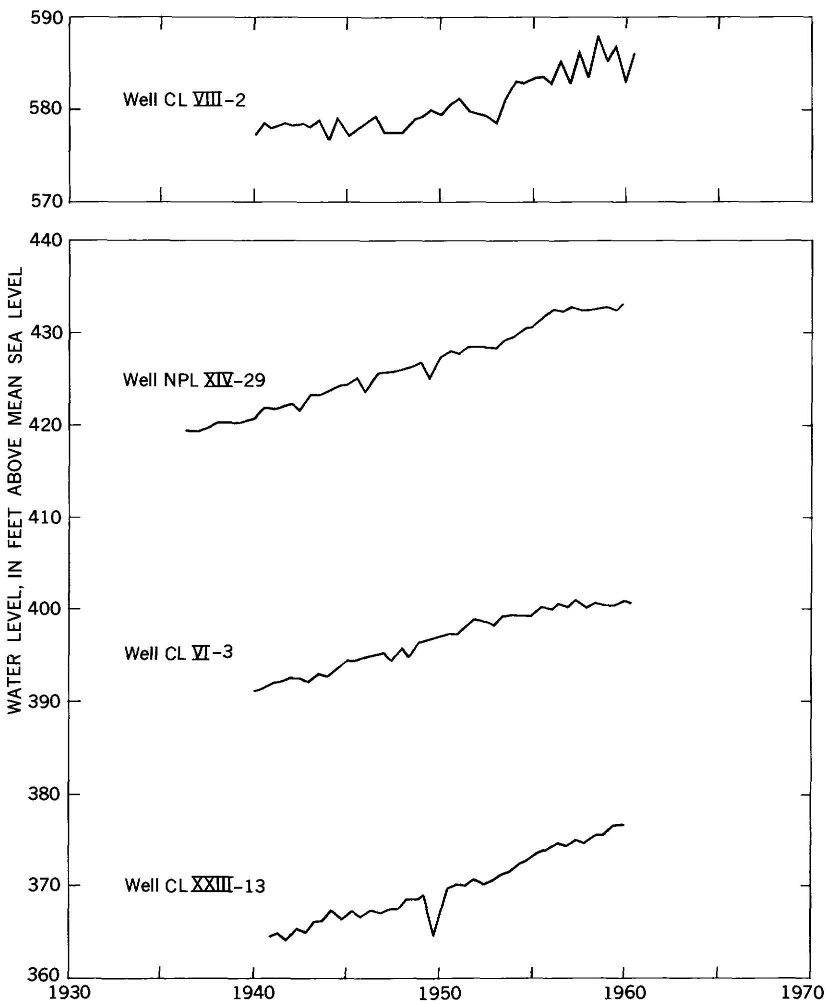

FIGURE 9.—Hydrographs for wells in Bāri Doāb.

hydrographs for the newer systems show no flattening of the gradient as yet, indicating that evapotranspiration is still considerably less than seepage in these areas.

In Bāri Doāb, as in Rechna and Chaj Doābs, the hydrographs for wells in the central part of each irrigated area are somewhat steeper than those for wells near the tail end of the system, or near the rivers. The pattern in which the flattening of the hydrographs occurs seems to be roughly similar to that in Rechna and Chaj, although it is not so clearly defined; the flattening begins at greater depths below land surface toward the tail ends of the systems than in the central parts of the irrigated areas. The trend is discernible in the areas irrigated by the Upper and Lower Bāri Doāb Canals; in the other areas the flattening has not yet set in on many of the hydrographs, and no statement can be made regarding its pattern.

The general rise of the water table in Bāri Doāb between 1900 and 1960 was somewhat less than in Rechna and Chaj Doābs. The changes in the water table shown on plate 1 indicate that the maximum rise was about 50 feet; this occurred over a relatively small area in the Lower Bāri Doāb Canal System. A rise of 40–50 feet occurred over a somewhat larger part of the area irrigated by this system. Throughout the rest of the doab the rise was less than 40 feet. This pattern of rise is not surprising. The areas commanded from the Sutlej, as well as the Sidnai Canal area, have not been subjected to irrigation for a sufficient length of time to allow the maximum rise to occur; and in the Upper Bāri Doāb Canal area, much of the change in water level must have occurred before 1890. The position of the water table in Bāri Doāb as of June 1960 is indicated on plate 10. In the northern part of the doab, in the vicinity of the Upper Bāri Doāb Canal, the water table is within 10 feet of land surface. It is within 30 feet of land surface over most of the rest of the doab, and is nowhere more than 40 feet below land surface. Maps showing the water table and depths to water for subsequent years will undoubtedly indicate a further general rise of the water table in Bāri Doāb, because hydrologic conditions in this doab have not yet reached a new equilibrium of the sort achieved in Rechna and Chaj Doābs.

The development of irrigation in Thal Doāb has lagged somewhat behind that in the other doabs. The Rangpur Canal was opened in 1939 and the Thal Canal, in 1947; the Muzaffargarh Canal was linked to the Taunsa Barrage works in 1958.

The Muzaffargarh Canal existed for sometime as an inundation system before its connection to the Taunsa Barrage Works. During the period of measurement in Thal, from 1935 until 1959, no appreciable change in water level occurred in the area irrigated by this system. It is doubtful that the system had much effect on the water table before 1935, because the canal in general parallels the Indus, irrigating an area in which the water table was undoubtedly high initially.

The Rangpur Canal similarly has had little effect upon the water table. The canal closely parallels the Chenāb River, traversing an area in which the water table was high before irrigation. Moreover, the distributary system is limited, and the irrigated area consists largely of a narrow belt in the vicinity of the canal itself. Thus, throughout the irrigated area, a rise of less than 10 feet was sufficient to bring the water table to a depth at which evapotranspiration and seepage were in balance. This is illustrated in the hydrographs of wells XVII–1–R and XXXIII–5 (fig. 10), which show a total rise of less than 10 feet before the graph becomes flat.

The maximum effect of irrigation on the water table in Thal Doāb has occurred in the area of the Thal Canal. The region supplied by this system is much more extensive than those supplied by the Rangpur or Muzaffargarh systems and includes areas in which the water table was fairly deep before irrigation. The changes in water level that occurred between the opening of the system and 1959 are indicated on plate 1. The maximum rise occurred in two small areas along the Muhajir Branch and amounted to slightly more than 30 feet. In general however, the areas supplied by the northern branches showed a rise of 20–30 feet, whereas the downstream areas showed increases of less than 20 feet.

Two hydrographs from the Thal Canal area, wells V–4 and VII–3, are shown in figure 10. The three divisions noted on the hydrographs of wells in Rechna and Chaj Doābs—the initial mild rise, the linear trend, and the flattening—also are evident in the hydrographs for Thal Doāb. The hydrograph of well VII–3 has not reached equilibrium; this is typical of the hydrographs for the Thal Canal area, because the water table throughout much of the area still is rising.

CAUSE OF RISING GROUND-WATER LEVELS

As it became evident that the rising water table and the consequent threats of waterlogging and salinity jeopardized the future of the irrigation economy, various investigations were made into the causes of the problem. It was recognized, of course, that irrigation activities were the root of the matter; the purpose of the investigations was to determine which specific factor was chiefly responsible, so that remedial measures would be effective.

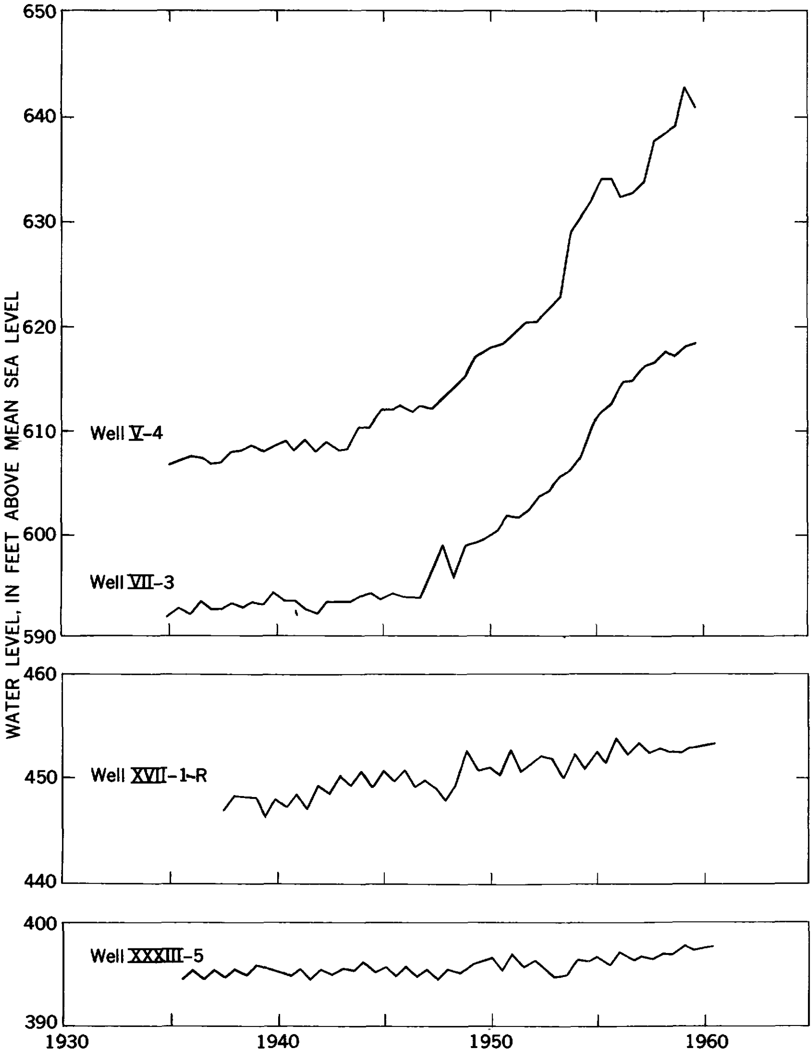

FIGURE 10.—Hydrographs for wells in Thal Doāb.

Carlston (1953) summarized the history and results of the various studies that had been made in the Punjab. According to Carlston, most attention had been focused on relating three factors to the rise in water levels. These factors were (1) increased recharge from precipitation owing to obstruction of natural drainage courses or to an increase in the annual precipitation, (2) infiltration of applied irrigation waters, and (3) leakage from the irrigation-distribution system. A fourth factor, the suballuvial ridge, had been cited by some investigators as the cause of the differential rise in the water table between the northern and southern parts of the doabs, evidently on the basis that it formed a barrier to subsurface drainage.

Carlston concluded from his examination of data for Rechna Doāb that the rise in the ground-water level was due primarily to seepage from canals and, to a lesser degree, to field seepage of surplus irrigation water; he further concluded that neither increased precipitation, nor disruption of surface drainage by the construction of canals and ancillary works, has contributed to the rise in the water table.

Carlston also examined the hydrologic influence of the suballuvial ridge and concluded that it had no significant regional effect on ground-water levels.

Subsequently, Karpov and Nebolsine[2] again raised the question of the influence of the suballuvial ridge on ground-water levels. According to their study of data for Rechna Doāb, the ridge acts as a barrier to ground-water drainage and was chiefly responsible for the more rapid rise in ground-water levels that has occurred upstream from the ridge.

The results of the current investigation in effect confirm Carlston's findings. Seepage studies in Rechna and Chaj Doābs (Patten and others, 1963) show that losses from the distribution system range from less than 1 cfs per mile for the small distributaries to more than 20 cfs per mile for the main-line canals. Furthermore, it is evident from the pattern of water-level change that leakage from the irrigation system was the major cause of the rise of the water table. The ground-water levels rose more rapidly near the main-line canals, and the maximum rate of rise occurred in the areas where the canal discharge was greatest. Thus, there is an obvious cause-and-effect relationship between seepage losses from the distribution system and the rise in ground-water levels.

Infiltration of applied irrigation water probably is a minor source of recharge, because the normal depth of application for most crops is insufficient even to satisfy the requirements of consumptive use, as reported by H. F. Blaney and W. D. Criddle.[3] This also is supported by the lysimeter studies of Asghar (1961), which show that among the irrigated crops sown in the Punjab, only rice causes accretion to the water table. Furthermore, the wide distribution of soil salinity is evidence that there is negligible infiltration of irrigation waters in those areas affected. Irrigation water used in the Punjab is generally of excellent quality and any considerable infiltration of the applied water would be sufficient to wash the salts out of the soil zone. Thus,

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[2] Hydrotechnic Corp., 1958, unpublished Engineering Report: New York.
[3] Report on irrigation water requirements for West Pakistan to the Pakistan Water Delegation, Washington, April 1957.

percolation from irrigated plots could not have exceeded, on the average, 1 or 2 inches per year.

The effects of precipitation also can be dismissed on logical grounds. There is no evidence of a long-term trend of increased annual precipitation, without which precipitation data cannot be correlated with the rise in ground-water levels. An examination of the hydrographs, moreover, indicates that, although precipitation may have caused a slight annual cycle in the water table, it had relatively little effect on the longer term trend during the period of rise.

Increased infiltration of precipitation due to blocking of natural drainage courses by canals, highways, and other structures also is a doubtful factor in the rise of the water table. In fact, it is very possible that the net effect of human activities has enhanced the surface drainage from the doabs rather than impeded it. It is probable that effects of blocking are, at the most, of minor importance.

The weight of available evidence indicates that the buried ridge has not been a major factor in the rise of the water table beneath Rechna and Chaj Doābs. Geologic evidence shows that the ridge is not a consistent barrier. As shown on plate 7, there are only four relatively small and widely separated areas in which the depth to bedrock is less than 400 feet. Even within these areas the depth to bedrock varies widely, so that there are many alluvium filled channels and depressions in the bedrock surface. The buried ridge has apparently been implicated in the waterlogging problem because waterlogging occurred earlier and is more severe in areas upstream from the ridge than in areas downstream. However, most of the irrigation works in both Rechna and Chaj Doābs are concentrated upgradient from the ridge, so that one could expect waterlogging to occur first in these upstream areas. In addition, the water table was initially deepest downstream from the ridge, and had further to rise before waterlogging could occur. Finally, the pattern of water-level rise in Bāri Doāb, where there is no possibility of implicating the ridge, is similar to that in Rechna and Chaj Doābs. Waterlogging is at present confined largely to certain areas in the upper half of Bāri Doāb. In the lower part of the doab, where the density of irrigation works is not so great, and where the water table was initially deepest, the depth to water is still relatively great. The only conclusion that can be drawn from these arguments is that the ridge has not been a significant factor in the waterlogging pattern, and that nearly the same pattern would have been observed if the ridge had not been present.

In summary, leakage from the irrigation-distribution system was the major cause of the rise in ground-water levels in the Punjab. If there had been no leakage, it is doubtful that the compound effects of all other factors would have caused a significant rise in water levels.

GROUND-WATER RECHARGE DURING THE EARLY PERIODS OF IRRIGATION

A rough estimate for the net ground-water recharge—that is, the rate at which ground water accumulated in storage—during the early periods of irrigation has been obtained from the records of observation wells measured during this period. Hydrographs of wells throughout Rechna Doāb were selected, and the slope of the linear portion of each hydrograph was measured. The later portions of the hydrographs, which show a reduced rate of rise due to increased evapotranspiration from the water table, were excluded from the analysis. The recharge figure obtained in the analysis therefore applies to the early period of irrigation, before excessive evapotranspiration from the water table had set in. In later periods the total seepage from the irrigation system was undoubtedly less, as the gradients around the canals were reduced; and the fraction of the seepage retained as net recharge was also less, owing to the increased evapotranspiration losses.

The hydrograph slopes were averaged, first for the doab as a whole and then for the upper, middle, and lower reaches of the doab. The average rate of rise for the doab as a whole was found to be 2.1 feet of ground water per year, which corresponds to a recharge of 0.5 foot of water per year, assuming a porosity of 25 percent. This choice of porosity figure is of course somewhat arbitrary and subject to doubt. The figure actually required is the average porosity of the sediments minus the water content per unit volume of sediment above the water table, during the period of record. The figure of 25 percent was chosen because it represented an approximate mean between porosity, as determined in the laboratory, and specific yield, as determined by gravity drainage in the field during pumping tests. These two figures would of course represent upper and lower limits, respectively, for the figure actually required in the calculation.

The average rates of water table rise computed separately for the upper, middle, and lower reaches of the doab amount to 2.86, 1.87, and 1.42 feet of ground water per year, respectively. At least three factors contribute to these differences in the rate of recharge. The climate becomes progressively more arid toward the southwest, and evapotranspiration losses from the water table therefore probably increase in this direction. In addition, the irrigation network is more heavily concentrated in the upper part of the doab. The Lower Chenāb Canal lies entirely in the upper half of the doab, as do several of its branches; the Upper Chenāb system is of course entirely confined to the upper half of the doab. Before the construction of the Haveli Canal in 1939, both the density of major channels and the total supply carried in the irrigation system decreased progressively through the lower half of the doab. Thus, it is probable that seepage losses also decreased progressively in a downgradient direction. A third factor which may have contributed to the variation in recharge was the fact that the Lower Chenāb system was put into operation some years before the Upper Chenāb system. The period of linear rise on the hydrographs of lower Rechna Doāb generally corresponds to the time in which the Lower Chenāb system was operating alone. Thus, the recharge estimate for lower Rechna reflects the effect of the Lower Chenāb system alone, whereas that for upper Rechna shows the effects of both Upper and Lower Chenāb systems. This factor is believed to be of minor significance, however, owing to the distances involved.

The same method of estimating recharge was used in Chaj Doāb. Hydrographs of wells in the areas served by both the Upper and Lower Jhelum Canal systems were used. The average rate of rise for the doab as a whole was found to be 2.07 feet of ground water per year, or again about 0.5 foot of water per year, assuming a porosity of 25 percent. As in Rechna Doāb, the averages calculated separately for the upper, middle, and lower reaches indicate that the distribution of recharge was not uniform. The averages are 2.7, 2.3, and 1.2 feet of ground water per year, for the upper, middle, and lower reaches, respectively.

In applying the analysis to Thal Doāb, only hydrographs of observation wells located within the various irrigated areas were utilized. Because the hydrographs were taken only from irrigated areas, the recharge estimate actually applies only to those areas. The average rate of rise indicated by the linear portions of these hydrographs was 2.0 feet per year, or again about 0.5 foot of water per year, assuming a porosity of 25 percent. The average annual diversions to Thal Doāb have been considerably lower than those to Rechna or Chaj Doābs, but the diversions per unit irrigated area have been of the same order of magnitude. The agreement between the recharge figure obtained for the irrigated areas of Thal Doāb and those obtained for Rechna and Chaj Doābs is therefore not surprising.

No meaningful evaluation of the average recharge for upper Bāri Doāb or for Bāri Doāb as a whole is possible, for the interval of linear rise in upper Bāri Doāb was largely over by the time systematic data collection was initiated. The average rate of rise in central Bāri Doāb was found to be 1.1 feet of ground water per year, which is roughly comparable to that in lower Rechna and lower Chaj. The area taken as central Bāri Doāb in the calculations lies at roughly the same latitude as lower Rechna and lower Chaj, and has similar conditions of climate and precipitation. Thus, the fraction of the diversions consumed in evapotranspiration in central Bāri should be roughly comparable to that in lower Rechna or lower Chaj; the fraction taken in as recharge should therefore also be comparable. In lower Bāri Doāb, where the climate is somewhat more arid and the total capacity of the irrigation network is relatively small, the rate of rise was only 0.7 foot of ground water per year.

The recharge estimate presented here may prove useful in connection with the planning of reclamation projects, but care should be taken not to overextend its application. In terms of future development it can be postulated that, when the water table is lowered approximately to its preirrigation position, the average recharge from the canal irrigation system should be roughly 0.5 foot of water per year, assuming that the intensity of canal irrigation is approximately equal to that used in the early periods of irrigation. If the intensity of irrigation is greater, there is little doubt that the recharge will be greater; in any case, the figure constitutes no more than crude approximation, inasmuch as hydrologic conditions during future reclamation work are bound to differ in many respects from those which prevailed during the early periods of irrigation. Whatever the magnitude of the recharge, however, the studies outlined in this section indicate that it will probably be unevenly distributed—the recharge in the northeastern part of the Punjab may be as much as two or three times that in the southwestern extremity.

CHANGES IN THE QUALITY OF GROUND WATER

The quality of the shallow ground water—that is, the water derived principally from leakage from the irrigation system—in Rechna and Chaj Doābs has been described, respectively, by Shamsi and Hamid (1960) and Gilani and Hamid (1960). Data on the quality of water from shallow sources in other parts of the Punjab are available in the files of WASID. In the course of the investigation, about 120,000 shallow dug or driven wells were inventoried, and the conductivity and pH of water samples were determined. In addition, complete chemical analyses of a large number of samples were made in the Quality-of-Water Laboratory of WASID. The following summary is based largely on these data.

The shallow ground water occupies the interval between the native preirrigation water table and the existing water table. In this zone, canal leakage has resulted in two related major changes: the saturation of formerly dry sediments with water of generally good quality and the dilution of the native ground water adjacent to the canals. The thickness of the shallow-water zone commonly ranges from less than 20 feet along the margins of the doabs to 100 feet or more in the lower and central parts of the doabs. Locally, however, seepage from the major canals has improved the quality of the native ground water to depths of 400–500 feet.

Plate 7, based on data compiled by Shamsi and Hamid (1960) and Gilani and Hamid (1960), shows the location of shallow-water sampling sites in Rechna and Chaj Doābs. The quality of ground water at shallow depths, in three ranges of mineral concentration, is indicated by different symbols in this illustration, which also is representative of conditions in other parts of the Punjab. The general pattern formed by the data approximately resembles the regional pattern of the underlying native water (pl. 9). Thus, in areas of predominantly saline native ground water, supplies from shallow sources generally are also saline, but mineral concentrations in the shallow water are less because of dilution by canal seepage. Water from shallow irrigation or domestic-supply wells in these areas contains generally less than 5,000 ppm; the common range of concentration is from 2,000 to 4,000 ppm. However, water having a similar degree of mineralization also may occur locally in the upper parts of the doabs. In general, water from shallow wells located near sources of recharge is of good quality. Along the rivers and in the upper reachers of the doabs where precipitation is a factor of recharge and maximum canal supplies are available, ground water contains commonly less than 1,000 ppm of total dissolved solids.

As suggested by plate 7, the quality of individual supplies is determined largely by the local environment, although the average conditions in the area are dominated by the effects of climate and the availability of recharge from the irrigation system. Shallow ground water, derived from canal leakage, is of acceptable quality in most of the area.

EFFECTS OF IRRIGATION ON RIVERFLOW

The irrigation activities in the Punjab have caused extensive modifications in the flow regimens of the rivers crossing the area. Before irrigation the discharge of each of the rivers fluctuated greatly during the year. During the summer months the discharges were high, owing to the high rate of snow melting and the heavy monsoon precipitation; during the winter months, when both melting and precipitation were low, the river discharges were correspondingly low. All the rivers were "losing" streams throughout most of their length and throughout most of the year—that is, their discharges gradually decreased in the downstream direction because of seepage losses to the groundwater system.

The initial effect of each irrigation diversion was simply to decrease the discharge at all points downstream from the diversion. The diverted water was either consumed in evapotranspiration or went into storage in the ground-water reservoir. At any station downstream from a diversion, both the total annual discharge and the discharge at any given time were less than before the construction of the diversion.

The initial effects of irrigation were followed by a long period of changing flow regimen in the rivers. As seepage from the irrigation systems caused the water table to rise, the hydraulic gradients in the vicinity of the rivers gradually lessened and the seepage losses from the rivers decreased. In many areas the water table in the central parts of the doab ultimately stabilized above the flood plain of the bounding rivers, so that ground-water flow was established from the axis of the doab to the flood plains. Although some of the ground-water flow is consumed by evapotranspiration in the flood plain, some river reaches have undoubtedly become consistently "gaining" while others have become alternately "gaining" and "losing," depending upon river stage. Thus, if the effects of a single diversion could be isolated, one would find that the discharge downstream from the head-works decreased abruptly immediately after construction, and that discharge gradually increased again as irrigation continued.

In addition to the changes in the magnitude of river discharge, significant changes in its annual distribution have occurred during irrigation. As the rivers became "gaining" or alternately "gaining" and "losing" streams along certain reaches, the seasonal fluctuations in riverflow that occurred before irrigation were reduced. A decrease in the midsummer flow occurred, for a large fraction of the peak flow now was diverted into the irrigation system and either consumed in irrigation or lost as seepage. Where the water table had reached approximate equilibrium, seepage into the aquifer from the irrigation network was either lost by evapotranspiration or was taken into storage and released gradually to the rivers. In at least some reaches, water taken into the aquifer during summer peak flow was released to the river during the winter. The winter base flow, therefore, generally became higher than in the preirrigation period. This change is illustrated by the base-flow recession curves (Qureshi, 1960) shown in figures 11 and 12. The upper curve in figure 11 represents the winter base-flow recession characteristics at Chela on the Jhelum River for the years 1947–55; the lower curve represents the winter base-flow recession at the same station for the years 1923–37. No headworks were constructed upstream from Chela between 1923 and 1955; differences between the two curves, therefore, are due entirely to changes in the relation between the ground-water system and the stream. The curves indicate that the minimum winter flow increased by about 20 percent between the two periods. A similar result is indicated in

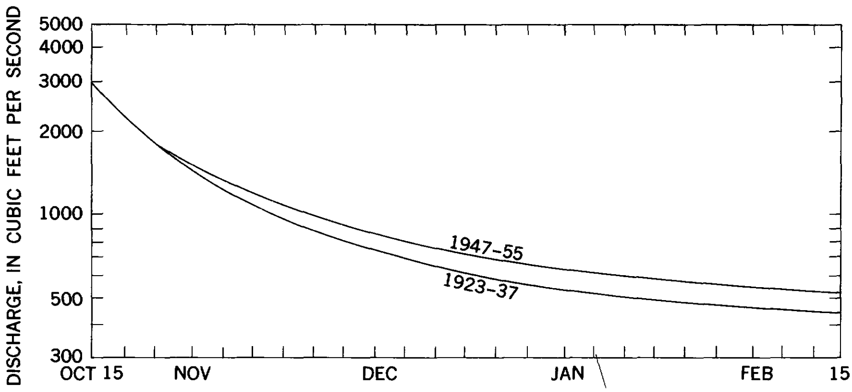

FIGURE 11.—Base-flow recession curves for Jhelum River at Chela. Adapted from Qureshi (1960).

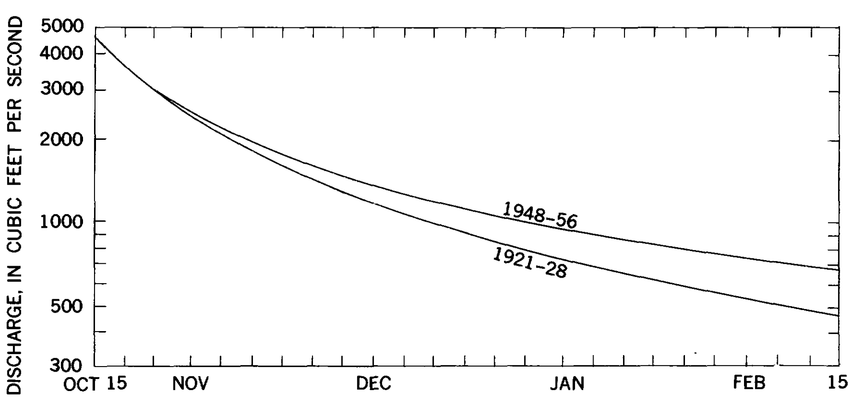

FIGURE 12.—Base-flow recession curves for Chenāb River at Rivaz Bridge. Adapted from Qureshi (1960).

figure 12 which shows two winter base-flow recession curves for the Chenāb River at Rivaz Bridge; the upper curve applies to the period 1948–56 and the lower curve, to the period 1921–28. Here again, no headworks were constructed upstream from Rivaz Bridge between these periods. An increase of about 50 percent in minimum winter flow occurred between the two periods.

Thus, it is apparent that a new equilibrium has been achieved between the ground-water system and the rivers in some parts of the Punjab. This new equilibrium is different in many respects from the one that existed before irrigation; the total annual discharge of the rivers generally is smaller than it was before irrigation, but the winter base flow has increased. In some areas the new equilibrium has not yet been achieved; the water table still is rising, and the river discharges are still adjusting to the changing ground-water regime. Even in those areas in which equilibrium has been achieved, however, further changes in riverflow are certain to arise as large-scale pumpage of ground water is undertaken. These changes are difficult to predict quantitatively, but it is certain that the rivers ultimately will become "losing" streams again, and that both the total annual discharge and the winter base flow will be reduced from their present values. A final equilibrium of river discharge will not be achieved unless the water table eventually comes to a new equilibrium under pumping conditions.

IMPLICATIONS OF THIS INVESTIGATION

For the planning of water-resources development in the Punjab, the significant findings of this investigation are as follows:

1. Geologic studies show that virtually the entire Punjab is underlain to depths of 1,000 feet or more by unconsolidated alluvium which is saturated to within a few feet of land surface. The alluvium varies in texture from medium sand to silty clay, but the sandy sediments predominate. According to WASID's experience, large capacity wells yielding 4 cfs or more can be developed at virtually any site.
2. Quality-of-water studies show that the alluvium beneath about two-thirds of the Punjab is saturated to an average depth of 500 feet or more, with water of acceptable quality for irrigation supply. The average concentration of dissolved solids in these supplies is less than 1,000 ppm; the upper limit of concentration of acceptable supplies is placed in the range of 1,800 to 2,000 ppm on the assumption that it is feasible to blend ground water with canal water at a ratio of 1:2. That limit probably is conservative. Reclamation planners now are thinking in terms of using more highly mineralized water under certain conditions. In any event, assuming an effective porosity of 20 percent for the saturated sediments, the volume of usable ground water in storage is on the order of 2 billion acre-feet.
3. Water-level studies indicate that leakage from the existing canal-distribution system is the principal cause of subsurface-drainage problems in the Punjab, and it also is the major component of ground-water recharge.

In view of the above findings, it is evident that the alluvial aquifer underlying the Punjab is a largely unexploited resource of enormous economic value—the more so, because it is highly susceptible to flexible operation and scientific management. It is recognized by reclamation officials in both Pakistan and international aid agencies abroad that scientific development and management of the ground-water resources is the key to permanent irrigated agriculture in the Punjab. From the results of the ground-water studies, the West Pakistan Water and Power Development Authority has prepared a long-range program for reclaiming the irrigated lands of the Punjab (WAPDA, 1961) that now is in progress. 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 wells discharge into the canal system, and the pumping rate of each well is determined by the supplemental irrigation requirements of the surrounding land. Thus, the ground-water withdrawals serve the dual purposes of satisfying irrigation requirements and providing subsurface drainage. The system offers a permanent solution to the problem of the leaking canal, because it both controls the effects of leakage and salvages the losses from the canals. Under this kind of operation, canal leakage may be an asset to the system rather than a liability, because it constitutes the major component of recharge to the ground-water reservoir.

In areas where the quality of ground water is unsatisfactory, the wells discharge into drainage ditches, and the pumping rate of each well is 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 the effects of leakage but do not salvage the losses; hence, canal leakage remains a liability and operates only to put an extra burden on the well-drainage system.

The first tubewell project under this program went into operation in 1961. It comprises nearly 2,000 wells which serve an area of about 1.2 million acres in Rechna Doāb (pl. 2). During 1962, construction was scheduled to begin on several other projects in Chaj Doāb. Future development is planned at the rate of about 1,500 wells per year until the system is extended to all the irrigated areas of the Punjab.

Tubewell reclamation methods are hydrologically feasible in the Punjab. That is, with respect to drainage, the position of the water table can be controlled by pumping; with respect to supplemental irrigation supplies, there is sufficient ground water in storage and adequate recharge to sustain large-scale withdrawals for an indefinite period. Furthermore, ground-water supplies offer some unique advantages to the irrigation system. Unlike canal supplies they are not subject to seasonal variations, and they can be developed to serve virtually any topographic situation. Thus, ground water can be used to meet seasonal deficiencies in canal supplies and to extend irrigation to areas that cannot be reached by canals.

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 that will require new solutions. Considered hydrologically, there are two distinct, but related, potential hazards which must be considered in the design and management of the tubewell projects.

Distribution of withdrawals is an obvious question of immediate concern which should be resolved before the tubewell reclamation program is far advanced. According to current estimates the ground-water resources of the Punjab appear to be adequate to meet the regional requirements for supplemental irrigation supplies. But there is not a favorable relationship throughout the Punjab between the availability of ground water and the need for supplemental supplies. The ground-water potential for irrigation use diminishes from northeast to southwest, or in a downgradient direction, and is negligible in the southwestern parts of the doabs where the ground water is too highly mineralized for use. On the other hand, the demand for supplemental irrigation supplies is in general uniform, but it tends to increase toward the more arid southwestern areas. Under these conditions it is evident that the design criteria for a program of maximum exploitation of the ground-water resources must be based on regional hydrologic factors rather than on local demand factors. In short, ground-water supplies must be developed where they are available and conveyed to points of use. Such a program will involve the transfer of water into the southern parts of Rechni, Chaj, and Bāri Doābs, which probably will require remodeling of the existing canal system, or construction of new canals. This, in turn, will amplify the problems of canal leakage and subsurface drainage in the areas where the quality of ground water is unfit for use and where the leakage cannot be salvaged by tubewells. In these areas, in the interest of conservation of water and economical drainage operations, it may be feasible to inhibit canal leakage by using the emulsion-type sealants that can be applied while the canals are in service. There are alternative methods of conserving water in the areas of deficient supply, such as reducing the intensity of cultivation or modifying the cropping pattern. Regardless of the details of the regional program, it is essential that individual tubewell projects be designed to accommodate the requirements of regional development. Otherwise, ground-water development will be unbalanced, and in some areas more serious problems may be created by overdevelopment of the aquifer than will be solved by the reclamation activities.

Maintenance of a favorable salt balance in the ground-water supply is a related problem—related in the sense that pumpage will trigger changes in the hydrologic environment, that, in turn, will influence the relationships of the quality of water in the aquifer. Several inherent factors in the tubewell systems may tend to depreciate the quality of ground water with time. First, the leaching of the soil profile, which will occur when full irrigation supplies are available, 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 residual of salts that have accumulated during the past years of irrigation are leached from the soil. Second, the reduction in volume of the ground water in storage, that will occur in response to pumping, will cause a proportional increase in the mineral concentration of the ground water. In the cycle of recirculation of water from the aquifer to the 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. Third, there will be an annual increment of salts derived from canal irrigation supplies, which also will be transported down to the water table. Finally, chemical reaction between the percolating recharge water and the unwatered sediments will bring more salts into solution. In addition to the above factors, which for the most part involve mobilization of salts, there are the added hazards of lateral and upward migration of saline water into fresh-water zones in response to pumping.

The effects of these factors will be mitigated somewhat by dilution with other components of recharge, such as seepage from canals and rivers and infiltration of precipitation, and by blending with ground water in storage in the aquifer. It is difficult to estimate the changes that may occur in the quality of ground water, because so many unknown variables are involved. But considering the enormous quantity of ground water in storage in relation to the annual rate of recharge under the reclamation program, it is reasonably certain that the rate of change in quality will be slow and that it will not present serious problems in the near future—probably not within the 40- to 50-year economic lifetime of the present group of projects. If the tubewell reclamation operations are continued indefinitely, it may ultimately be necessary to provide for the removal of salts from the area of development, unless technologic advances in the meantime offer a better alternative. It may also be feasible to enhance the quality of the ground water by promoting artificial recharge through canals and other structures that are designed to leak.

It may be premature to speculate on possible remedies for this problem. But it is essential to continue a program of hydrologic studies to monitor the effects of reclamation activities on the quality of the ground water. If that is done, there is little doubt that appropriate measures can be adopted to protect the salt-balance of the irrigation supplies long before serious problems develop.

The implications of the tubewell program go beyond the immediate irrigation problems of the Punjab. If the program is successful, it may point the way to a final solution for the most vexing problem of water management in West Pakistan—that of storage. The potential for on-channel storage in West Pakistan is inadequate to provide full control of riverflow, and even the most favorable reservoir sites have serious shortcomings. For example, the two major dams included in the current development program, Mangla on the Jhelum River and Tarbela on the Indus River, each have a reservoir capacity of only about 5 million acre-feet. That amount is less than 10 percent of the discharge of the Indus Basin, and the storage capacity can only be utilized once a year, owing to the characteristics of the river flows. The reservoirs are remote from areas of water use, and they are relatively short lived because of the high sediment load of the rivers. There are few other feasible reservoir sites in West Pakistan, and they are similarly handicapped. For long-term developments it probably will be necessary to develop other storage facilities for surface runoff.

Diversion of surplus surface-water to ground-water storage appears to offer the most favorable prospects for control of the runoff in the Indus Basin. The alluvial aquifer that underlies the Punjab is ideal for the purpose in nearly all respects. It is favorably situated with respect both to 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 equal to many times the annual flow of the Indus River system, 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.

The major problem involved in the management of the aquifer as a reservoir is that of promoting artificial recharge at a sufficient rate to accommodate surplus surface supplies during the periods of high runoff. Although the problem is formidable, a solution probably will be found as a normal consequence of operations under the tubewell reclamation program. If the history of other areas is repeated in the Punjab, demand for ground-water supplies will increase through the years, and the threat of overdevelopment will stimulate research on methods of conserving water and inducing recharge. In that manner, the tubewell reclamation program ultimately may evolve into a broader water-management operation simply by the process of diverting more and more of the surface runoff to ground-water storage until the entire supply is allocated.

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INDEX

[Italic page numbers indicate major references]

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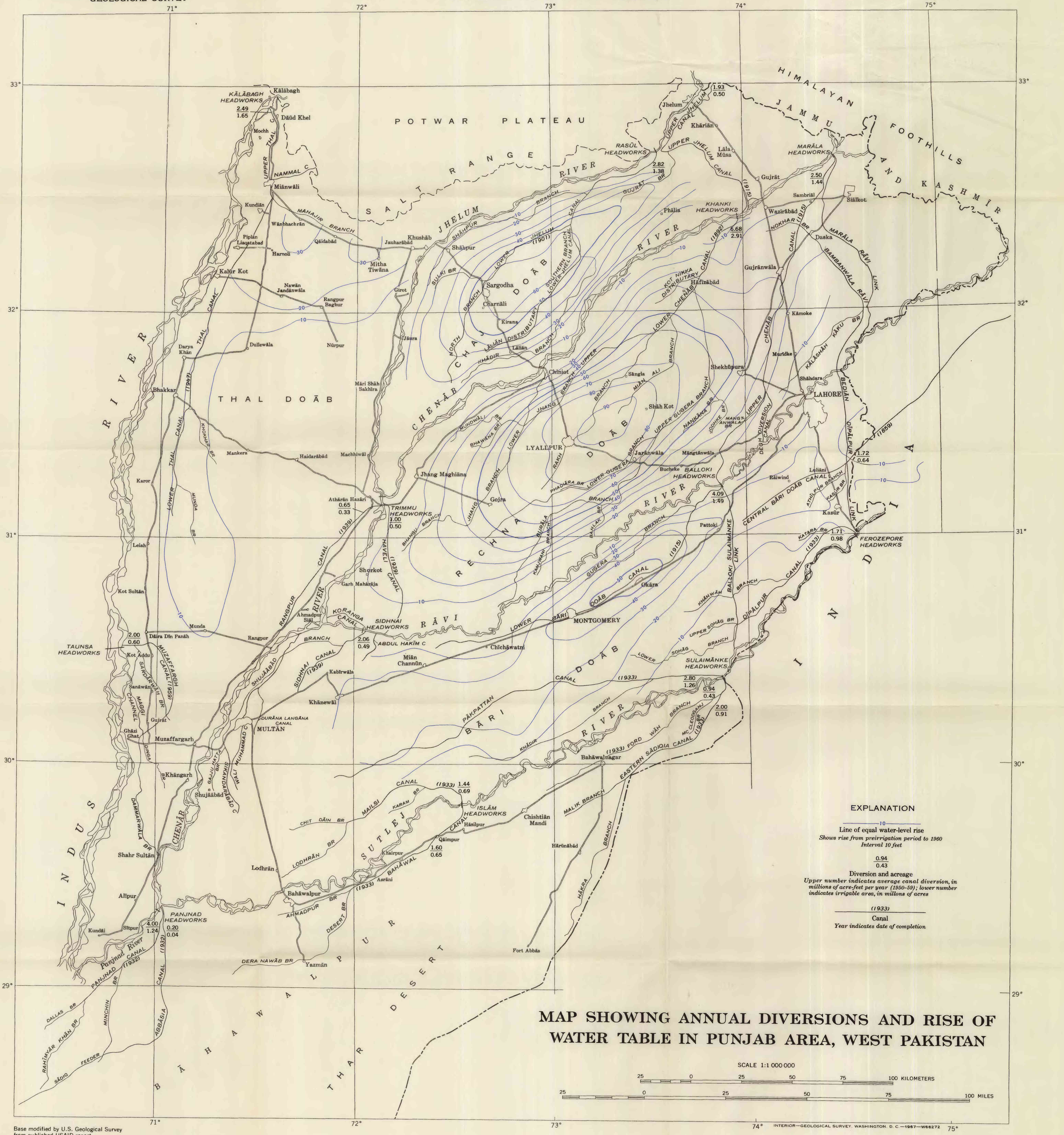

MAP SHOWING ANNUAL DIVERSIONS AND RISE OF WATER TABLE IN PUNJAB AREA, WEST PAKISTAN

Base modified by U.S. Geological Survey
from published USAID report

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.—1967—W66272

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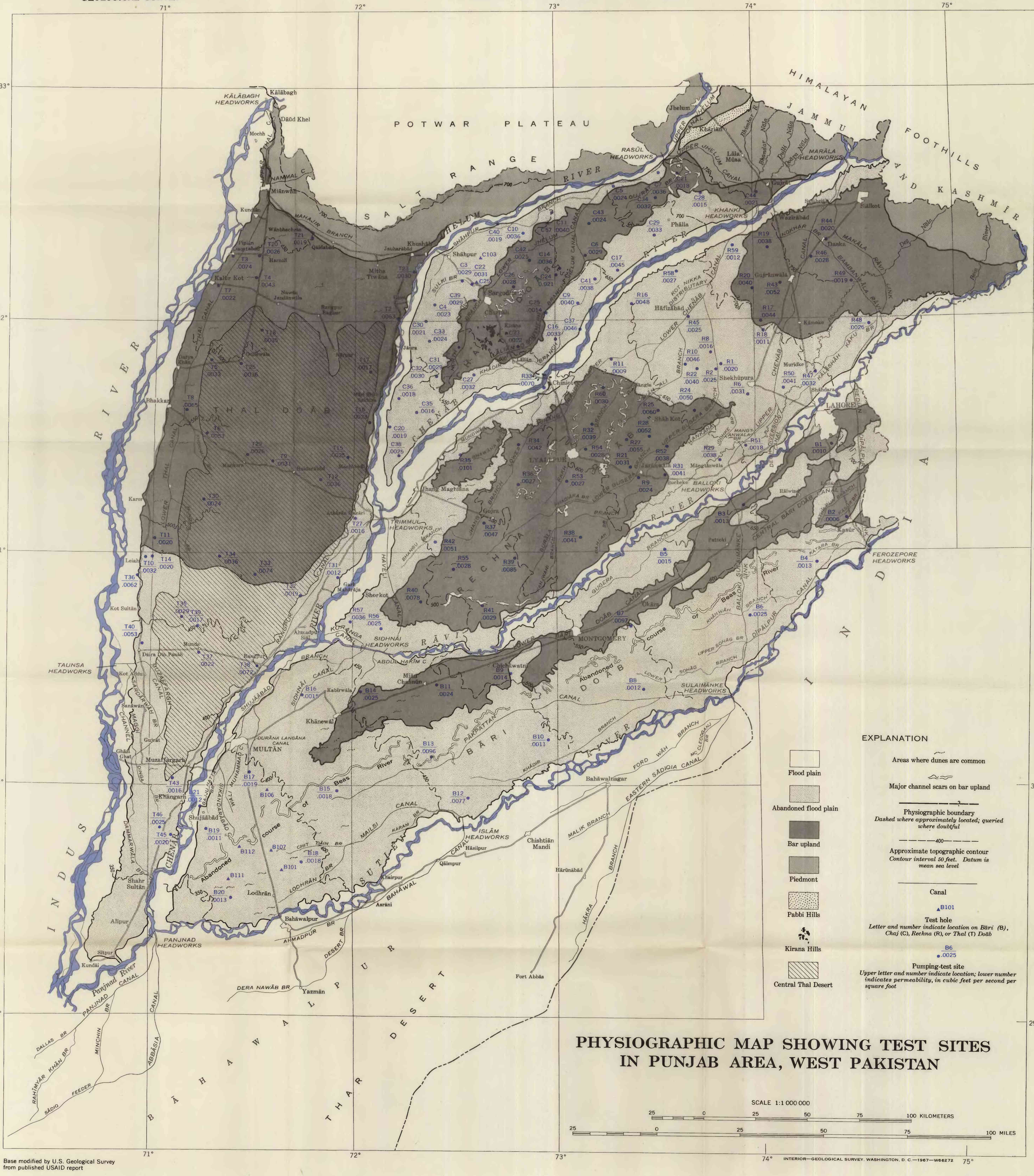
WATER-SUPPLY PAPER 1608–H
PLATE 2



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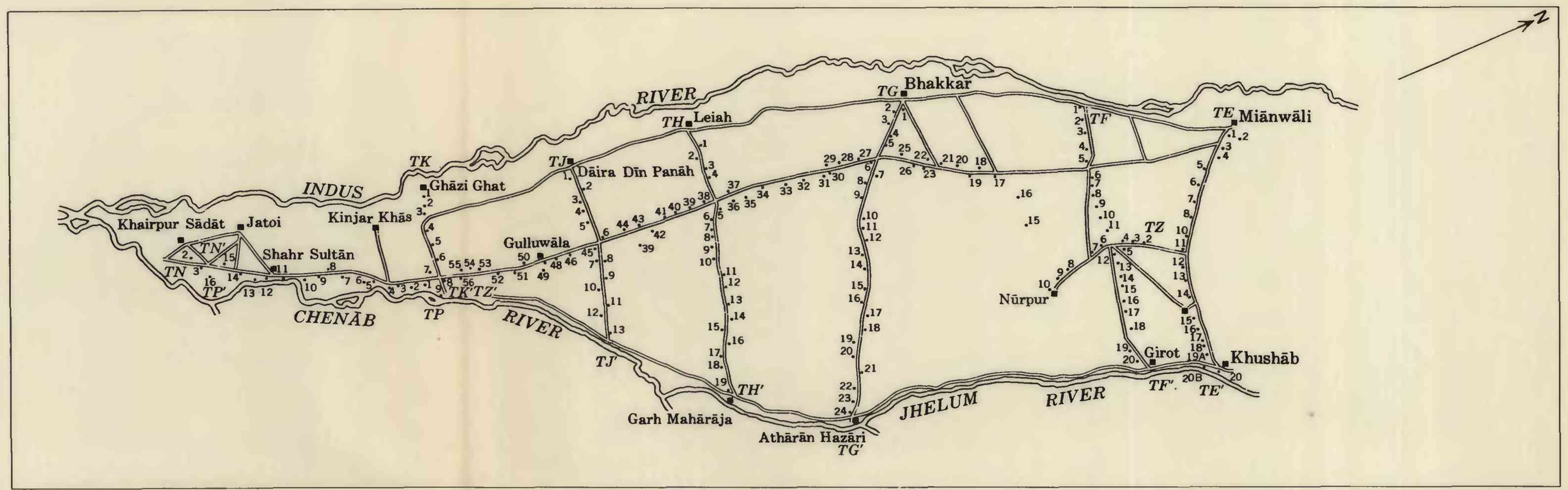
WATER-SUPPLY PAPER 1608-H
PLATE 3



INDEX MAP OF THAL DOĀB

0 8 16 24 32 KILOMETERS

0 8 16 24 32 MILES

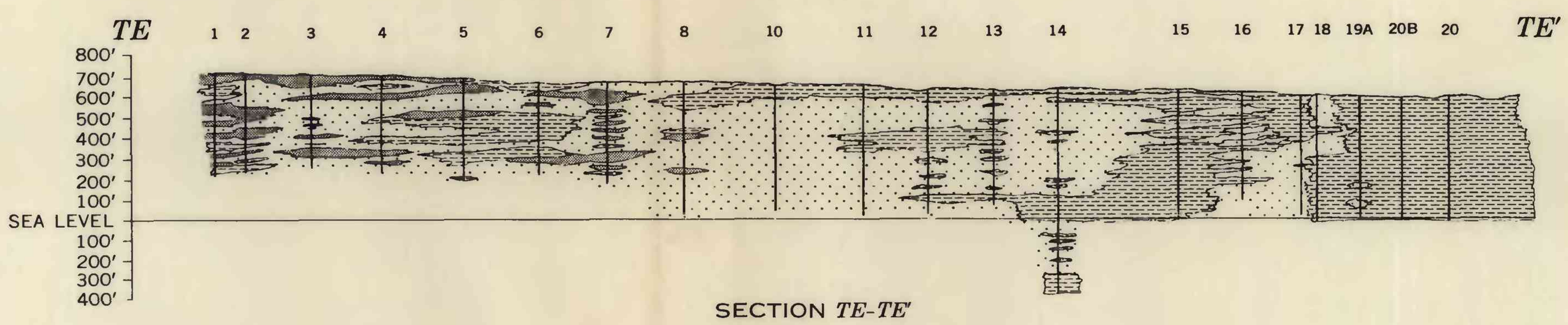
EXPLANATION

Sand, very fine to very coarse; gravel

Silt; silt, clayey and sandy; kankar

Clay; clay, silty and sandy; kankar

.15 Test hole and number



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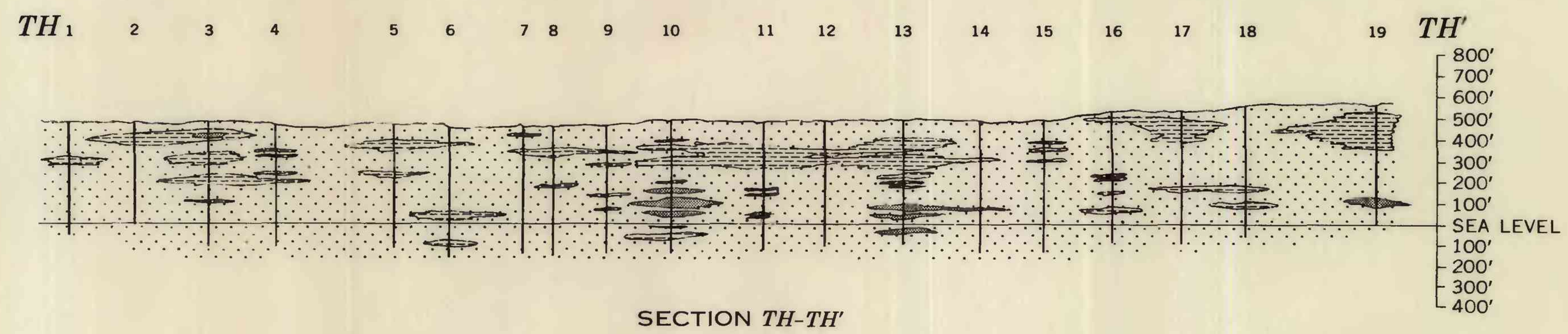

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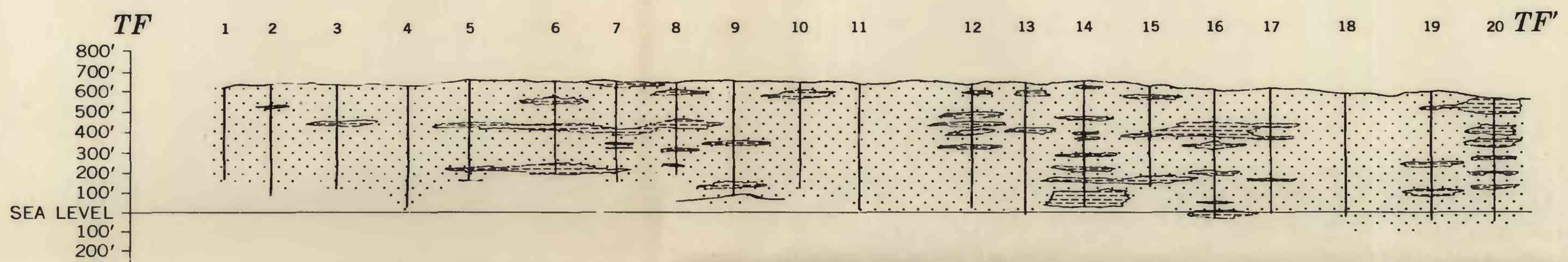

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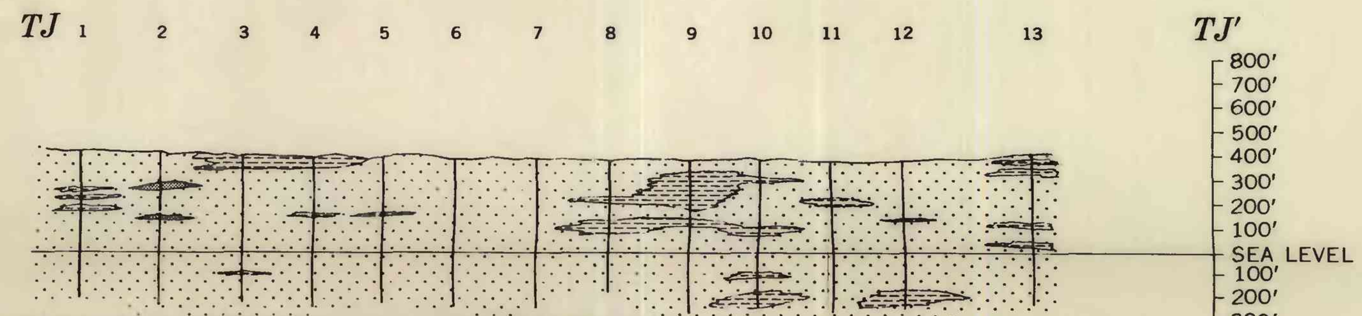

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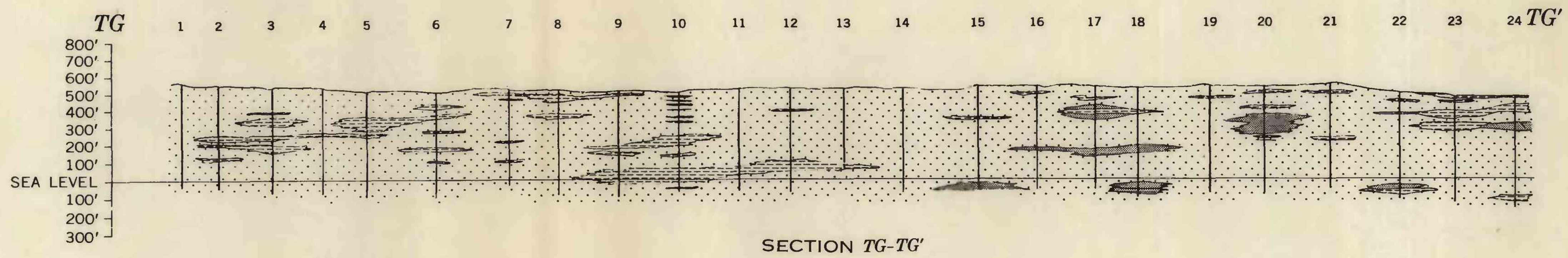

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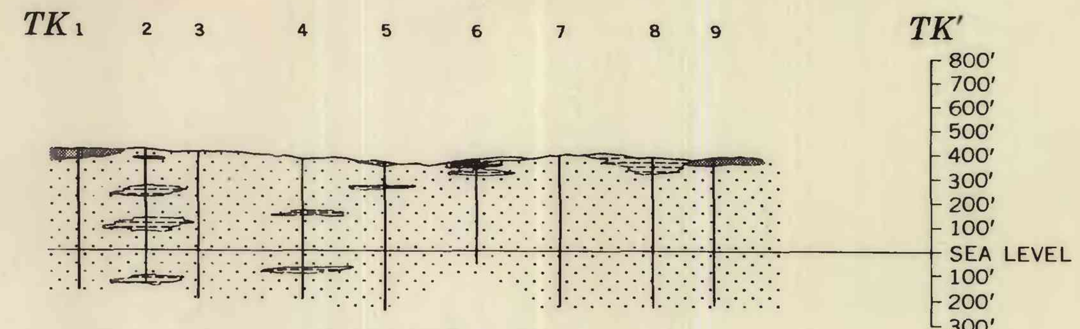

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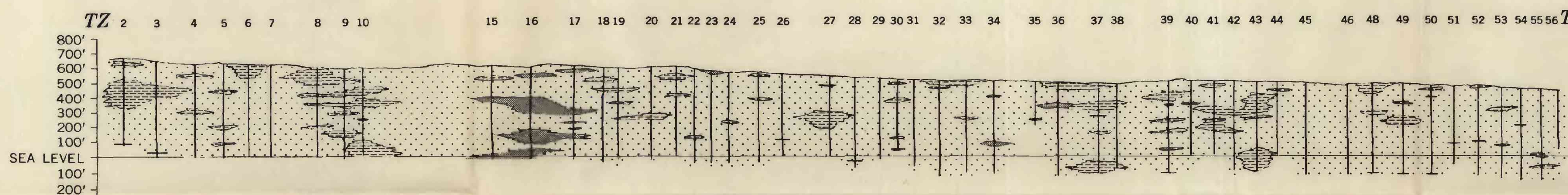

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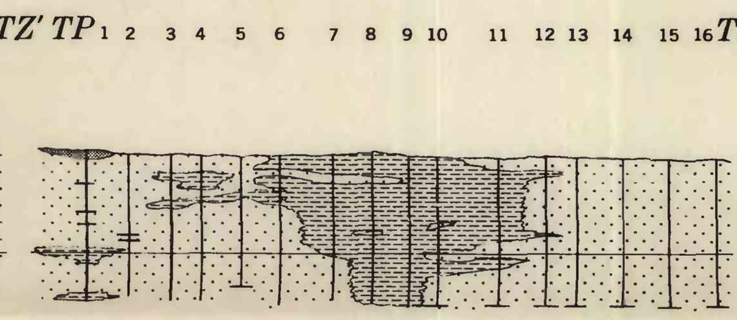

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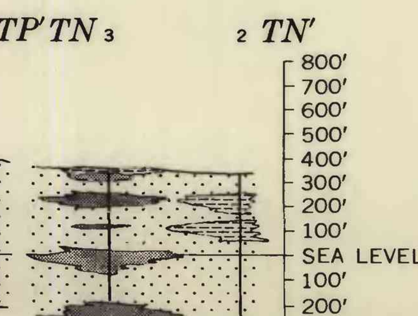

SECTION *TN-TN'*

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HORIZONTAL SCALE SECTION *TZ-TZ'*

1:500 000
4 0 4 8 KILOMETERS
4 0 4 8 MILES
HORIZONTAL SCALE SECTIONS *TE-TE'* TO *TP-TP'*

GEOLOGIC SECTIONS, THAL DOĀB, PUNJAB AREA, WEST PAKISTAN

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WATER-SUPPLY PAPER 1608-H
PLATE 4

EXPLANATION

Sand, very fine to very coarse; gravel

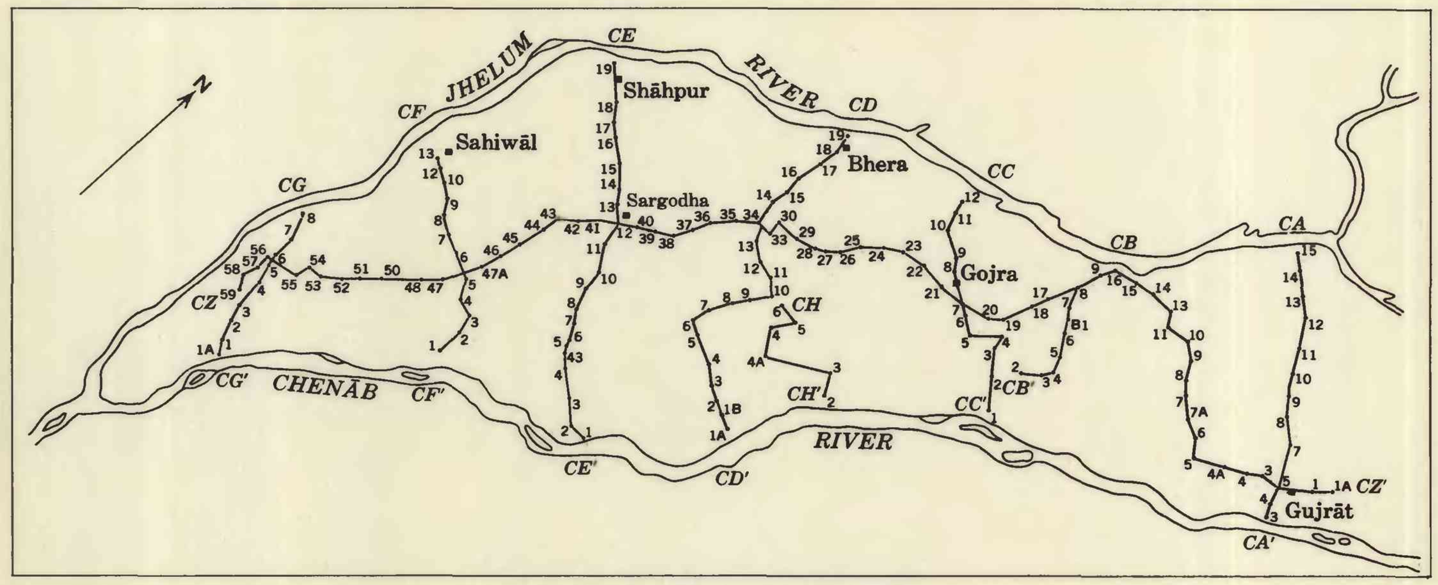
Silt, gravelly, sandy, silty, and kankariferous

Clay, gravelly, sandy, silty, and kankariferous

Siwalik Group
Mostly sandstone, siltstone, and conglomerate

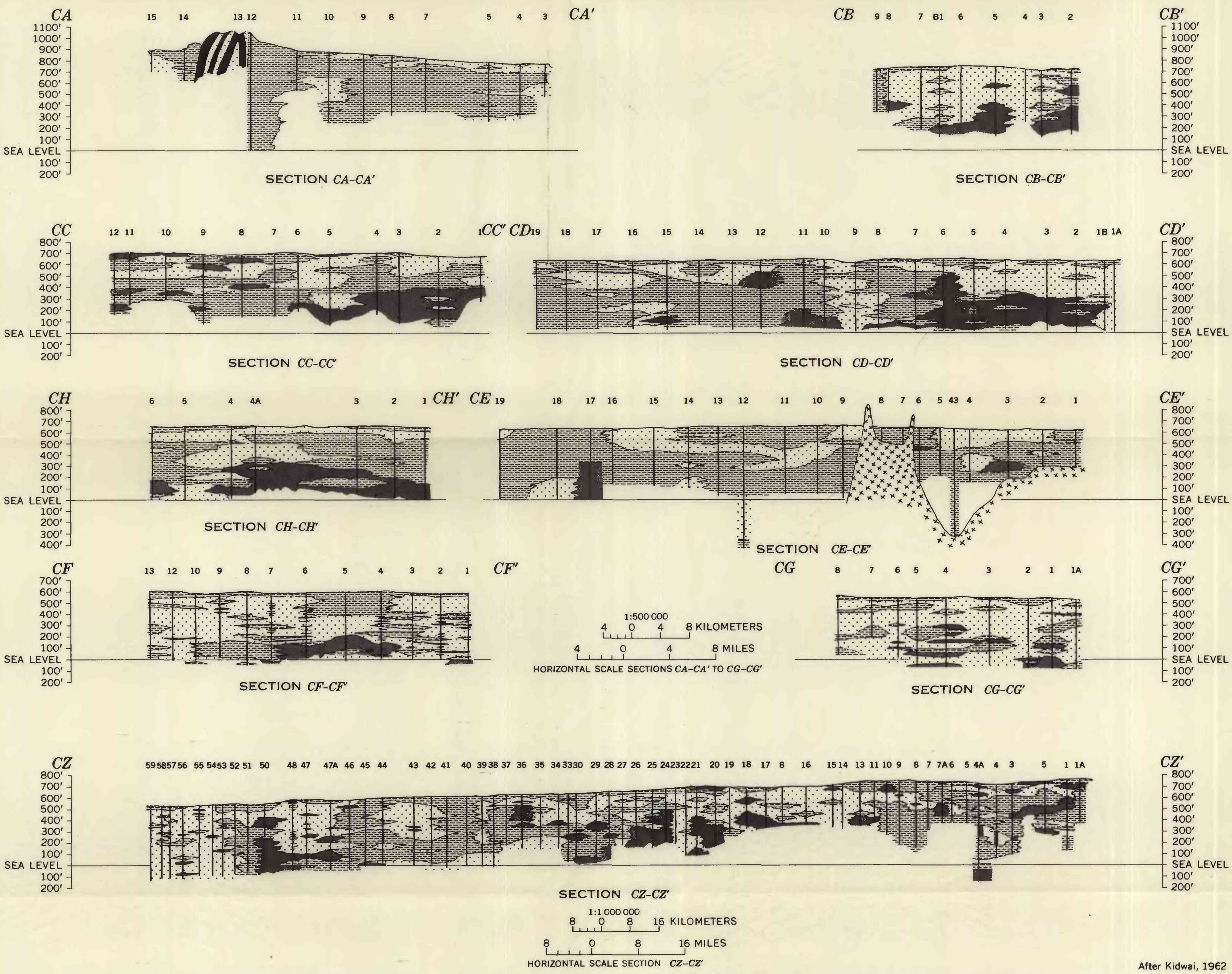
Precambrian
Metamorphic and igneous rocks

58
Test hole and number



INDEX MAP OF CHAJ DOĀB

0 12 24 KILOMETERS
0 12 24 MILES



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GEOLOGIC SECTIONS, CHAJ DOĀB, PUNJAB AREA, WEST PAKISTAN

257-729 O - 67 (In plate volume)

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EXPLANATION

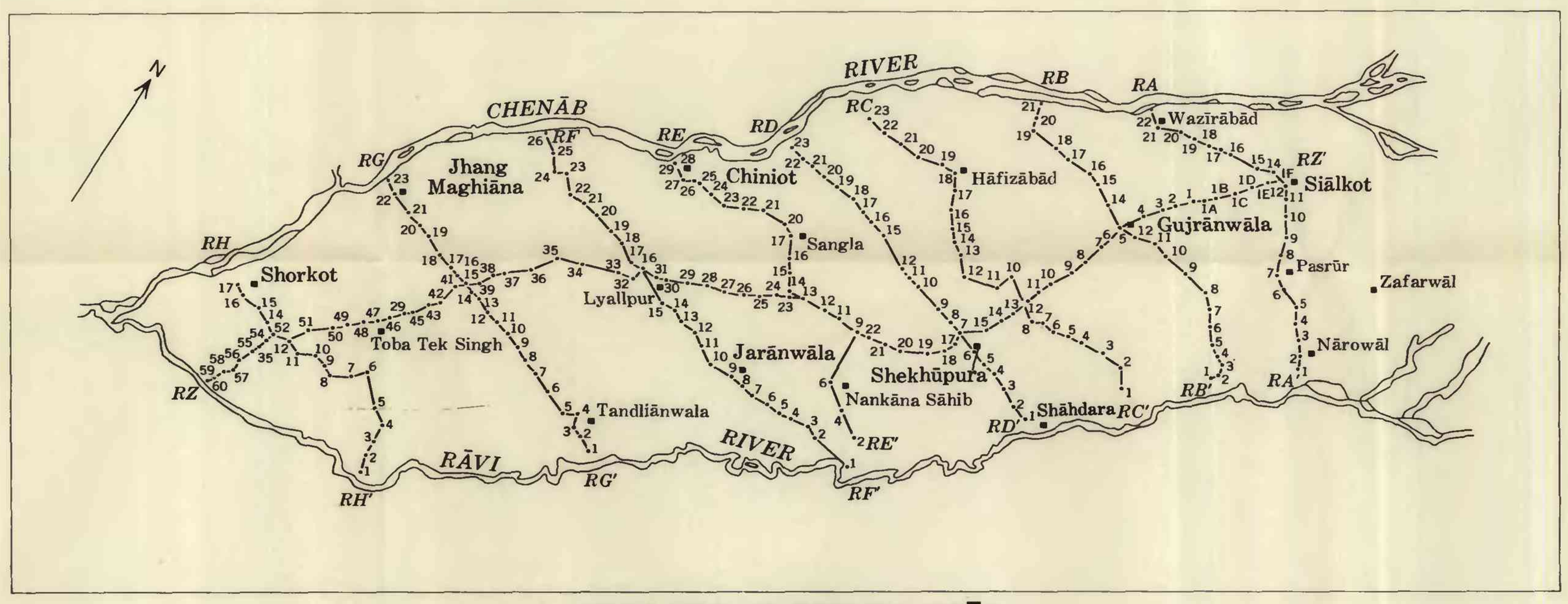
Sand, very fine to very coarse; gravel and kankar

Clay, gravelly, sandy, and kankariferous

Silt, gravelly, sandy, clayey, and kankariferous; silty sand

Precambrian
Metamorphic and igneous rocks

•11
Test hole and number



INDEX MAP OF RECHNA DOĀB

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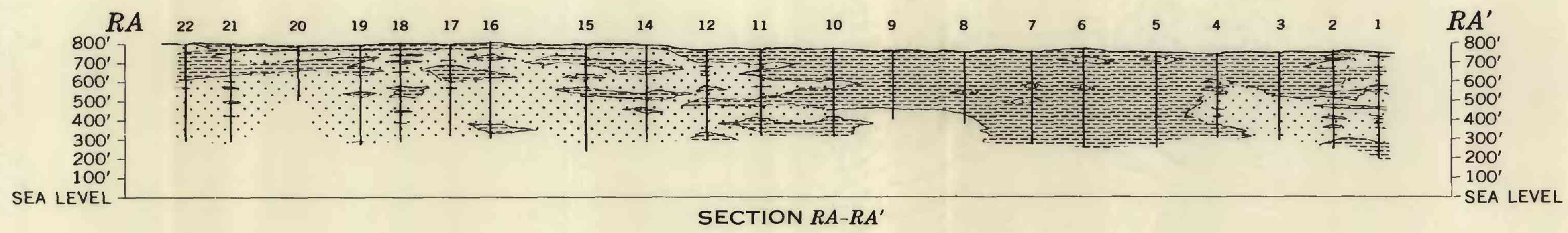
0 16 32 MILES



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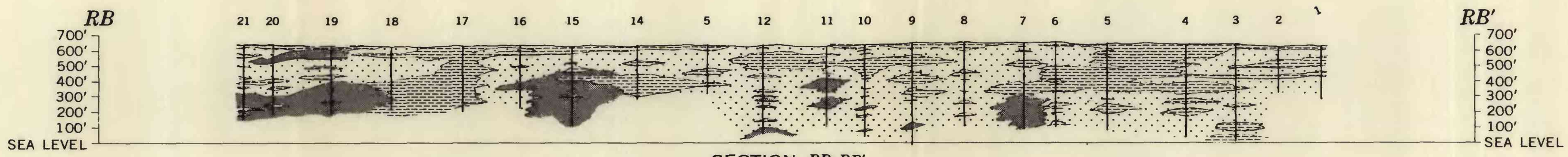

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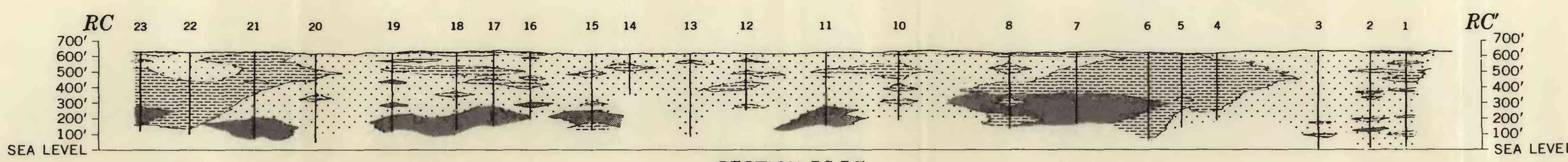

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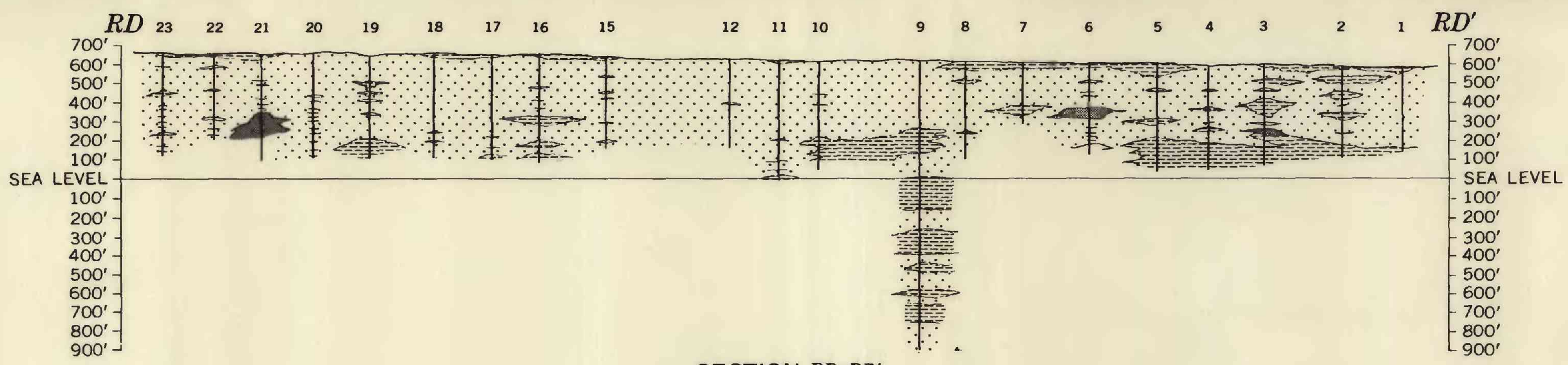

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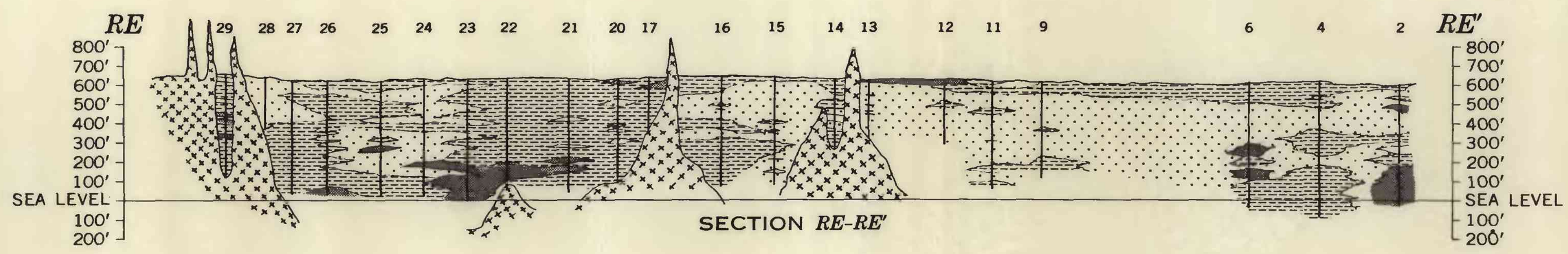

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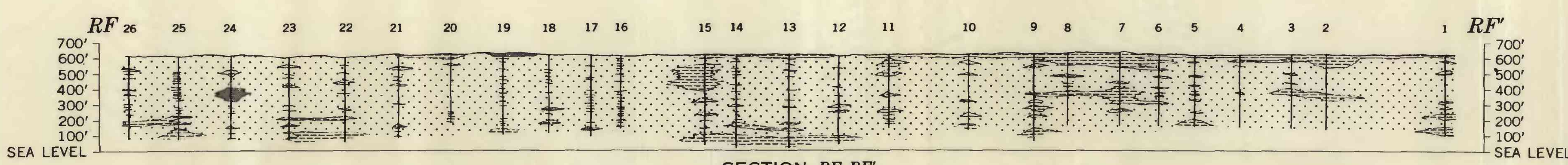

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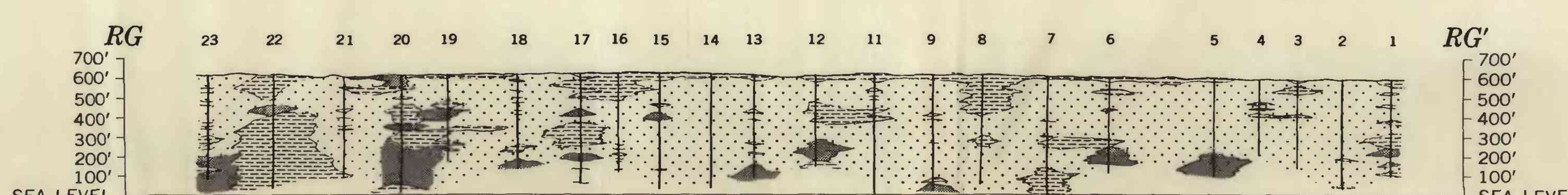

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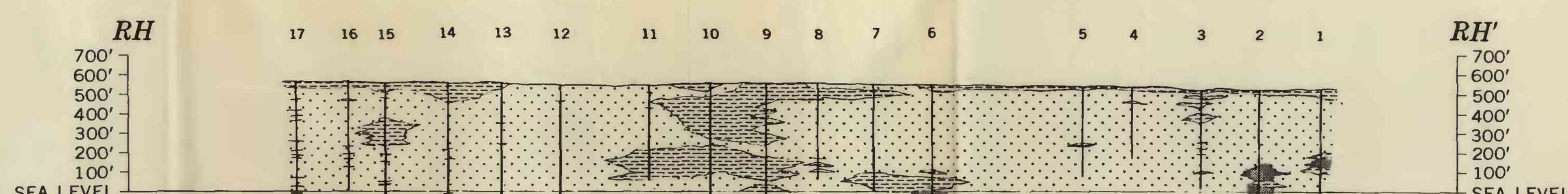

SECTION *RH-RH'*

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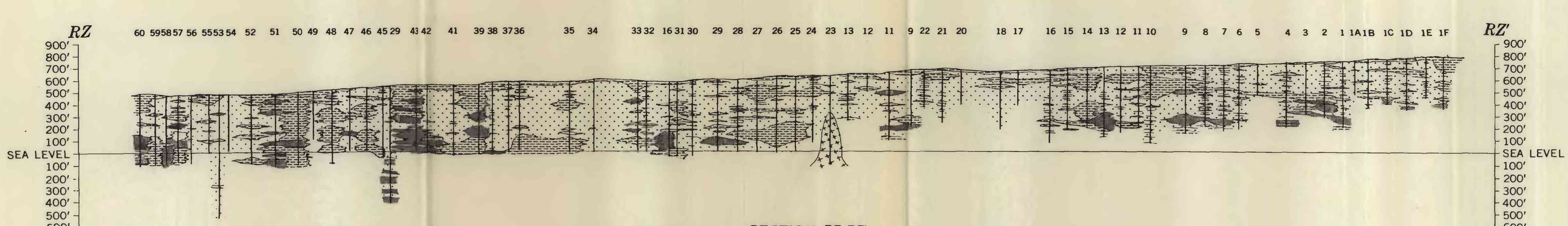
HORIZONTAL SCALE SECTIONS *RA-RA'* TO *RH-RH'*



SECTION *RZ-RZ'*

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8 0 8 16 MILES
HORIZONTAL SCALE SECTION *RZ-RZ'*

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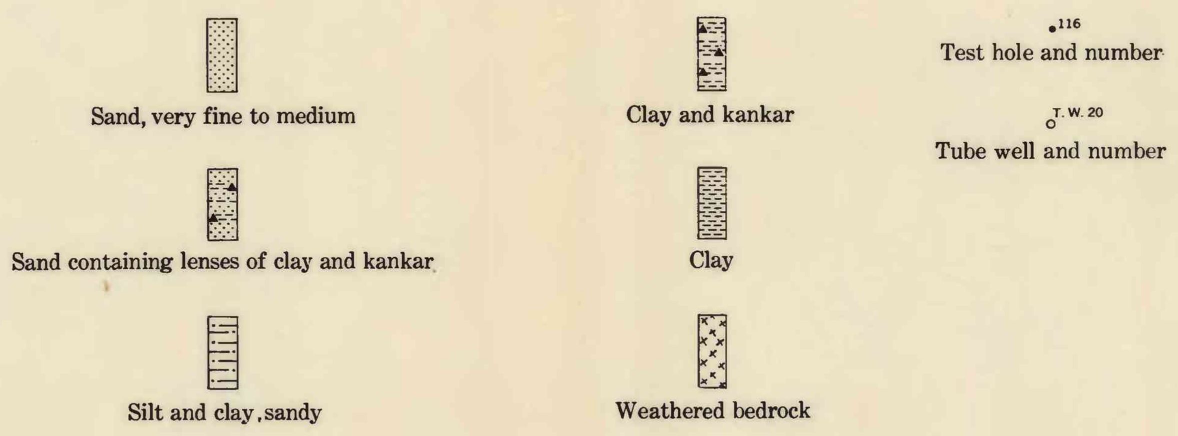
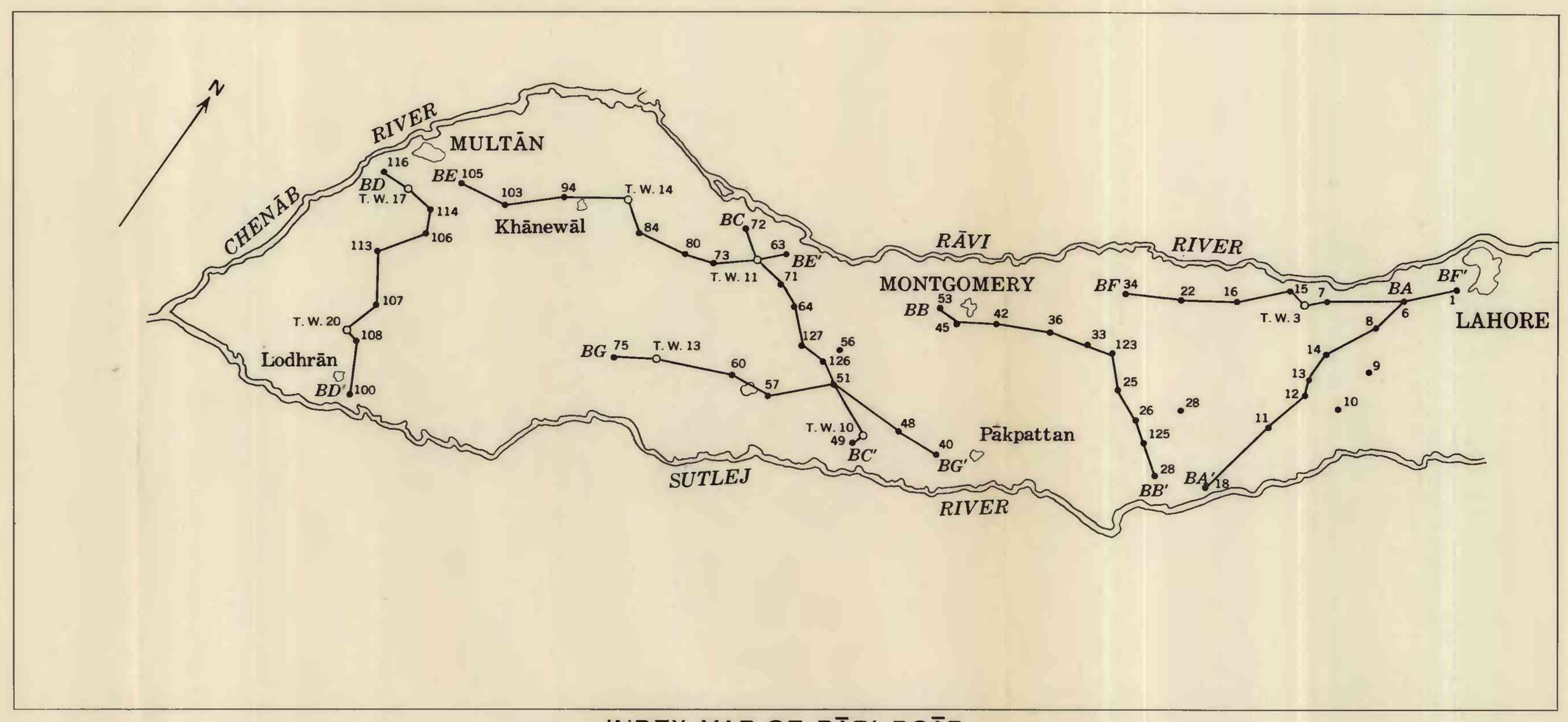
EXPLANATION





INDEX MAP OF BĀRI DOĀB

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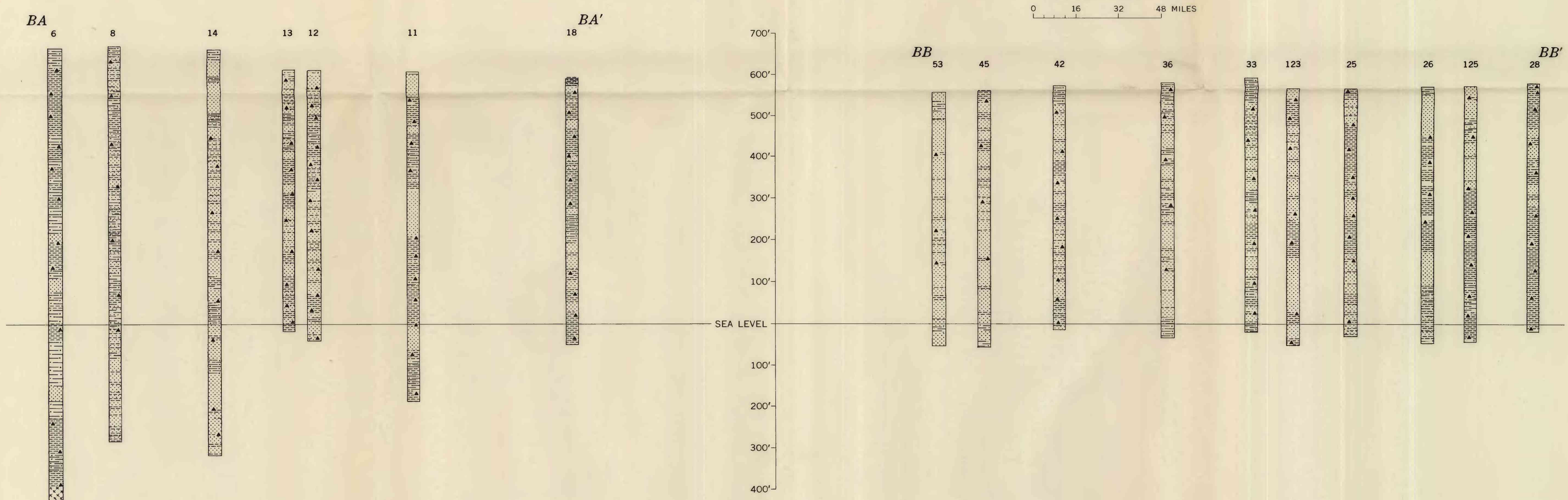
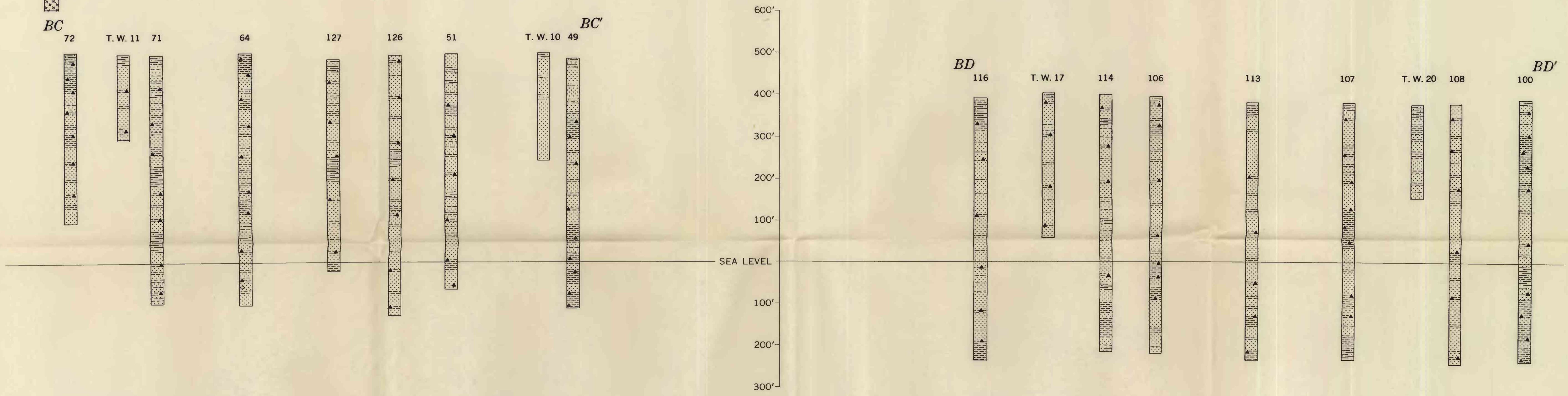
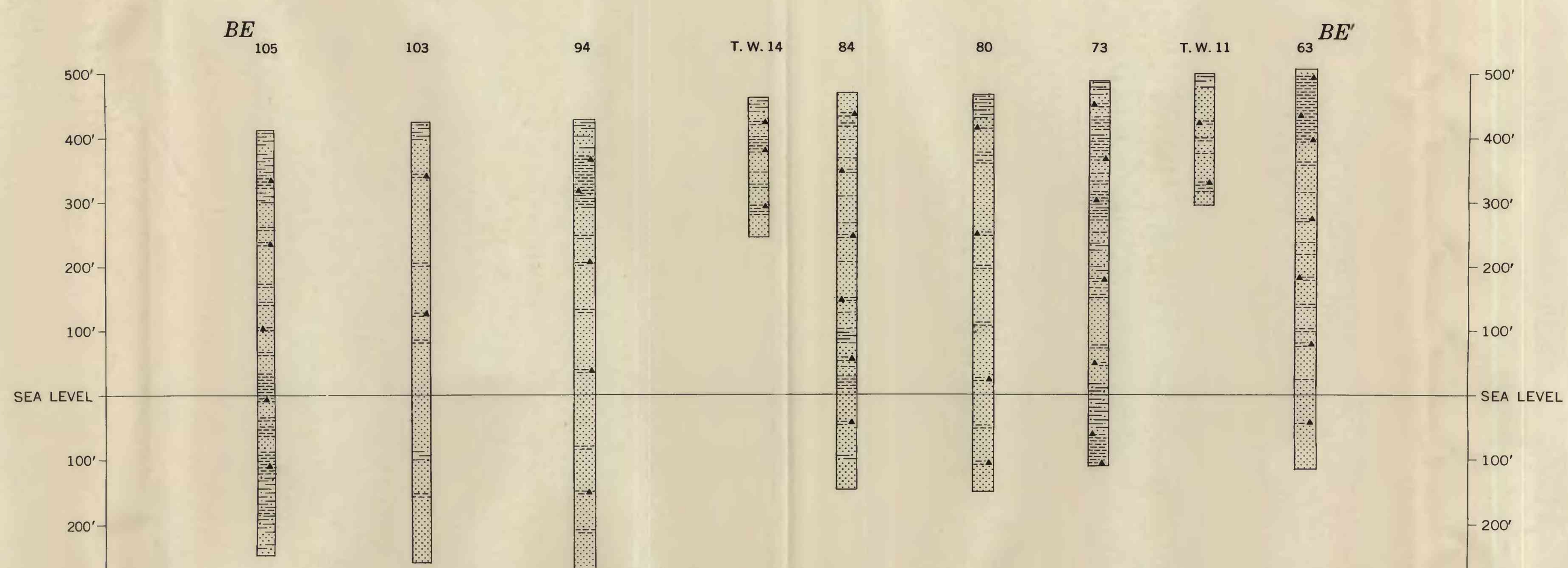
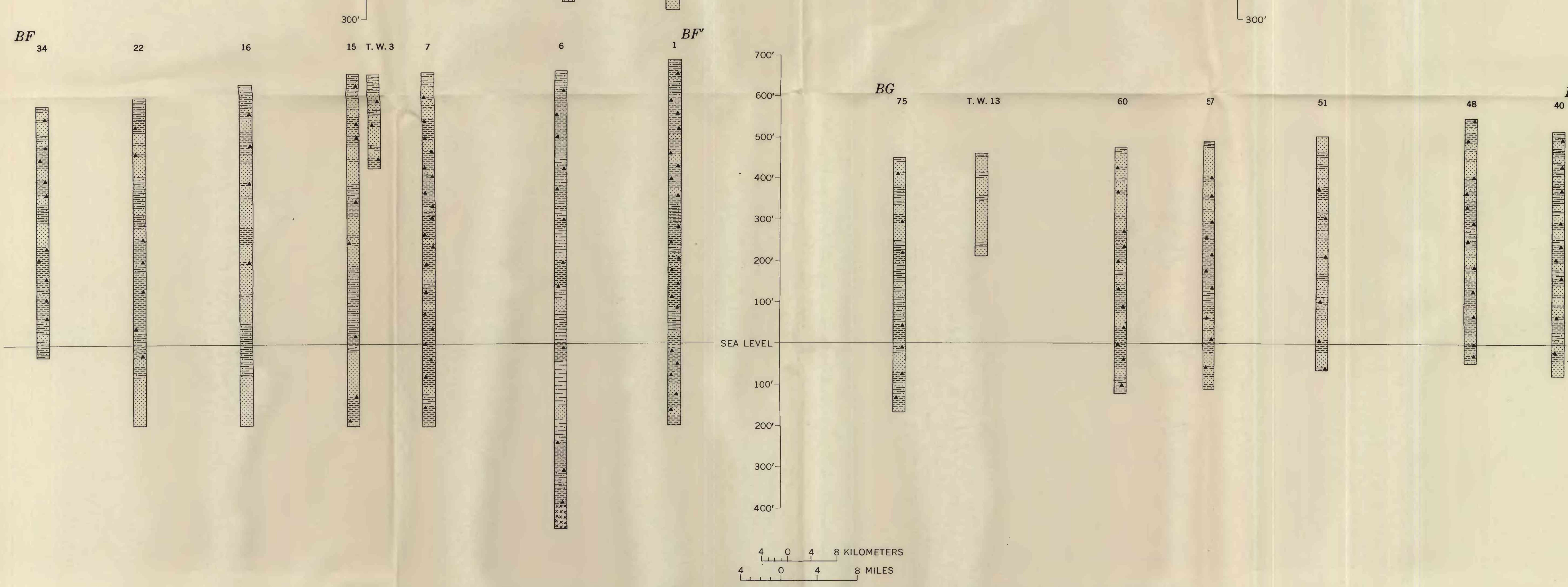
0 16 32 48 MILES









4 0 4 8 KILOMETERS
4 0 4 8 MILES

GEOLOGIC SECTIONS, BĀRI DOĀB, PUNJAB AREA, WEST PAKISTAN

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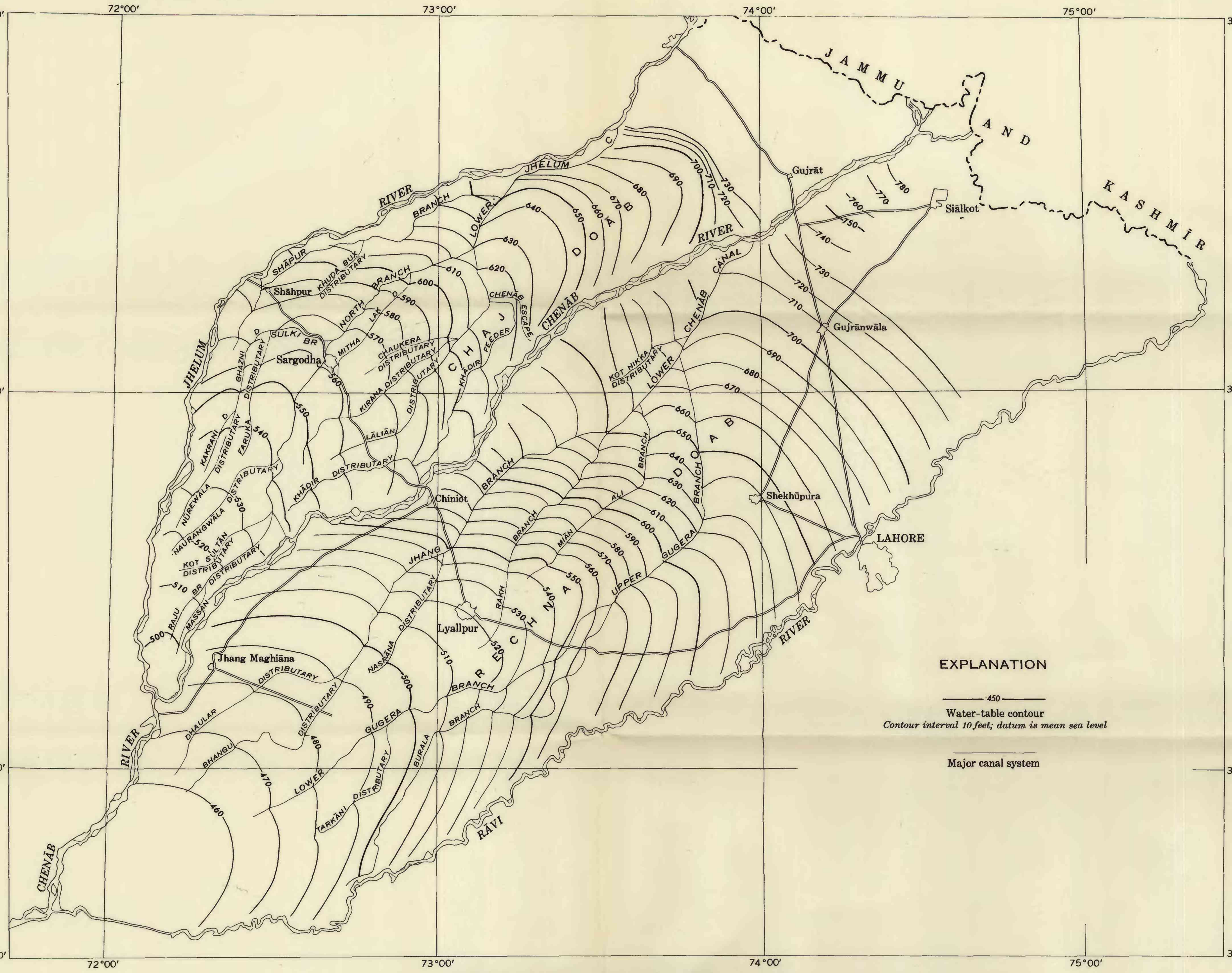
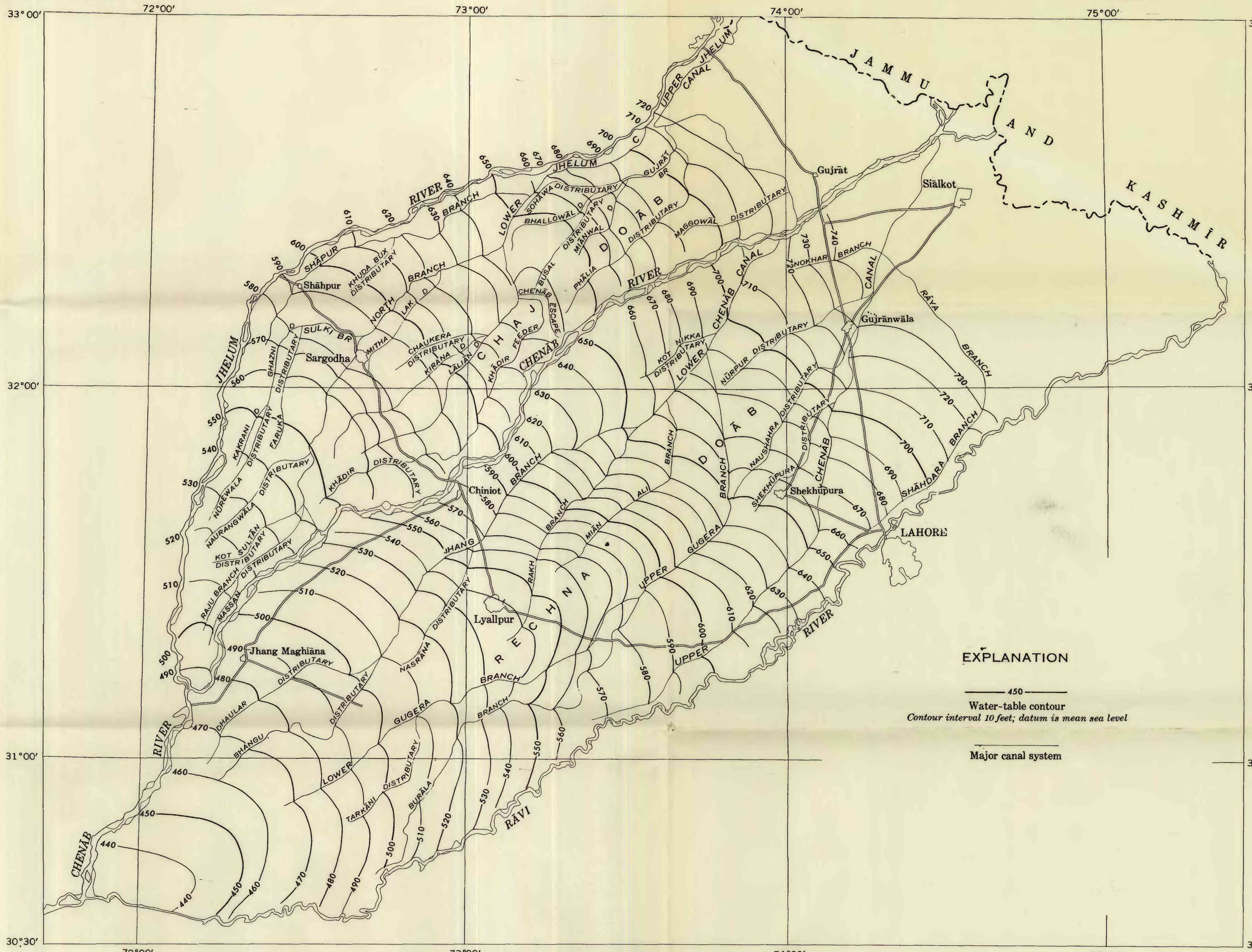
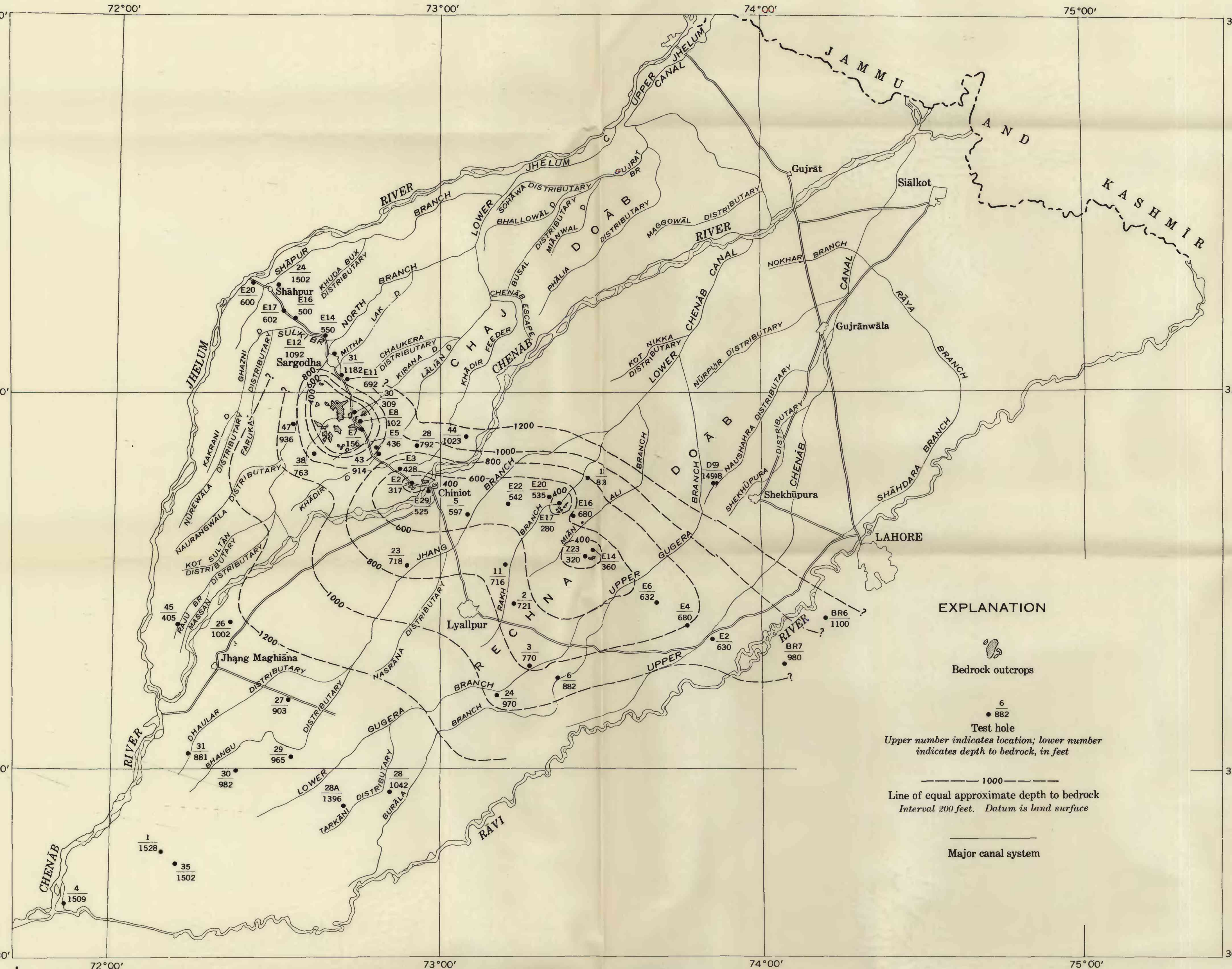
WATER-SUPPLY PAPER 1608-H
PLATE 7



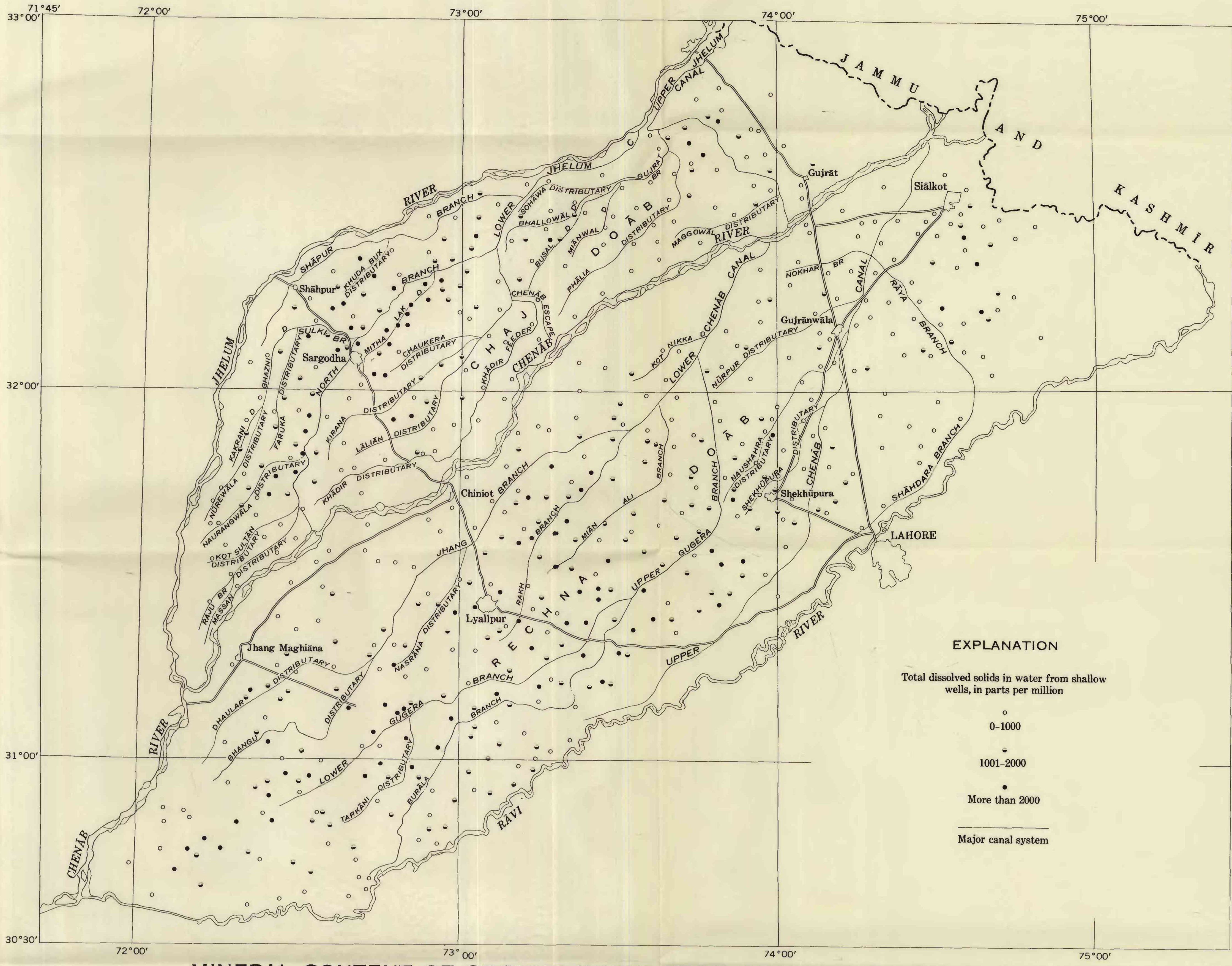
WATER-TABLE CONTOURS, 1910



WATER-TABLE CONTOURS, 1920



DEPTH TO BEDROCK



MINERAL CONTENT OF GROUND WATER FROM SHALLOW SOURCES, 1955–60

MAP SHOWING GROUND-WATER FEATURES OF RECHNA AND CHAJ DOĀBS, PUNJAB AREA, WEST PAKISTAN

SCALE 1:1 000 000

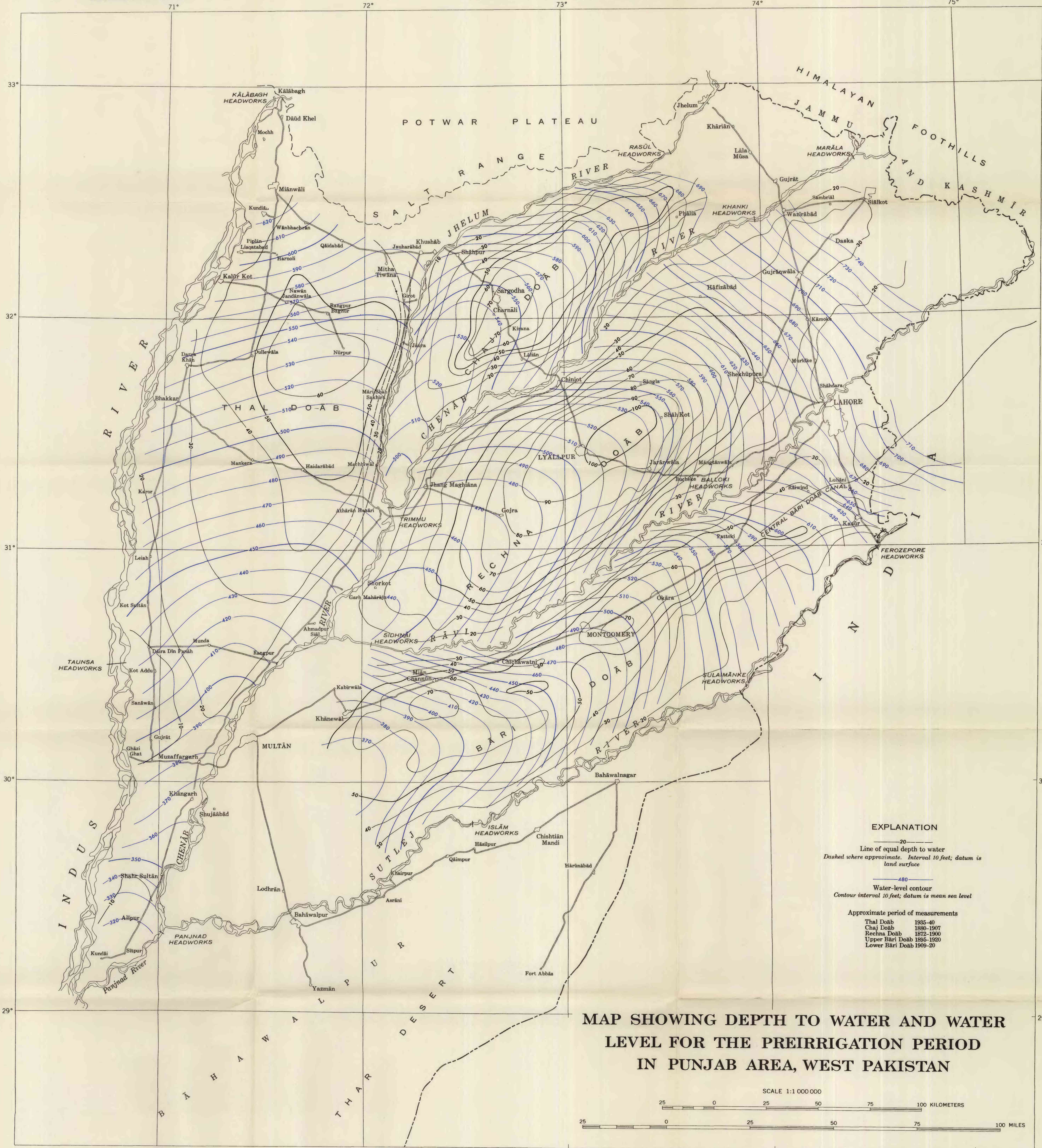
25 0 25 50 75 100 KILOMETERS

25 0 25 50 75 100 MILES

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
WEST PAKISTAN WATER AND POWER DEVELOPMENT AUTHORITY
UNDER THE AUSPICES OF THE
U.S. AGENCY FOR INTERNATIONAL DEVELOPMENT

WATER-SUPPLY PAPER 1608-H
PLATE 8



MAP SHOWING DEPTH TO WATER AND WATER LEVEL FOR THE PREIRRIGATION PERIOD IN PUNJAB AREA, WEST PAKISTAN

SCALE 1:1 000 000

25 0 25 50 75 100 KILOMETERS

25 0 25 50 75 100 MILES

EXPLANATION

——20——
Line of equal depth to water
Dashed where approximate. Interval 10 feet; datum is land surface

——480——
Water-level contour
Contour interval 10 feet; datum is mean sea level

Approximate period of measurements

Thal Doāb	1935–40
Chaj Doāb	1880–1907
Rechna Doāb	1872–1900
Upper Bāri Doāb	1895–1920
Lower Bāri Doāb	1909–20

Base modified by U.S. Geological Survey from published USAID report

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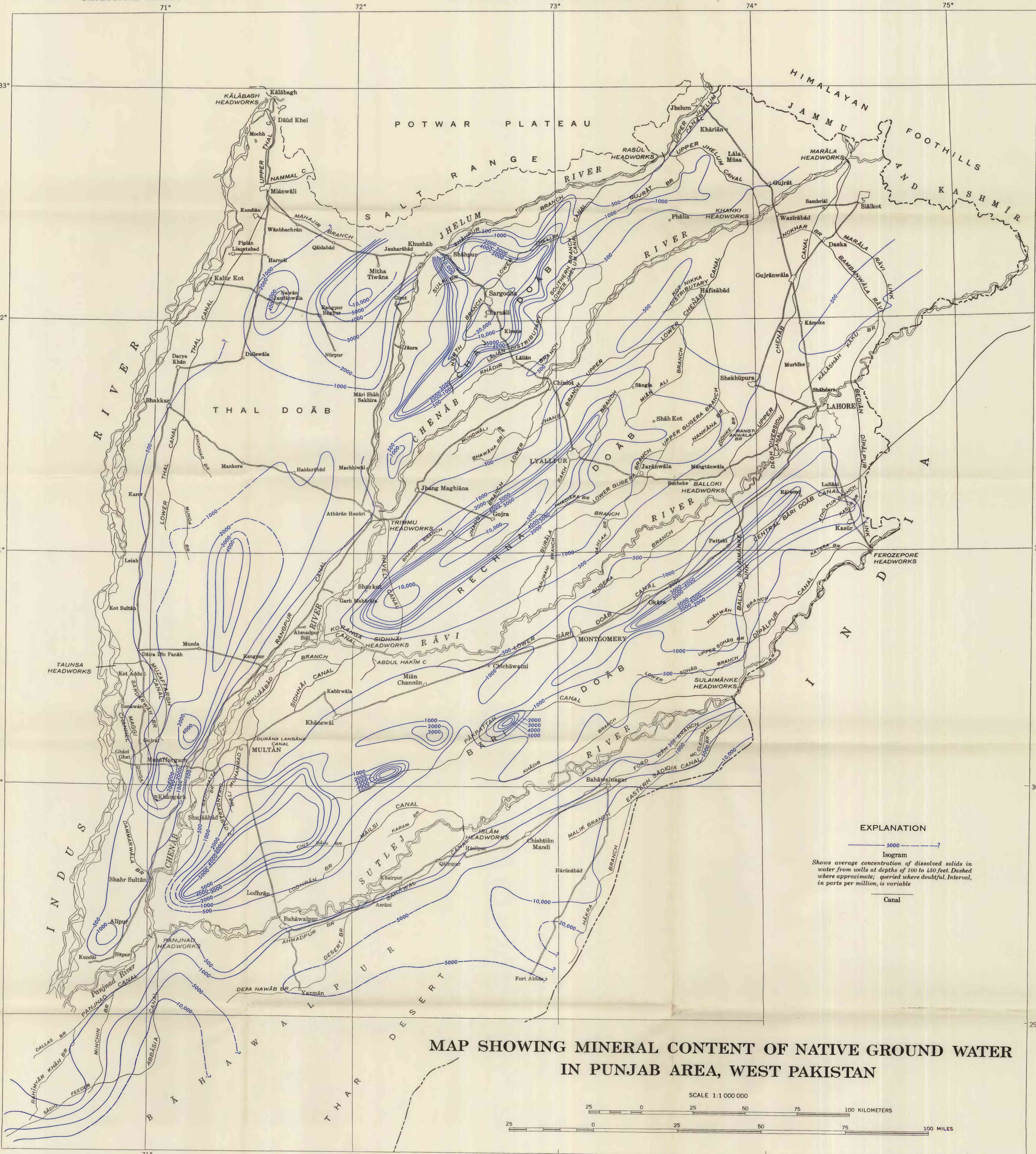

MAP SHOWING MINERAL CONTENT OF NATIVE GROUND WATER IN PUNJAB AREA, WEST PAKISTAN

SCALE 1:1 000 000

25 0 25 50 75 100 KILOMETERS

25 0 25 50 75 100 MILES

EXPLANATION

5000 ——?

Isogram

Shows average concentration of dissolved solids in water from wells at depths of 100 to 450 feet. Dashed where approximate; queried where doubtful. Interval, in parts per million, is variable

Canal

Base modified by U.S. Geological Survey
from published USAID report

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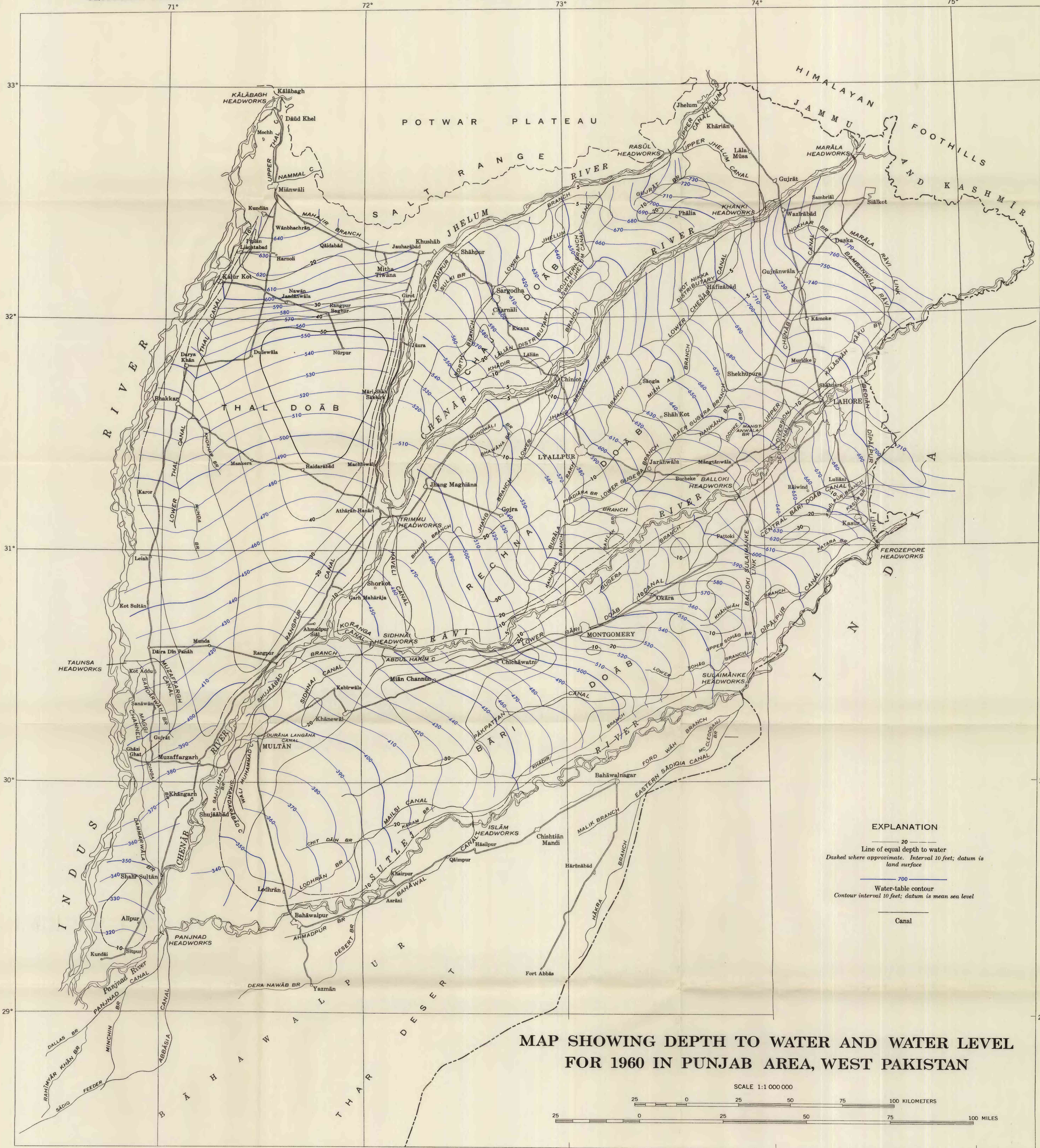
WATER-SUPPLY PAPER 1608-H
PLATE 10



MAP SHOWING DEPTH TO WATER AND WATER LEVEL FOR 1960 IN PUNJAB AREA, WEST PAKISTAN

Base modified by U.S. Geological Survey
from published USAID report

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