Water Resources and Related Geology of Dera Ismāīl Khān District, West Pakistan, With Reference to the Availability of Ground Water for Development

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1608-K

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 JAMES W. HOOD, LUTFE ALI KHAN, *and* KHALID JAWAID

CONTRIBUTIONS TO THE HYDROLOGY OF ASIA AND OCEANIA

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GLOSSARY

Both text and illustrations in this report contain words, names, and descriptive terms that are derived from the Urdu, Punjabi, Pashto, Persian, and other languages. These are explained below, both to define the word more fully than in the text and to provide the reader with familiarity in order that he is not distracted from the primary technical intent of the report. Language origins and derivations of words generally are not given, but derivation may be given where it is important to the understanding.

Ab: River, stream.

Administrative units: Pakistan is divided into administrative units, arranged in descending order of size as follows: *Province, division, district, tahsīl.*

Algad: Stream. Usage appears to equate it with *zām* and *toi.*

Bar: In the Punjab Plain, the highest part of each interfluve. Once an aggradational surface, the bars or bar uplands are now 30 to 50 feet above present river levels and generally are no longer inundated by floods.

Baranī: Dryland farming that depends entirely on rainfall for the maturing of crops. This method is practiced extensively in upland areas where no canal or flood supplies are available.

Barrage: Low dam for diverting water from rivers into canal systems by raising the river level a few feet or tens of feet. Permanence of barrages depends primarily on their great mass. Floodflow passes over them in controlled weirs. Barrages, with their auxiliary dikes (bunds), may be several miles long in the Punjab Plain.

Bhittanni: A tribal unit of the Pathans, or hill tribesmen who live in the western mountains of West Pakistan.

Daman tract: Gently to steeply sloping area of the piedmont plain.

Dera: A place, or the place of.

District: An administrative unit, approximately equivalent to a State in the United States. Principal official is the District Commissioner. District may include special or tribal areas.

Division: An administrative unit including several *Districts* and, in the western part of West Pakistan, special or tribal areas.

Doāb: Two + river; a geographic or physiographic subdivision of the Punjab that includes the land between two rivers; interfluve.

Garah: A village.

Kālāpani: Black + water; a continuous source of water, such as a spring or perennial stream, presumably called kālāpani because such water is clear and therefore dark in appearance, as contrasted to the turbid, muddy storm runoff.

Kankar: An interstitial and a nodular form of calcium carbonate found in the sands and clays of the Punjab. Equivalent to the term "caliche" in the United States. Wadia (1961, p. 395) considers an abundance of kankar as indicative of Pleistocene age.

Kārez: An infiltration gallery made by digging a series of vertical shafts and connecting them with a tunnel that intersects the water table and thus drains part of the ground water and conveys it by gravity to the surface downslope on alluvial fans and similar sloping areas. This method of obtaining water is used across a wide area through the Middle East and north Africa.

Kaur: Stream. Usage appears to equate it with nāla.

Khad: Stream or drainageway. Usage appears to equate it with nāla.

Kharif: Summer growing season, generally extending from April to the middle of October.

Kot: Fort; thus in village names, a walled or fortified village.

Marwat: Tribal unit of the Pathans, or western hill tribesmen.

Monsoon: Rain-bearing airmasses of the summer months. In western West

Pakistan, the monsoon begins about July 15 and ends in September, sometimes as late as October 1. The rains result from the circulation of moist air northward and then northwestward from the Bay of Bengal and the Arabian Sea. In the Dera Ismāīl Khān District, much of the moisture of the monsoon airmass has been depleted and rains are light compared to the heavier rains that fall to the east.

Nāla: An abandoned stream channel; a drainageway; an intermittent stream. This or a similar word also means an artificial drain.

Open well: A dug well. For a specialized form see *Persian well.*

Pahār: Mountain, ridge, hill(s).

Persian well: Dug well, pumped by animal power. (See fig. 7.) An endless chain of clay pots mounted on a rope cable is driven by wooden gears which are turned by bullocks, a donkey, or a camel. Most such wells are shallow, but some are as much as 200 feet deep. They can yield as much as 100 gallons per minute. These wells are used throughout the Punjab to irrigate both canal-irrigated lands as supplementary sources and lands not supplied by canal.

Piedmont plain: Along border of Indus Plain, the steeper slopes that reach from the bordering hills and mountains to the level area of the plain.

Province: Administrative unit of Pakistan. East and West Pakistan are Provinces, each headed by a governor.

Punjab: Five + river; the region of the northern Indus Plain watered and drained by the five rivers — Beas, Jhelum, Chenāb, Rāvi, and Sutlej.

Pur: Suffix, meaning a place, or the place of.

Rabi: Winter growing season that includes the period from the middle of October to the end of March.

Rūd: Stream; usage appears to equate it with *nāla.*

Rūd kohi or **rod kohi:** Stream and mountain + of; therefore, a mountain stream or hill torrent. System of irrigation that uses floodflow from the intermittent streams of the *piedmont plain.* Fields are diked and the floodwaters directed into the field for a short period of time. The dike is then cut and the water is drained to the next lower diked field.

Sailaba or **sailab:** Most ancient form of irrigation in the Punjab. It is still practiced on the lowest terrace, or active flood plain, adjacent to the low-water channels of the rivers that are inundated during the flood season. When floodwater subsides, the lands are tilled and planted. Residual soil moisture and water from the capillary rise of the water table sustain crops to maturity. Unseasonably late floods may destroy crops.

Shirāni: Tribal unit of the Pathans.

Sulaimān: Solomon. Takht-i-Sulaimān, the throne of Solomon, is the highest point in the Sulaimān Range, altitude 11,085 feet.

Tahsīl: Administrative unit, approximately equivalent to a county in the United States.

Thal: Sand dunes.

Toi: River or stream.

Tubewell: Drilled and cased well of modern design. The term is derived from the tube or casing of iron or steel pipe. The term is an established technical term in West Pakistan and used to distinguish such wells from the heretofore more common large-diameter open or Persian well, which may be only a dug pit or rarely may be curbed with brick or stone and may contain a stairway to the water level.

Zām: Stream. Usage indicates a mountain or perennial stream.

The names in this glossary and other locally derived names and descriptive terms that appear in this report are generally given the spelling recommended by the U.S. Board on Geographic Names. Spellings that differ from BGN forms are used because of their customary geologic usage in the United States or because the form was used in fieldwork or other research. A few names have not been verified by BGN.

Not all villages mentioned in this report are shown on maps. The locations of these villages generally are at the hydrologic data point with which the village is associated.

Where the BGN form of a stream name does not include the stream type, the foreign geographic name for the type has been added in parentheses in the text and on the maps; these types are defined in this glossary and on plates 1 and 6.

WATER RESOURCES AND RELATED GEOLOGY OF DERA ISMĀĪL KHĀN DISTRICT, WEST PAKISTAN, WITH REFERENCE TO THE AVAILABILITY OF GROUND WATER FOR DEVELOPMENT

By JAMES W. HOOD, LUTFE ALI KHAN, and KHALID JAWAID

ABSTRACT

Dera Ismāīl (D.I.) Khān District contains an area of 3,450 square miles between the right bank of the Indus River and the Sulaimān Range in west-central West Pakistan. Agriculture is the principal source of income in the District, but only a small part of the arable land is fully utilized. The region is semiarid and has an average annual rainfall of about 9 inches and a potential evapotranspirational rate of eight to nine times the annual rainfall. Thus, rainfall alone is not adequate for high-intensity cropping.

Irrigation is practiced near the Indus River; the Pahārpur Canal is used, as well as the traditional inundation method. Elsewhere in the District, adequate water is supplied to local areas by kārezes, perennial streams from the mountains, and some recently installed tubewells (see "Glossary"). Further development of ground-water supplies would permit a more effective utilization of most of the presently tilled land and would allow additional land to be farmed.

D.I. Khān District is primarily an alluvial plain that slopes from the mountain ranges in the northern and western parts of the District toward the Indus River. Rocks in the bordering mountains are of Paleozoic to early or middle Pleistocene age. The unconsolidated rocks of the plain, of middle(?) Pleistocene to Holocene (Recent) age, consist of piedmont deposits derived from the hills to the north and west and of alluvium laid down by the Indus River. These deposits interfinger in a transitional zone about 8 to 12 miles west of the river. Lithologic and structural features indicate that the unconsolidated rocks possibly may be divided into broad units.

The investigations in D.I. Khān District have revealed two main areas of potential ground-water development based on considerations of both permeability and chemical quality of the ground water:

1. A belt about 10 miles wide parallels the Indus River from the Khisor Range southward to the area immediately south of D.I. Khān town. In this belt, the material penetrated by test holes and tubewells consists predominantly of sand, which in tubewells can yield from 2 to 3 cfs (cubic feet per second) of water with only moderate drawdown. Also in this belt, ground water of good chemical quality extends to depths of 1,000 feet or more.
2. The area from the mouth of the Gumal River gorge to the vicinity of Kot

Azam contains sand and gravel strata that may yield from 1 to 3 cfs of water, which contains 500 to 1,500 ppm (parts per million) of total dissolved solids.

Other marginal parts of the District also contain water of good chemical quality, but developmental prospects are somewhat poorer because of greater depths to water, lower permeabilities, or greater depths to aquifers, all of which would require greater costs in the tubewell installations.

The stratification or zoning of water of different chemical qualities to some extent governs the local availability of useful water. Generally, the ground water of poorest quality is found in the shallow zone, and quality improves with depth. The central part of the District, in a belt reaching from the vicinity of Tānk southward to the Indus River near Dera Ghāzi Khān District, contains highly mineralized water and few aquifers. The mineralization of water in this belt is due primarily to large concentrations of sodium and sulfate and thus differs from the main part of the Punjab region where highly mineralized waters are generally chloride waters. Radical changes in water quality, both horizontally and vertically, are common in the District. Changes in chemical quality of water from large-capacity wells near areas of highly mineralized water are taking place, and further changes may be expected as withdrawals continue and increase in magnitude.

Under present conditions, surface-water supplies are fully utilized, and ground water is the largest supply available for development—other than that from the Indus River.

INTRODUCTION

Dera Ismāīl (D.I.) Khān District, like other semiarid parts of the Province of West Pakistan (fig. 1), has an agricultural economy and is supplied with water from precipitation and streamflow that are poorly distributed during the year and from wells. Since the establishment of Pakistan as an independent nation, the need for water in the District has grown, partly because of the increasing population. The increasing stability of the indigenous population has lead to better living conditions, and an influx of people has occurred owing to the large-scale population shifts that accompanied the partition of British India in 1947.

PURPOSE AND SCOPE

Because D.I. Khān District is marginal to the Punjab Plain, the investigation described in this report is an extension of the studies in that region. In the Punjab, some parts of canal-irrigated areas are afflicted with saline soils and waterlogging due to rising water levels. The decline in agricultural productivity together with the need for additional land and water supplies led to a comprehensive program of study of the soils and water resources of the region. In D.I. Khān District, the studies have the principal purpose of determining the availability of usable ground water.

Field studies in D.I. Khān District included drilling of test holes and aquifer-test wells and the collection of data from existing ground-water sources (pl. 1). Thirty-seven test holes were drilled

FIGURE 1—Location of Dera Ismāīl (D.I.) Khān District, West Pakistan.

to depths ranging from about 100 to more than 1,500 feet. From these holes, samples of drill cuttings, cores from shallow beds, electric logs, and water samples from specific zones in each hole were collected. After drilling and sampling operations were completed, observation pipes were installed in most of the holes to provide a means of periodically measuring water-level fluctuations at the test-hole sites. On the basis of the test-hole logs, 10 aquifer-test wells were installed, and the hydraulic characteristics of the aquifers were determined.

Existing ground-water sources were inventoried, and water samples were obtained from many of them. Records of representative private and government tubewells, open and Persian water-wheel wells, and hand-pumped wells were accumulated for study. These records include a large quantity of data, from the Irrigation Branch, Public Works Department (PWD), which were integrated with the field data and were of value in interpreting ground-water conditions near the Indus River.

Water levels in all observation pipes were measured biweekly to monthly from the time of installation through June 1964. Representative dug wells were measured during the period November 1962 through June 1964. Long-term records of observations by the Irrigation Branch were obtained for dug wells between the Pahārpur Canal and the Indus River for the period 1934–62 and were extended to 1964 by field measurements.

Data on the discharge and chemical quality of surface water and climatological records were obtained. Geologic and physiographic observations were made in the field and from aerial photographs. Supplementary geologic data about the mountain areas were obtained through field observations.

Base maps were constructed, and supplemental horizontal and vertical controls were established from landform maps of a survey (Fraser, 1958) sponsored by the Colombo Plan and from topographic maps of the Survey of Pakistan. Altitudes of specific locations were determined by spirit leveling from Survey of Pakistan bench marks.

LOCATION

D.I. Khān District in west-central West Pakistan is an elongate irregularly shaped area which lies between lat 31°15′ and 32°30′ N. and long 70°20′ and 71°20′ E. (fig. 1 and pl. 1). The east limit is the Indus River; the north boundary is the watershed of the Marwat Range and a part of the eastern Bhittanni Range. The west boundary approximates the eastern base of a part of the Bhittanni Range and of the Shirāni Hills. The south boundary does not coincide with any natural feature.

PREVIOUS INVESTIGATIONS

Geologic studies in the vicinity of D.I. Khān District prior to 1958 were largely investigations such as that of T. O. Morris, who studied the Bain boulder bed. Many of these studies, although published, have not been readily available. They are, however, generally incorporated into the works of Wadia (1961) and Krishman (1960), who describe the geology of the Indian subcontinent. Prior to and concurrent with the present investigation, the Geological Survey of Pakistan had prepared detailed geologic maps of the District, but these had not been published as of 1964. The results, however, were incorporated into "Geologic Map of Pakistan" (Bakr and Jackson, 1964).

Under the Colombo Plan, the Government of Canada surveyed the landforms, soils, and land use of the Indus Plain. The results (Fraser, 1958) provided much useful information for this study.

Since 1960, surface-water supplies in the District have been studied by the Surface Water Circle of the Water and Soils Investigation Division (WASID), West Pakistan Water and Power Development Authority (WAPDA), and the data obtained have been published in a series of annual reports (West Pakistan Water and Power Development Authority, 1962–64).

An important published report is that on aquifer tests in the Punjab region of West Pakistan (Bennett and others, 1967).

ACKNOWLEDGMENTS

This report is a product of a comprehensive program of water and soils investigations that were initiated in 1954 in the Punjab region and adjacent areas in West Pakistan. Currently (1965) the program is sustained by a cooperative agreement between the West Pakistan WAPDA and the United States Agency for International Development (AID).

The project work in D.I. Khān District was under the general supervision of Mr. S. M. Said, chief engineer, and Mr. Z. U. Kidwai, superintending geologist, both of WASID, and Mr. M. J. Mundorff of the United States Geological Survey. Mr. S. A. T. Kazmi and, later, Mr. L. A. Khan, senior geologists of WASID, directed field operations during test drilling, and Mr. Khalid Jawaid directed the water-level program and coordinated the tabulation of test data. Ground-water hydraulics studies were made under the supervision of Mr. M. A. Lateef, superintending engineer of WASID, and Mr. G. D. Bennett, of the U.S. Geological Survey. Water sampling and analysis were directed by Mr. Abdul Hamid, senior research officer in charge of the WASID quality of water laboratory at Lahore. Mr. J. W. Hood, of the U.S. Geological Survey, helped in planning the investigation, worked in the field periodically, and helped compile the report.

A part of D.I. Khān District south of Tānk (pl. 1), extending from the mountains southeastward almost to D.I. Khān town, is in the Gumal River Development Scheme, and the investigations in that area were funded by the Planning and Investigation Division, WAPDA.

Mr. W. R. Hemphill of the U.S. Geological Survey and Mr. A. H. Kidwai of the Geological Survey of Pakistan provided supplementary geologic information with regard to the consolidated rocks of the mountain areas in northern D.I. Khān District and to the west of the District.

The District Commissioner at D.I. Khān made facilities available

to the field party, and the Irrigation Branch, PWD of Pakistan, provided data on water levels, canal flow, and weather at its installations in the District.

Published reference sources (see "Selected references") and unpublished data have been freely used wherever they contained data relating to the study described herein.

GEOGRAPHY

D.I. Khān District is an administrative part of D.I. Khān Division in the province of West Pakistan, Pakistan. The Division is a part of that area in former British India known as the North-West Frontier Province and the tribal agencies of North and South Wazīristān. The District is subdivided into D.I. Khān, Tānk, and Kulāchi Tahsīls, and the total area of the District is about 2.2 million acres or about 3,450 square miles.

The main towns are D.I. Khān, the District headquarters; Tānk; and Kulāchi. Other towns of importance, or of some size, are Pahārpur, Band Kurai, Paroa, Kirri Shamozai, Chaudhwān, Darāban, Hathāla, Ama Khel, Mullāzai, and the Frontier Constabulary Post of Manzai. Pezu, in Bannu District, is in the drainage basin and is at an important road junction. Although many smaller communities (pl. 1) are scattered throughout the District, the bulk of the population appears to be concentrated in, and adjacent to, the fertile Indus River lowland.

SURFACE FEATURES

LANDFORMS

The physiographic divisions used herein are based largely on data from Fraser (1958), but on plate 1 they have been somewhat modified for purposes of this study. The hilly and mountainous areas are largely older consolidated rocks whose forms are closely related to the folded geologic structure. The Khisor and Marwat Ranges are asymmetric and trend northeastward. They have steep southeastern faces and gentler northwestern slopes. The southwestern ends of the two ranges are the Sūr Ghar Mountains and the Shaikh Budīn Hills (fig. 2), respectively, which are irregular masses that interrupt the linear trends of the two ranges. The northeastern limb of the Bhittanni Range, which trends southeastward, is a strongly dissected elongate domal area that is connected with the southwestern limb by a curving cliff-like area of uplift. The southeast face of the southwestern limb is steep and is dissected by transverse streams. South of Manzai, at the reentrant of the Gumal River, the upland areas are less uniform in appearance, and southward the regional structural trends change from

FIGURE 2—Village of Paniāla in northeastern D.I. Khān District. Immediate foreground and distant slopes of Shaikh Budīn Hills show natural condition of sparse vegetation. Around Paniāla substantial amounts of ground water are available from springs and kārezes. These irrigate date palms and gardens beneath the palms, as well as adjacent fields of small grains.

southwestward to southward. In the latter area, the Shirāni Hills, the hills slope steeply upward from the edge of the plain, and behind the first crest is a series of southward-trending ridges which rise in succession westward to the foot of the Sulaimān Range.

At most places in the District, the upland areas are separated from the plain by coalescing gravel and sand fans (fig. 3). The major belts of such fans are immediately below the valley between the Khisor and Marwat Ranges; adjacent to the mouth of Tānk Zām; at the mouth of the Gumal River gorge, southwest of Manzai; and at the mouths of the Khora River and Chaudhwān Zām gorges, near Darāban and Chaudhwān.

The gravel fans grade in slope southward and eastward into the piedmont plain (pl. 1). This plain is a relatively smooth surface into which modern drainage channels (nālas) are being incised. The plain ends rather abruptly at the river lowlands.

The river lowlands (fig. 4) show at least three stages of flood-plain evolution. The present river level and the active flood plain are relatively limited, but in this area the river is actively meandering. The modified or abandoned flood plain is somewhat higher and possibly may be separated from a third level, equivalent to the bar uplands of the Punjab. The western edge of this latter surface, or of the modified flood plain, is clearly delineated by low bluffs near Band Kurai and near Ramak to the south. Parts of this surface are covered with alluvium from the major nālas that cross them.

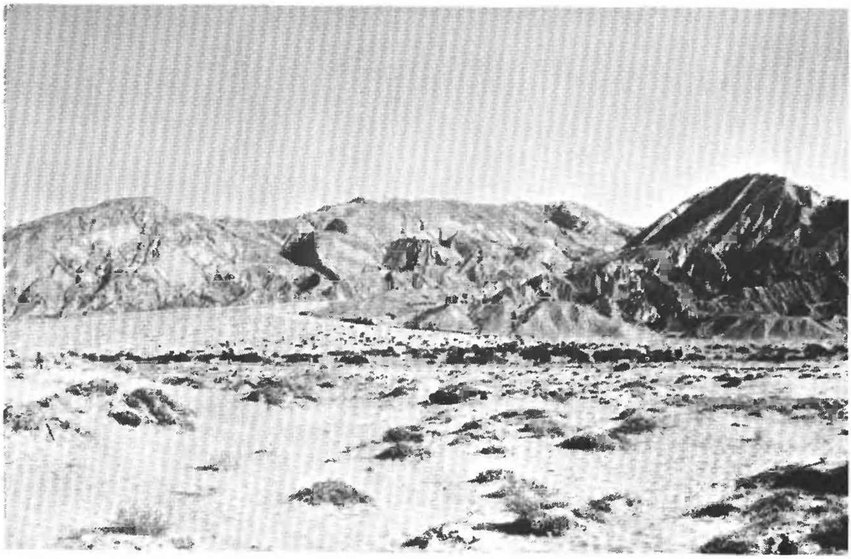


FIGURE 3—Dry, bare western flank of Shaikh Budīn Hills. Rocks are of Cretaceous and Jurassic age and are severely distorted. Large sand fan debouches from valley along axis of syncline. Canyon at right has small drainage basin and almost no fan. Foreground shows sparse growth on rolling sand plain and a little scrub near toe of fan.

FIGURE 4—Indus River and its active flood plain from the northeastern slope of Khisor Range. River is beginning low flood in May. The large volume of flow threads through a series of braided channels cut in the plain, which is inundated at high flood. Active flood plain is covered with a dense growth of grasses and cattails. Thick growth of palms in gully at right foreground is sustained by spring flow. Here the shattered consolidated rocks in the front of the range are otherwise almost devoid of vegetation.

ALTITUDE

The lowest point in the District is at the south end, on the Indus River, and is approximately 500 feet above mean sea level. The highest point is 4,516 feet above mean sea level in the Shaikh Budīn Hills.

The altitude in the major part of D.I. Khān District ranges between 500 and 1,000 feet, and most of the land-surface gradients are low. Near the mountains, gradients are steepest on the gravel fans and diminish toward the Indus River. Thus, in the north, the gradients range from about 17 feet per mile in the upper area through a range of 5 to 10 feet per mile in the midslope area to 5 feet per mile or less near the flood plain of the Indus. In the south, the piedmont plain is narrower and slopes eastward at about 15 feet per mile. In the flood plain of the Indus, the gradient along a straight line approximates that of the Indus River, between 1 and 1.5 feet per mile.

DRAINAGE

In D.I. Khān District, the master stream is the Indus River. Tributaries that enter the Indus through the District arise both west of and within the District. The several large drainage basins that debouch from the western mountains occupy a large part of western West Pakistan and the adjacent part of Afghanistan and sustain perennial streams. These stream channels for the most part appear to be controlled by the geologic structure of the region. Where the streams pass through the mountains, however, they have the appearance of superposed or antecedent streams, because they transect the regional geologic structure. Small details of the stream routing, however, are consequent in origin.

The flow of the perennial streams and of those intermittent streams that rise in the mountains varies through a wide range. (See "Surface Water.") Low flow commonly is only a few cubic feet per second, but when snowmelt or thunderstorms occur, the flow increases rapidly to peaks of several thousand cubic feet per second of water heavily laden with suspended sediment, which floods the piedmont plain and lowlands in the District.

D.I. Khān District is laced with a complex of stream channels, only a part of which are shown on plate 1. Some of these are the distributaries of the mountain streams, and the rest head on the piedmont plain. All are intermittent except those sustained directly by runoff from the mountains. Most of the natural stream channels show evidence of active development as indicated by their cutting into the piedmont plain. Steep-walled channels are accompanied by dendritic drainage patterns in most of the District, but they appear to be most prominently developed in the area north of Tānk. In some of the major drainageways, two or more levels present in streambanks appear to indicate that the current pattern of active erosion is of relatively recent origin. Superimposed on the natural drainage system are numerous diversion channels built by farmers to utilize both perennial flow and floodflow. Although these are common throughout the District, they are most dense in the area from Takwāra northwestward to the mouths of the Gumal River and Tānk Zām. Such diversion works are generally temporary and may be destroyed when flooding from the mountains occurs. During such floods, the major streams overflow, and sheet flooding of interstream areas occasionally devastates fields, roads, and houses.

CLIMATE

According to Wladimir Koppen's classification of climate (Trewartha, 1954, p. 381–383), D.I. Khān District lies in an area of hot semiarid steppes. The climate is classified as hot because the annual average air temperature is in excess of 64.4°F. Most precipitation occurs as rain during the monsoon season from July through September. The long intervening season is generally dry, but it is broken by a modest winter and spring rainy season.

PRECIPITATION

Precipitation in and west of D.I. Khān District is the source of part of the recharge to the water-bearing formations of the District; therefore, an understanding of the distribution and characteristics of the precipitation is essential to the interpretation of the areal hydrology.

Within the region around D.I. Khān District, the annual precipitation increases northward along the valley of the Indus River and the Indus Plains—from about 6 inches at Dera Ghāzi (D.G.) Khān to more than 10 inches at Miānwāli. (See also Sheikh and Hussain, 1960). In the hills and mountains north and west of the Indus Plains, the annual rate of precipitation is party controlled by topography; in general, the higher areas receive more precipitation than the lowlands. Thus, D.I. Khān town, in the Indus River lowland, receives about 9.2 inches annually, whereas Mūsa Khel Bāzār, in the Sulaimān Range to the southwest, receives more than 16 inches. Figure 5 shows the regional distribution of precipitation.

Most of the precipitation that falls on the District and the drainage basin to the west occurs as rain. In the highest parts of the Sulaimān Range, however, some snow accumulates during the relatively brief winter and subsequently contributes to the flow of the larger streams. The rainfall generally occurs as intense localized thunderstorms, but regional storms occasionally result in widespread, relatively uniform rains.

The annual and monthly variations in precipitation in D.I. Khān District and the surrounding area are shown in the records for the several stations. Although some of these records are quite long,

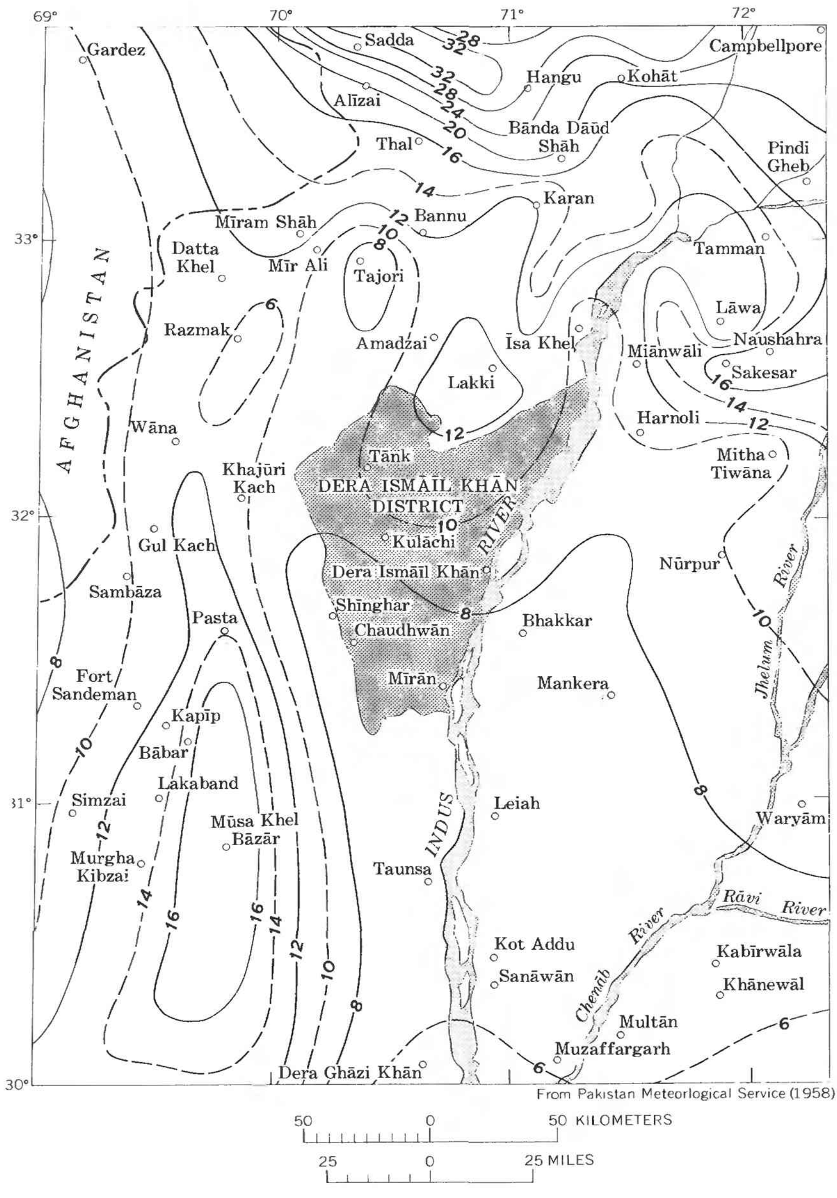


FIGURE 5—Regional distribution of normal annual precipitation, in inches, in and near D.I. Khān District. Based on normals in 1940.

most of the data immediately available were fragmentary and were obtained from several sources. The Meteorological Service of Pakistan reports for a number of primary stations and also obtains records from stations maintained by other government agencies. The Irrigation Branch, PWD, maintains rain gages at many of its installations, such as the Pahārpur Canal headworks at Chasma; and the Surface Water Circle of WASID maintains climatological observation stations near some of its gaging stations as part of its hydrologic data network. Rainfall data for many of the main towns and smaller villages are published in the Gazette of Pakistan. These sources were canvassed to abstract the following data.

Table 1 shows the annual amounts of precipitation recorded at

TABLE 1.—*Annual total precipitation, in inches, at nine stations in and near D.I. Khān District, West Pakistan*

[Source of records: IB, Irrigation Branch of PWD; MS, Meteorological Service; SW, Surface Water Circle, WASID, WAPDA; GP, Gazette of West Pakistan]

Station	Chasma Headworks	D.I. Khān	Girsar	Khajūri Kach	Kulāchi	Leiah	Miānwāli	Tānk	Wāna
Source of records	IB	MS	IB	SW	GP	SW	SW	SW	MS
Altitude ft	620	570	585	2,250	710	490	620	850	4,460
Year									
1941		12.49							5.20
1942		13.27							6.68
1943		[1]6.5							7.03
1944		7.80							6.12
1945		[1]3.4							[1]4.0
1946									
1947		1.97							4.29
1948		10.50							
1949		4.12							
1950	7.90	7.07	9.98						
1951	8.46	6.20	6.16						
1952	5.38	2.12	8.65						6.66
1953	9.06	9.08	12.59						
1954	11.51	7.21	6.99						6.81
1955	9.83	10.85	13.40						8.34
1956	14.40	24.21	16.43						
1957	10.50	14.81	15.43						11.41
1958	9.99	8.18	7.60						5.63
1959	20.63	19.34	16.16						11.67
1960	5.38	10.91	9.85						7.18
1961		9.31						13.33	
1962		10.45			[1]7.3	[1]4.6	[1]15.0	9.61	15.57
1963				10.27		9.13	14.82	8.84	

[1] Annual total for incomplete year's record where missing monthly total is estimated to be small.

nine stations in the D.I. Khān region; only four had available records of appreciable length. The record at D.I. Khān is known to begin in 1880 and extends to the present. The normal precipitation at that station for 1880–1940 was 9.09 inches, and the corrected average for the periods 1941–45 and 1947–62, inclusive, was 9.52 inches. The weighted average annual precipitation at D.I. Khān is 9.20 inches for the period 1880–1962. The monthly distribution of average precipitation at D.I. Khān town is shown in figure 6; the annual total precipitation for 1941–62 is shown on plate 2A.

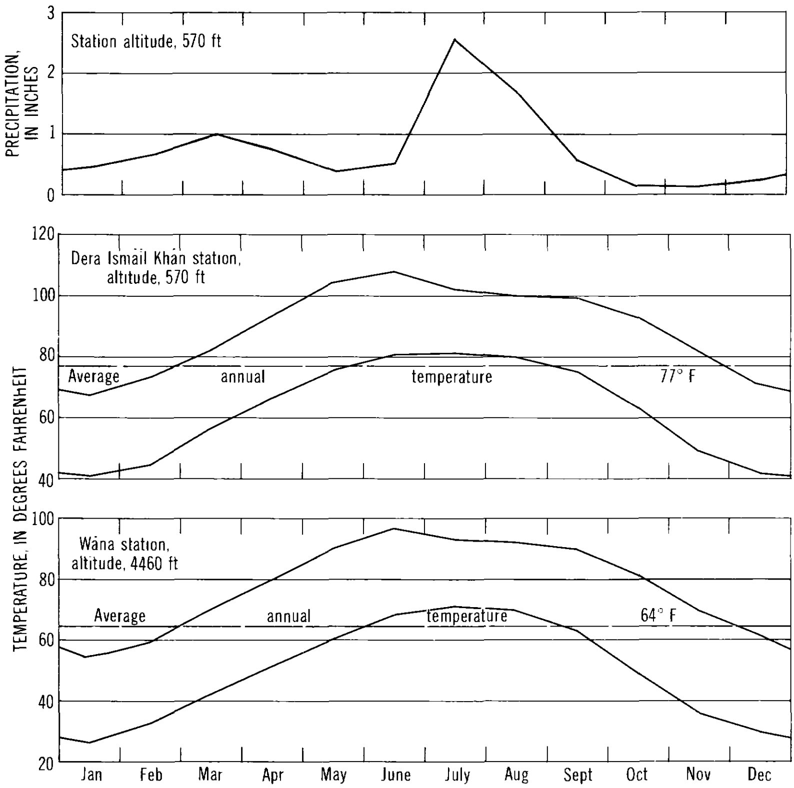


FIGURE 6—Monthly average precipitation at D.I. Khān, 1880–1962, and monthly average maximum and minimum air temperatures at D.I. Khān and Wāna, 1941–62.

At Wāna, in the hilly area to the west of D.I. Khān District, the average annual precipitation for 1941–62 is 7.04 inches, based on the sum of the monthly averages for that period. The available records for the remaining stations were too short to provide useful averages. Table 2, however, gives comparative data for seven of the stations for 1962 and shows the generally erratic distribution

TABLE 2.—*Monthly and annual precipitation in inches, at seven stations in and near D.I. Khān District, 1962*

[Source of records: MS, Meteorological Service; SW, Surface Water Circle, WASID, WAPDA; GP, Gazette of West Pakistan]

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Chaudhwān (GP)	----	----	----	----	----	----	4.00	1.05	0.30	0.06	0.00	0.50	-----
D.I. Khān (MS)	0.07	1.17	1.10	0.00	0.68	0.10	.79	4.16	.73	1.15	.03	.47	10.45
Kulāchi (P)	.60	.69	1.99	.35	----	----	.96	1.90	.10	.00	.30	.38	[1] 7.28
Leiah (SW)		.07	1.20	.00	.26	.00	2.04	.11	.49	.00	.13	.27	[1] 4.57
Miānwāli (SW)		.29	2.91	.62	.79	.93	.98	4.75	2.15	.00	.58	.92	[1] 14.92
Tānk (SW)	.23	1.06	1.21	.79	.08	.28	2.20	2.53	.22	.08	.52	.41	9.61
Tānk (GP)	.75	.76	1.95	.70	----	----	1.65	2.00	----	.10	.47	.42	[1] 8.80
Wāna (MS)	.00	1.10	5.89	.90	.65	2.15	2.69	.00	1.12	.37	.00	.70	15.57

[1] Annual total for incomplete year's record where missing monthly total is estimated to be small.

of precipitation in the region. Plate 2B shows the recorded monthly precipitation at three stations for the period May 1961 through April 1964. These precipitation data are provided for comparison with the records of streamflow and the fluctuations of water levels in observation wells.

The records cited demonstrate that year-to-year precipitation is extremely variable. At D.I. Khān, for example, 2.12 inches of rain fell in 1952 and 24.21 inches, in 1956. Moreover, there is considerable difference among stations for individual months; but, in general, when a wet month occurs, all stations record more precipitation. Superimposed on the year-to-year variability, there is a long-term trend that includes both periods of below-normal precipitation (relative drought) and periods of above-normal precipitation. Plate 2C shows the cumulative departure from average annual precipitation during 1941–62 at D.I. Khān. This figure indicates that the period 1942–54, inclusive, was one of generally below-normal precipitation and was preceded and followed by periods of generally above-normal precipitation. This pattern of dry and wet years is similar to the patterns for some stations in the southwestern United States during the same period (Thomas, 1962, 1963).

TEMPERATURE

Seasonal and daily temperatures in the District fluctuate widely. Lowest temperatures occur in January, and although freezing temperatures are not uncommon, average January low temperatures are near 40°F. Annual highest temperatures occur in June when the average maximum temperatures range between 107° and 112°F. The average annual temperature at D.I. Khān is 77°F. (fig. 6). In the mountain areas to the west of the District, temperatures are somewhat lower owing to the higher altitude. At Wāna, for example, the average annual temperature for 1941–62 was 64°F (fig. 6). At both stations a sag in July in the average monthly maximum curve reflects inflow of cooler air at the onset of the monsoon.

RELATIVE HUMIDITY

In the lowland along the Indus River, the average relative humidity generally stays at about 70 percent during most of the year and may decrease appreciably during the very hot dry months of May and June. In the upland parts of D.I. Khān District, however, relative humidity remains low during most of the year and is appreciably more than 50 percent only during the monsoon. At Wāna, for example, the monthly average relative humidity was 29 percent in June 1963 and 53 percent in August 1963.

EVAPORATION

Owing to the prevailing high temperature, potential evaporation in D.I. Khān District is greatly in excess of precipitation, a condition which limits both the supplies of water available from streams and those supplies available for recharge to the ground-water reservoir in the District. Table 3 lists the fragmentary records of evaporation available in the vicinity of D.I. Khān District. (See also fig. 14.) These records indicate that long-term annual evaporation from an evaporation pan may be greater than 100 inches in the Indus River lowland and on the order of 130 inches in the western part of the region. Thus, the potential evaporation and the evaporation from free-water surfaces may be on the order of the rate cited by Hiatt (1964) for Khānpur and Bahāwalpur, that is, 60 to 70 inches. This rate is eight to nine times greater than the annual precipitation.

GROWING SEASON

In the D.I. Khān District, as in most of the Indus Plain region, the growing season is not limited by killing frosts, which are rare. The cropping practice in the District, however, is governed by the distribution of temperature, and crops are divided into those raised in summer (kharif) and winter (rabi). Commonly, the mild weather of the fall and winter months permits the growing of sensitive rabi crops in much of the District, whereas, kharif crops are mainly heat resistant and are grown only in areas of assured water supply.

DEVELOPMENT

D.I. Khān District is an agricultural and grazing region. Industrial and manufacturing development is directed mainly to supply and maintenance of farm and governmental needs. The District is relatively isolated from adjacent parts of West Pakistan. Because of this isolation and historical circumstance, the District is not fully developed. Maximum development has taken place where water has been readily available and where the agricultural population has had protection from independent hill tribesmen, whose reputation for aggression, even in recent years, has inhibited development of parts of the District. The population is concentrated in larger towns and villages, some of which are walled for defense. From these, the people go out to work in the surrounding fields.

AGRICULTURE

The principal source of income in the District is the land and its products. Of the 2.2 million acres, about 1.5 million appear to be culturable, but only part of the culturable land is farmed. Through-

TABLE 3.—*Available records of evaporation, in inches, at three stations near D.I. Khān District, 1962–64*

[Data from Surface Water Circle, WASID. WAPDA]

Station	Station altitude (ft)	Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Khajūri Kach (on Gumal River)	2,250	1963	----	----	----	----	----	26.42	17.86	[1]14.94	13.10	9.35	5.14	4.40	----
		1964	2.72	3.87	8.23	10.54	----	----	----	----	----	----	----	----	----
Leiah (on Indus River)	490	1962	----	3.95	4.50	8.04	----	15.59	12.53	[1]8.45	8.25	6.60	4.05	2.58	----
		1963	[1]3.00	4.18	5.99	8.55	10.61	13.18	[1]11.54	10.70	10.90	8.59	3.91	2.91	94.16
		1964	2.65	4.83	7.66	10.51	----	----	----	----	----	----	----	----	----
Miānwāli (on Indus River)	620	1962	----	1.76	2.88	5.18	13.70	16.37	14.02	11.21	8.36	7.22	4.20	2.35	----
		1963	3.09	3.39	5.85	9.15	10.82	15.64	14.90	12.45	10.24	8.67	3.82	2.92	100.94
		1964	2.38	3.55	6.98	9.55	----	----	----	----	----	----	----	----	----

[1] Estimated from incomplete monthly record.

out the District there is evidence that much of the land has been farmed at one time or another but then left fallow, either because of deficient water or because other lands were subsequently tilled. The principal source of water is the Indus River. About 100,000 acres is under the command of the Pahārpur Canal, but generally only about half of this land is actually farmed and watered from the canal. In addition, perhaps 50,000 acres is watered by the inundation (sailaba) method in the lowlands adjacent to the river. Above the river lowlands, small areas, such as at Paniāla (fig. 2), are watered from infiltration gallery (kārez) sources, and small areas are adequately irrigated from the perennial flow (kālāpani) of mountain streams, such as the Tānk Zām, Gumal River, and Khora River (called Darāban Zām in the piedmont plain). In the rest of the District, from 0.25 to 0.5 million acres are farmed using rainfall alone (baranī) and with flood runoff from the mountain streams (rūd kohi). In recent years additional lands have come under cultivation through the development of government and private irrigation wells.

The crops raised are largely those needed for immediate local use, and the seasonal distribution of temperature determines the kinds of crops planted. Fraser (1958, chap. 10) gives an excellent discussion of the soils distribution and crop statistics of the District and states that more than 80 percent of the kharif crop in 1953 consisted of millet and other cereals but also included small acreages of other crops, such as sugarcane and cotton on a total of about 83,000 acres. The rabi crop in 1954 was planted on about 0.22 million acres and consisted mainly of cereals and gram and other pulses. Oil seeds, vegetables, fodder, and other crops were included in the rabi crop. The large difference in the acreage between the two cropping seasons is due to the planting during rabi season of large upland areas to cereals and pulses in order to make use of the winter rains. These upland areas may receive rain adequate to mature a crop but have little prospect of such moisture during the kharif season.

WATER UTILIZATION

The methods of water utilization in D.I. Khān District range from the very primitive to the very modern and are governed both by the availability of water and the relative cost of development.

MUNICIPAL AND DOMESTIC SUPPLIES

The bulk of the water used for culinary and other domestic purposes is obtained from individual sources, such as dug (open) wells, hand pumps on shallow driven wells, ponds that store runoff, the river, and irrigation ditches or perennial streams. Along the Indus

River flood plain and adjacent terraces, shallow water is readily available, but in the upland areas (for example, at Kirri Shamozai) wells have been dug as deep as 100 feet or more to obtain domestic supplies. In broad areas of the District the shallowest water was found to be saline, and the population has had to depend on water stored in open ponds that supply all needs. Data supplied in this report can aid in alleviating the shortage of domestic water in a part of the area.

Municipal supplies are provided from surface-water sources at Tānk and from drilled wells in part of the town of D.I. Khān and in the village of Paroa.

IRRIGATION

Sailaba irrigation along the flood plain of the Indus River does not assure dependable yields because of the variability of riverflow —in some years recurrent floods may destroy crops already planted. On the other hand, in dry years small floods may not sufficiently cover all the available sailaba lands.

Rūd kohi irrigation near the streams on the piedmont slope of the District is similarly undependable. In dry years the water supply is deficient, and in some years flash floods destroy crop plantings.

Irrigation systems based on the perennial flow from the mountain streams utilize all the low flow and part of the floodflow and spread the water over a broad area. Although the water provided by the ditches is carefully used, the distribution systems largely are earthen ditches and partly are natural drainageways that absorb much of the flow. These systems like the rūd kohi are subject to occasional flood damage. For a description of kārez irrigation see "Glossary."

The Pahārpur Canal is the best developed of the surface-water sources. It was opened in 1934 as a project of the Irrigation Branch, PWD, and subsequently has been extended and otherwise improved. The canal takes water from the Indus River and is an inundation canal; that is, its flow depends on the natural river stage. Its flow is diverted from the Indus River at Chasma Headworks and is routed through a semicontrolled waterway to Bilot Headworks where the Pahārpur Canal proper leaves the Indus River flood plain and flows southward across the modified or abandoned flood plain. The canal has 256,000 feet (49½ miles) of main-line channel, four or more distributaries, and numerous minor distributaries, all of which are equipped with concrete control works. The canal and its distributaries, however, are not lined, and leakage from them has contributed to rising water levels in the adjacent lowlands. The canal serves lands that extend from near Bilot southward to about 6 miles south of D.I. Khān town.

In recent years, starting in the mid-1950's, an increasing number of drilled irrigation wells have been installed both by private individuals and government agencies. These tubewells, are pumped with turbine pumps that are powered with electric motors. The tubewells have been installed mainly in the lower piedmont slope above the Pahārpur Canal west of D.I. Khān town and in the flood plain south of the town. In terms of the local economy, tubewells are very expensive, but their relatively large yields contrast strongly with the low yields of the dug (Persian) wells (figs. 7 and 8) that supply both main and supplementary irrigation water in parts of the District and in the Punjab as a whole.

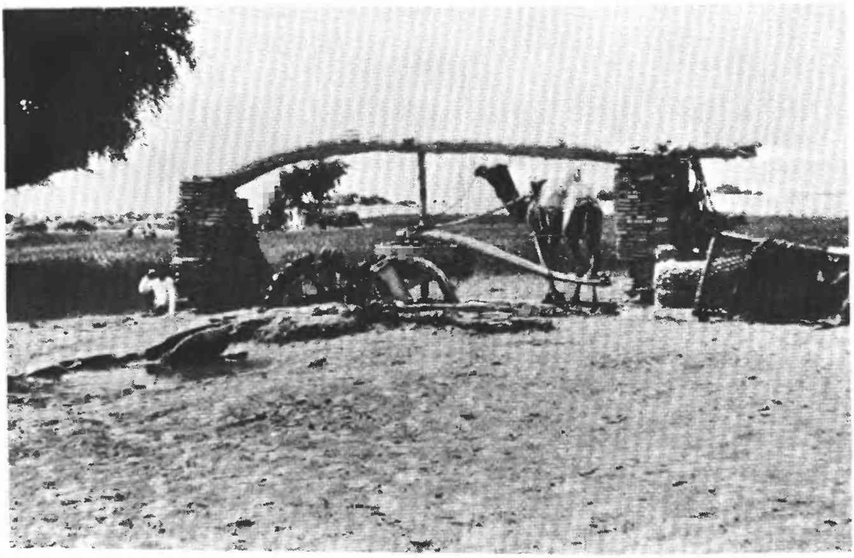


FIGURE 7—Persian well, a widely used type of open well in West Patkistan. Wells generally are shallow but at some places are as deep as 200 feet. (See "Glossary.") Naturally bare sand in foreground and background contrast strongly with irrigated crops. Photograph by S. A. T. Kazmi.

GEOLOGY RELATED TO THE GROUND-WATER RESERVOIR IN D.I. KHĀN DISTRICT

The ground-water reservoir in D.I. Khān District consists mainly of unconsolidated to semiconsolidated rocks of Quaternary age. Those rocks laid down during the late Pleistocene and Holocene (Recent) epochs immediately underlie most of the District, and their composition and distribution have been influenced both by the character of the adjacent older rocks and by the crustal move-

FIGURE 8—Well GZ-2 pumping about 450 gallons per minute under test. This test tubewell demonstrated the availability of ground water in western D.I. Khān District. The water was charged with silt, partly because the pipe perforations and gravel in envelope were too large. *Bare ground and sparse vegetation in this part of the upper piedmont plain and lower alluvial fan are typical of much of D.I. Khān District.*

ments that began in middle Tertiary time and have continued into the Holocene.

Older consolidated rocks that range mainly from late Paleozoic to early or middle Pleistocene age crop out in the northern part of the District and in the tribal areas immediately west of the District (pl. 1). Although they probably contain aquifers, the main importance of the consolidated rocks is that they are both past and present sources of Quaternary erosional debris. Their chemical composition, moreover, influences the chemical quality of both the surface water that recharges the Quaternary fill and the ground water that moves through the fill. A few data imply that the fill receives some recharge from the youngest consolidated rocks by interformational leakage.

CONSOLIDATED ROCKS

All known consolidated rocks in the area of D.I. Khān District are of sedimentary origin and are described below according to their ages and generic types.

ROCKS OF PALEOZOIC AGE

The oldest rocks in D.I. Khān District are reported to be of Cambrian age (Bakr and Jackson, 1964) and crop out in a small area at the southeast edge of the Sūr Ghar Mountains. These rocks were not studied by the writers but are reported to include sandstone, limestone, and possibly evaporites such as gypsum and salt. As elsewhere in the Punjab (Greenman and others, 1967) where unconsolidated deposits abut the Cambrian, the quality of ground water in the unconsolidated fill of northern D.I. Khān District does not reflect the presence of Cambrian evaporites.

Rocks that are Permian and possibly late Carboniferous in age crop out in the southeastern escarpment of the Khisor Range. Bakr and Jackson (1964) include all these rocks in the Permian system. Observations of the rocks at Bilot Headworks indicate that dark-gray, dense, hard limestone rich in *Productus* sp. crops out 250 feet above the Indus River and also occurs in scree boulders originating above that level. Near river level at Bilot Headworks, a zone of small pink to red boulders of igneous rocks was found associated with sandstone and red shale in the face of the bluff. The general appearance and composition of the boulder zone strongly suggest that it may belong to the boulder bed of the Talchir Series of late Carboniferous age. At Chasma Headworks, from river level to 900 feet or more above the river, is a section of sandy limestone and limy sandstone underlain at river level by green to black fissile shale. The limestone is relatively rich in single and communal corals, crinoidal(?) debris, and other fossils that identify the section as Permian, according to Wadia (1961) and Krishnan (1960). At both Bilot and Chasma Headworks, tectonic distortion and shattering of the rocks did not permit the distinction of stratigraphic relations. Aerial photographs of the Chasma area indicate that much of the east face of the Khisor Range is flexed downward and at places is step faulted so that the section may be repeated.

Most of the Permian rocks have a low permeability, but springs rise at a few places where joints or faulting provide secondary permeability. (See fig. 4.)

ROCKS OF MESOZOIC AGE

Rocks belonging to the Triassic and Jurassic systems crop out in the rugged upland areas of the Shaikh Budīn Hills and the Sūr Ghar Mountains. The area of outcrop extends along the upper part of the backslope of the Khisor Range, where the strata dip steeply northwestward. These rocks include both limestone and clastic beds. In the section described by Wadia (1961, p. 260) in the Shaikh Budīn Hills northeast of Chunda, a chaotic complex of iron-rich sandstone, shale, and limestone was found above the large alluvial fans that mark the edge of the alluvial basin in D.I. Khān District. Debris in the fans contains much limestone from the beds that overlie the sandstone section. W. R. Hemphill and A. H. Kidwai (written commun., 1964) indicate that both upland areas probably contain rocks of Cretaceous age; Bakr and Jackson (1964) map such rocks in the Shaikh Budīn Hills. At the north side of Shaikh Budīn, a narrow outcrop of steeply dipping Cretaceous rocks was found to be overlain by rocks apparently belonging to the Siwalik Group. The rocks of Cretaceous age include shale beds rich in *Belemnites*. In both upland areas, complex structural distortion of the rocks of Mesozoic age is apparent.

West of D.I. Khān District and within the drainage basins that contribute to the District, limestone of Jurassic age comprises the highest part of the Sulaimān Range. On the east flank of the range, limestone, shale, and sandstone of Cretaceous age dip eastward beneath rocks of early Tertiary age. Bakr and Jackson (1964) indicate that the rocks of Jurassic and Cretaceous age extend northward from the Sulaimān Range through the drainage basins of the Gumal River and Tānk Zām in the area west of the Bhittanni Range.

ROCKS OF CENOZOIC AGE

The rocks that adjoin the unconsolidated fill on the western, northwestern, and north-central borders of D.I. Khān District were deposited during Tertiary and early to middle Pleistocene time. As in other parts of West Pakistan, these rocks are divided into a section of marine epicontinental origin and an overlying section of fluviatile continental origin. Although rocks from both sections have contributed debris to the unconsolidated fill in the District, the marine section probably has the greatest effect on the chemical quality of water in the District, and the section of continental rocks probably has contributed most of the coarse-grained clastic debris that makes up permeable zones in the fill.

The marine section observed in the valley of the Khora River from the edge of the piedmont plain to the vicinity of Drazinda consists of a sequence of alternating limestone, shale, and sandstone that lie in a syncline trending northward. Parts of this section are rich in Foraminifera, such as *Nummulites*, and are the source of the transported specimens found in the drill cuttings from test holes 2A, 4, 6B, and 16 in the unconsolidated fill. The presence of these stream-transported and redeposited *Nummulites* fossils in test hole 4 indicates that marine rocks of Tertiary age also crop out on the back slope of the Khisor Range, east of Paniāla.

The marine rocks of Tertiary age have a strong influence on the chemical quality of water in D.I. Khān District, because they are a source of sulfate minerals. W. R. Hemphill and A. H. Kidwai (written commun., 1964) state that some of the shale in the lower Tertiary south of Drazinda contains celestite (strontium sulfate). Shale exposed in hillsides near Drazinda were observed to be encrusted at places with a white mineral efflorescence, presumably sulfate minerals. Bedded gypsum was found in the right bank of the Khora River gorge, west of Darāban, in rocks that appear to be a transitional zone from marine to continental rocks. Similarly, a partly dissolved fragment of gypsum float was found in the Gumal River bed at the gaging station near Kot Murtaza Rest House. The softness and solubility of the fragment show that it originated nearby and could not have been transported far.

The section of consolidated clastic continental deposits is part of the Siwalik Group, which ranges in age from middle Miocene to early or middle Pleistocene. (See table 4.) These rocks are shown on plate 1 as Miocene-Pliocene, modified from Bakr and Jackson (1964), who include inseparable beds of Oligocene and Pleistocene age under their map symbol, Tpm. They indicate a maximum thickness of as much as 15,000 feet, whereas the generalized thicknesses given by Wadia (1961) and by Krishnan (1960) in the type sections are on the order of 16,000–23,000 feet for the Kamlial stage through the boulder conglomerate only.

Parts of the Siwalik Group were observed in the gorges of Khuiwāli (Nāla), southwest of Gurwāli, Chaudhwān Zām, and the Khora and Gumal Rivers, and in the vicinity of Pezu. In the southwestern area, the section observed is thick and consists mainly of massive crossbedded sandstone that contains some conglomerate and an overlying boulder conglomerate that in general dips eastward beneath the piedmont plain. At the mouth of the Khora River, a part of the section appears to cut out by faulting and is relatively thin. In the disturbed area of the fault is a small wedge(?) of deep red rocks that may be part of the Kamlial stage and that contain the bedded gypsum described above. At this location the boulder conglomerate contains an internal unconformity that appears to be related to movement along the adjacent fault. The upper part of the bed contains small boulders, cobbles, and pebbles that appear to grade upward into the overlying gravel fan and piedmont deposits.

To the north, strongly deformed cemented boulder beds form the walls of the gorge of the Gumal River west of Kot Murtaza. In the asymmetric spur that extends southward from Manzai, semiconsolidated boulder and gravel conglomerates are well exposed, especially on the western slope. Test holes 5 and 5A were drilled in the less consolidated boulder beds or in debris immediately derived from them.

TABLE 4.—*Approximate correlation of Middle to Late Tertiary and Quaternary rocks in northern West Pakistan*

[This correlation chart is not intended to be definitive, but rather a compromise among several sources of data (Flint, 1951; Wadia, 1961; Krishnan, 1960; and Bakr and Jackson, 1964). It is intended to show the general age and positional relations of the several rock units in the general vicinity of D.I. Khān District, as well as their lithologic character]

Period	Epoch		Stratigraphic unit			Lithology	Remarks
Quaternary	Holocene					Alluvium in modern river flood plains and terraces; alluvium in beds of modern tributary drainage channels; eolian sand.	Also called newer or younger alluvium.
Quaternary	Pleistocene	Late				Redeposited silts, sand, and gravel.	Also called older alluvium; partly derived from Potwar deposits. Constitutes much of the upper piedmont deposits along base of mountains adjacent to Punjab Plain. Equivalent to fourth glacial advance in Kashmir.
Quaternary	Pleistocene	Late				Erosional interval.	Equivalent to third interglacial interval in Kashmir.
Quaternary	Pleistocene	Late			Potwar Loess	Loess-like silt and gravel.	Pluvial interval equivalent to third glacial advance in Kashmir. Probably called older alluvium at places.
Quaternary	Pleistocene	Middle				Erositional interval.	Interpulvial interval equivalent to the long second interglacial interval in Kashmir.
Quaternary	Pleistocene	Middle	Siwalik Group	Upper	Boulder conglomerate	Coarse boulder and gravel conglomerate, thick earthy clay, sand, pebbly grits that grade up into older alluvium.	Pluvial interval equivalent to second glacial advance in Kashmir.
Quaternary	Pleistocene	Early	Siwalik Group	Upper	Pinjor zone	Coarse grit, sandstone, and conglomerate. Includes(?) Bain boulder bed of T. O. Morris.	Interpluvial interval equivalent to the first interglacial interval in Kashmir. Boulder conglomerates appear generally to be transgressive.
Quaternary / Tertiary	Pleistocene / Pliocene	Early	Siwalik Group	Upper	Tatrot zone	Soft sandstone, drab clay, and some conglomerate.	Pluvial interval equivalent to first glacial advance in Kashmir. Wadia and Flint indicate Siwalik rocks transitional from Pliocene to lower Pleistocene.
Tertiary	Miocene	Late	Siwalik Group	Middle	Dhok Pathan zone	Gray, white, and brown sandstone; clay and shale of drab color.	
Tertiary	Miocene	Late	Siwalik Group	Middle	Nagri zone	Massive, thick gray sandstone and subordinate shale.	
Tertiary	Miocene	Middle	Siwalik Group	Lower	Chinji stage	Bright-red nodular shale and clay with some gray sandstone and pseudoconglomerates.	
Tertiary	Miocene	Middle	Siwalik Group	Lower	Kamlial stage	Dark-red, hard sandstone; red and purple shale; and pseudoconglomerate.	May include bedded gypsum. Beds similar to this found in area east of Sulaimān Range at mouth of Khora River.
Tertiary	Oligocene		Nari Formation			*Limestone and shale.*	Upper source of marine fossils found redeposited in unconsolidated rocks in piedmont areas adjacent to Punjab Plain.

In the low ridge that expresses an anticlinal fold in the Siwalik rocks east and southeast of Kot Āzam, gravel beds are intercalated with beds of silty clay that can be traced over distances of several miles along the stream channels that breach the ridge. The clays in this local section are, in the megascopic sense, identical with those of the adjacent unconsolidated deposits of the piedmont plain; the relation between these clays will be discussed in the section "Unconsolidated deposits."

Northeastward from Manzai the character of the Siwalik Group changes. First, the rocks adjacent to the fill appear to be older than those in the southwestern part of the District. In the vicinity of Pezu, much of the Siwalik section appears to be as described for the Dhok Pathan zone and possibly as described for the Tatrot zone. Most of the beds observed north and west of Pezu consist of sandstone and semiconsolidated sand intercalated with thick beds of drab-colored shale or clay (fig. 9). Test hole 1, and possibly

FIGURE 9—Tilted Tertiary alluvial deposits and Pleistocene glacial outwash north of Pezu and northwest of Shaikh Budīn Hills. Sand and clay from this area have been redeposited in the adjacent piedmont plain, and consequently the older alluvium in the District closely resembles the fluvioglacial materials.

others, may have penetrated part of this section, but such beds could not be positively identified because their lithology and that of the overlying fill are very similar.

In addition to the apparent difference in age of the rocks near Pezu, the rocks of the Siwalik Group appear to become finer grained toward the northeast. W. R. Hemphill and A. H. Kidwai (oral commun., 1963) confirmed that the grain size within given units appears to diminish northeastward. This trend in grain size within the Siwalik Group is considered significant with regard to the distribution of the unconsolidated rocks of the piedmont plain.

Tectonic distortion of the Siwalik rocks, as observed and as pointed out by W. R. Hemphill and A. H. Kidwai (oral commun., 1963), consists mainly of folding that involves the entire section of rocks at least as young as early to middle Pleistocene. The folding also involves older consolidated rocks of the Sulaimān Range and of the Khisor Range. The folding was caused by relative movement that was mainly eastward near the Sulaimān Range and was mainly southeastward in the eastern Bhittanni-Marwat-Khisor Range area. Most faults that resulted from the movement are moderate to low-angle thrusts. Exceptions are the several smaller cross faults that transect regional structures, as in the eastern Khisor Range, the high-angle faults that are inferred to be associated with the Sūr Ghar-Shaikh Budīn upland areas, and the fault that bisects the domal area in the Bhittanni Range between Pezu and Bain. As a result of these movements, the Siwalik Group dips beneath the unconsolidated deposits at almost all locations westward and southward from Pezu to the vicinity of Gurwāli and beyond.

Rocks of the Siwalik Group not only have been sources of the clastic debris that contributed to the unconsolidated rocks in D.I. Khān District but also appear to be involved in the movement of ground water in the District. That the permeable beds can receive recharge and transmit water is indicated by their physical character and by the occurrence of springs at favorable locations in the hill areas. The boulder conglomerate and related beds along the western side of the District, although strongly cemented at places, appear to be relatively permeable and are so situated that they can receive recharge both from streamflow across them and from precipitation. The ground water then moves downdip beneath the unconsolidated deposits, and the latter receives recharge downgradient by upward leakage from the older rocks. That this mechanism functions appears to be confirmed by the flow system in the fill and by the chemical quality of water samples from depth in several test holes.

UNCONSOLIDATED DEPOSITS

The unconsolidated deposits in D.I. Khān District range from middle(?) or later Pleistocene to Holocene in age (table 4). They include possible equivalents to the Potwar Loess; the redeposited silt, sand, and gravel of late Pleistocene age; and the surficial deposits of Holocene age. As described in this report, the unconsolidated deposits, or fill as it will be called hereafter, may include unidentified parts of the Siwalik Group. These deposits, although of divergent origin and lithologic type, function as a single unit in the complex ground-water system of the District. Most of the unconsolidated deposits were laid down as a filling in a topographically low area that was created by crustal downwarping and that probably subsided further as the filling progressed.

The nature of the unconsolidated fill was determined by drilling test holes in a pattern that covered most of the District. (See pl. 1) Drill cuttings, cores, electrical resistivity and sponstaneous potential logs, and some drilling-time logs provide the test-hole data for compilation, analyses, and interpretation. In this report representative composite logs (pl. 3), a map showing the distribution of permeable beds in the fill (pl. 1), diagrammatic sections of the fill (pl. 4), and representative mechanical analyses of drill cuttings (pl. 5) were selected to illustrate the character of the unconsolidated fill.

LITHOLOGY OF UNCONSOLIDATED DEPOSITS

In general, the unconsolidated fill consists of a large body of older fill that is overlain by surficial deposits of Holocene age. (See pl. 1) The latter deposits consist of dune sand south of Gurwāli and near Paniāla, Pahārpur, Yārik, and Pezu; some recent alluvial fans; thin alluvium along modern drainageways; and the surficial alluvium in the Indus River flood plain and its associated terraces. In plate 1, the alluvium in streambeds that cross the piedmont plain and that alluvium from the western tributaries, which has been deposited on the river terraces, have not been shown.

The oldest unconsolidated fill, the probable equivalent to the Potwar Loess, is known to crop out at only two locations, although it may be incorporated in thick fill that occupies most of the District. In the vicinity of Kot Āzam, flat beds of a fine cream to yellow silt are being actively eroded. This material, like the Potwar Loess, develops steep cutbanks and associated piping that drains water from the upper surface of the material down to the foot of the cutbank. Similar material is being actively eroded by the Khora River in the valley behind the Shirāni Hills, at Drazinda. There the loess-like silt has intercalated beds of gravel and, where eroded, has developed vertical banks 20 to 50 feet high. The beds are virtually flat and lie upon the marine rocks of early Tertiary age.

Within the main part of the District, the fill can be divided into two broad types. One is derived entirely from the mountains to the west and the other was laid down by the large rivers that emplaced the alluvium of the Indus Plain. Test drilling shows that these two types interfinger in a transitional zone that parallels the Indus River 8 to 14 miles west of the river. East of the zone, Punjab-type sand deposits are extant and closely resemble the sands found beneath Thal Doāb (Greenman and others, 1967; and Siddiqi and Kazmi, 1963). West of the transitional zone, the fill is mainly silty clay that contains beds of fine to medium sand and, near the mountains, gravel that is derived from the consolidated rocks. (See pls. 3, 4, and 5.)

The Punjab-type deposits consist of a sand section that contains little intercalated clay, generally is 750 to 1,000 feet thick, and is underlain by a thick section of clay. In test hole 14, however, sand extended to a depth of 1,402 feet, the total depth, and no thick clay was penetrated. The data for test holes in Punjab-type deposits are summarized, in downstream order, as follows:

Test hole	Total depth (ft)	Thickness of sand section (ft)	Remarks
9A	1,042	960	Thick clay at bottom, but entire sand section may not have been penetrated.
24	842	842	At edge of transitional zone.
9	1,522	1,160	All clay below 1,160 feet.
14	1,402	1,402	No thick clay penetrated.
23	1,442	905	Small amount of sand below 905 feet.
17	1,222	1,000	Thick clay contains hard 50-ft. zone at bottom.
20	982	982	No thick clay beds penetrated.

Conditions in the transitional zone are delineated by the data from test holes 24, 8, 11, 16, 19, and 22. In this zone, the fill consists of alternating thick beds of sand and clay, which demonstrate that the river which laid down the Punjab-type sand shifted cyclically from east to west and back, as would a meandering stream, for example.

The character of the locally derived fill, west of the transitional zone, are indicated by the data from the western and northern test holes, such as 1, 4, 7, and 13. Most of these piedmont deposits are silty clay, and the bedding generally is thin. As a result, their bulk capacity to transmit water is much lower than that of the Punjab-type deposits of river sand.

Permeable beds consist mainly of deposits ranging in grain size from silt to medium sand. (See pl. 5.) Coarse sand and fine gravel are less common. In some test holes, such as TH–6 and 9, pseudogravels were logged because the drilling bit cut up thin layers of sand or silt cemented with calcium carbonate. In the piedmont plain, such pseudogravels commonly were drilled up from beds of clay. Some discrete fragments of calcium carbonate (kankar) were also recovered in the drill cuttings. A second type of soluble evaporite was found in cores and drill cuttings of clay from the central part of the District. In such test holes as TH–7 and 13, the clays were found to contain discrete fragments and crystals of a sulfate mineral, probably gypsum, that appeared to have grown in place. Owing to the abundance of sulfate minerals available in the District, it seems probable that these sulfate crystals represent a local equivalent to kankar.

The piedmont deposits, or fill, become coarser grained near the mountains, particularly in the upper part of the fill and in those areas near the mouths of the larger mountain canyons. These conditions are shown by data from such test holes as TH–15, which penetrated a number of gravel beds. There is, on the whole, a trend of decreasing grain size from south to north. Part of this trend can be attributed to the fact that the divergence of the mountains and Indus River northward provides a greater distance for grain-size differentiation during transport eastward across the piedmont area. The main cause for the decrease of grain size northward, however, appears to be the decrease in grain size of the source material in the Siwalik Group.

Beneath both the river lowlands and the piedmont plain, the deeper fill appears to be even finer grained than that near the surface. Plate 1 shows the percentage of permeable beds in the first 500 feet below the land surface, as determined from test-hole data. In much of the piedmont plain, permeable beds make up less than 25 percent of the fill; but near the mountains, the percentage is somewhat larger. Near the Indus River, however, the percentage of permeable beds increases abruptly across the transitional zone to 90 percent or more. Plate 1 also indicates a trench of somewhat more permeable fill, which coincides approximately with the present course of the Gumal River system of distributary nālas. Related information is shown in the diagrammatic sections, plate 4.

VERTICAL DIFFERENTIATION OF FILL

It was noted during the study of field data that most of the test holes along the Indus River penetrated a "thick clay" section beneath the section of river sand. This occurrence lead to the examination of the detailed field reports for the other test holes. In these it was found that the fill at many sites could be divided into an upper zone in which sand is present and a lower more homogeneous zone which consists almost entirely of clay.

In the piedmont plain, the postulated "thick clay" section was more difficult to define. At most places near the mountains, the section seemingly does not exist. In the deep test holes, such as TH–13, however, the top of the section was determined by picking the base of the deepest bed of sand, or the base of the section in which interbedded sand and clay occur, below which few sand beds were penetrated. In such test holes as TH–1 and 19, the hardness of the formation and other factors also were used as criteria for selection.

Plate 1 shows the chosen altitudes of the top of the "thick clay" section where it could be delineated. A contour map of these altitudes yields a coherent pattern that appears related to the structural configuration of the consolidated rocks at the edges of the unconsolidated fill. The shape of the top of the "thick clay" section also appears to relate to geographic features such as the Gumal River and correlates with data regarding the slope of the water table and the chemical quality of ground water.

The contours show that the top of the "thick clay" section is deep beneath and adjacent to the Indus River and slopes steeply upward beneath the transitional zone between river and piedmont area. Whereas the top of the clay is well below sea level near the river and most of the transitional zone, it is from 100 to 300 feet above sea level in the area extending from Hathāla northward to the vicinity of Ama Khel and Tānk. In the south end of the District, a less distinct area of the clay zone appears to be as much as 110 feet or more above sea level south of the Gudh (Nāla). Between these two areas, however, a trench of more permeable fill appears to lie as deep as sea level to about 100 feet below sea level from the area of TH–23 northwestward along the Gumal River system of nālas to the vicinity of Rori. (See also pl. 4.)

The differentiation of the fill into an upper more permeable zone and a deep clay zone is at best an approximate division. It seems probable that other, less obvious subdivisions might also be made.

THICKNESS OF FILL

With respect to the base of the unconsolidated fill, again, no direct evidence is available, owing to the similarity of the piedmont deposits with the source materials. It would be expected, however, that older rocks beneath the fill would be somewhat more consolidated.

At four locations, hard or firm zones were reported. In test hole 1, drilling was discontinued because drilling progress slowed to about 1 foot per hour below 625 feet and 2 hours were required to drill the last foot of hole. This hole is immediately downslope from outcrops of the Siwalik Group north-northeast of Ama Khel. South-southeast of test hole 1, drilling was stopped at 782 feet in test hole 3 because the clay reportedly became very hard below 750 feet. South of D.I. Khān town, drilling was discontinued in TH–17 at 1,222 feet because the rate of drilling with a new bit had decreased to 2¼ feet per hour at and below 1,170 feet. In test hole 16, a hard zone reportedly was encountered at 1,050 feet, or 52 feet above the bottom of the hole. In none of the holes was the hard material reported to be appreciably different from the overlying unconsolided material. In test hole 21, the bottom of the hole at 1,072 feet may have approached a permeable zone in or adjacent to older rock, because the total dissolved solids in the water sample from about 975 feet was very low and the water was of bicarbonate type. Bicarbonate is an anion that appears to be associated with some rocks of the Siwalik Group and their immediate derivatives. (See section "Chemical quality of water.") In other widely spaced parts of the District, test holes as deep as 1,100 to 1,500 feet showed no evidence of an underlying bedrock.

STRATIGRAPHIC AND STRUCTURAL IMPLICATIONS OF "THICK CLAY" SECTION

The interpretation of conditions within the unconsolidated deposits of D.I. Khān District is complicated, as noted above, by the general similarity among the nearest source rocks, the deeper or older fill, and the shallower, more permeable fill. The sand deposits of the Punjab Plain and the shallower fill are demonstrably contemporaneous, but other data seem to indicate that the deeper "thick clay" section predates the deposition of the river sand, at least that sand extending as deep as 1,400 feet in TH–14 at D.I. Khān town. This older clay section of necessity would have been involved in all or part of the folding and faulting that created the bedrock depression beneath the Punjab Plain and in the later subsidence that occurred as the depression was loaded by sedimentation and as other tectonic movements rejuvenated existing structural features.

That the "thick clay" section (pl. 1) is relatively old is indicated by the degree to which its surface appears to be an extension of the structure of the rocks in the Siwalik Group. Despite potential large-scale erosion, the general agreement is too uniform to be caused by erosion alone. The apparent relation also of the top of the clay section to the anticlinal structure east of Kot Āzam, as implied on plate 4, appears to tie the structure of the clay section directly to that of the Siwalik Group.

It should be noted, however, that the tectonic activity originally affecting the rocks of the Siwalik Group has been renewed from time to time. At the mouth of the Khora River west of Darāban it was noted that the boulder beds there had one or more internal unconformities apparently related to movement along an adjacent fault. The upper boulder beds appeared to be generally smaller in grain size and may have been derived from the older beds. Part of the tectonic activity is relatively late. The anticlinal structure east of Kot Āzam, for example, lies directly astride the Gumal River drainage system and is breached by the distributaries, Lūni River (Nāla) and Kot Āzam Nāla. The breaching could have been accomplished only by the structure rising while the streams concurrently cut down in it. Also the breaching is so recent that the shape of the structure has not been modified to any large extent. Rejuvenation also is indicated in some of the test-hole logs. Test hole 4, for example, contains thick beds of sand which indicate that the drainage basin of the Murin Wāh was uplifted two or more times while the fill, penetrated by the test hole, was being deposited. The recentness of the latest rejuvenation is indicated by the fault scarp in unconsolidated fill at the nearby village of Paniāla as well as by the 300-foot gradational section of surficial gravel and sand in the test hole. In addition, the several levels of terraces, both in the river and the tributary streams in the District, are in part probably due to recent, stepwise renewals in stream gradients.

For the subsurface data, attention is called to the character of the "thick clay" section found in the lower parts of test holes 9, 23, and 17. These clay beds are like the fine-grained parts of the fill in the transitional zone but exhibit no interbedding with river sand. The top of the clay section is apparently a relatively smooth surface that slopes from an altitude of about 300 feet above to nearly 600 feet below sea level. (See also pl. 4.) Assuming for computation a flat clay surface, data from test holes 16, 17, and 23 indicate a dip of about 1° east-southeastward with a strike of about 28° east of north. Similar data from test holes 8, 9 and 9A indicate a dip of 30 minutes with a strike of 32° east of north; both strikes approximate that of the eastern Khisor Range (about 36° NE.). Projecting the dips to the location of test hole 14 indicates that the clay zone should have been found at 1,100 to 1,200 feet, but no evidence of clay was found in test hole 14 at a depth of 1,402 feet. These data would seem to indicate that an older clay section was warped or faulted down along a line that trends southward, east of test holes 9, 23, and 17 and west of test holes 14 and 20.

Alternatively, river sand may have been emplaced farther east contemporaneously with the deposition of the "thick clay" section, and in response to tectonic movement or upstream changes in the drainage regimen, the river may have then shifted westward quickly and started cutting the clay section. Downcutting would be indicated because between test hole 14 and test holes 9 and 23 there is little indication of lateral movement of the stream. The onset of river sand deposition in an area that previously had received fine-grained sediment also suggests a regional hydrologic change, such as the onset of a pluvial interval or a large-scale regional rejuvenation.

As earth movements recurred in the area of the piedmont plain, streams that crossed the surface of the "thick clay" section would have dissected the surface to a considerable extent before renewed sedimentation covered the eroded surface. The processes of dissection and subsequent burial probably occurred several times, but the maximum effect seems to have been along the one major drainage, that of the Gumal River. This stream is the largest that crosses the piedmont plain in D.I. Khān District; it has the largest drainage area and now discharges the most water. The Gumal River apparently predates the modern geologic structure because in the gross sense it appears to be an antecedent or, perhaps, a superposed stream. The river thus appears to have existed early in the history of the unconsolidated fill and possibly to have carved out, or occupied and later backfilled, the trench of more permeable piedmont deposits that now underlie its system of distributary nālas. There is no evidence that the Tānk Zām channeled permeable deposits into the area downslope from its present gorge in the mountains. The Khora River and the Chaudhwān Zām likewise do not appear to have channeled the older clay section, but they have contributed some permeable material as far east as the *Nummulites*-bearing gravel zone in test hole 16.

In summary, the vertical differentiation of the unconsolidated deposits into an older "thick clay" section and a younger more permeable zone with the attendant evidence of tectonic distortion leads to a tentative and approximate chronology for the unconsolidated fill as follows:

Epoch	Rock unit	Tectonic event	Remarks
Holocene	Alluvium in streambeds and terraces; eolian sand.	Late phase or phases of intermittent continuing upland rejuvenation or lowland subsidence.	Major and minor streams now attacking older unconsolidated rocks.
Late Pleistocene.	Shallower piedmont deposits, fill in the transitional zone, and Punjab-type river deposits.	Recurrent rejuvenation of existing structures.	Renewed pluvial interval. Equated with the redeposited silt (table 4). Wadia (1961, p. 413) refers "Daman" tracts to Pleistocene because of Kankar content.
	Erosional interval(?)		
		Major(?) tectonic movement(?), distortion of the "thick clay" section, and further(?) distortion of Siwalik Group.	
(?)	Deposition of the "thick clay" section.		
(?)	Erosional interval(?)		

(Table continued on page 34)

Epoch	Rock unit	Tectonic event	Remarks
------------------------------------		First and probably main structural distortion of Siwalik Group.	
Middle Pleistocene.	Deposition of boulder conglomerate of Siwalik Group.	----------------------------	Deposition may have been continuous locally into deposits equivalent to "thick clay" section.

Comparison of this table with table 4 would lead one to equate the "thick clay" section with the Potwar Loess or its equivalent, and such correlation might very well be justified. The nature of the contact between the Siwalik Group and the "thick clay" section, however, has not been determined, and the relation of the river sand section to deeper unconsolidated deposits beneath Thal Doāb to the east and in D.G. Khān District to the south must be determined before the idea can be finally accepted that the "thick clay" section predates the river deposits.

SUMMARY OF WATER-BEARING PROPERTIES OF FILL

The results of the test-drilling program make it clear that the most permeable and extensive aquifer in the unconsolidated fill in D.I. Khān District is the Punjab-type river sand that underlies the Indus River lowland and immediately adjacent areas. This sand contains relatively little clay and constitutes a single aquifer.

Within the area of the piedmont plain, the largest part of the fill consists mainly of silty clay with relatively thin beds of fine to medium sand. The fill has a low bulk permeability, but owing to grain size, saturated sand of individual beds or groups of beds should be capable of yielding usable quantities of water to wells that are properly finished. The results of drilling aquifer-test tube-wells show that attention must be given to the sizes of well-screen slots and of grains in gravel envelopes.

Much of the marginal area of western and northern D.I. Khān District is underlain by unconsolidated fill that contains sufficient coarse-grained material to indicate favorable potential areas for ground-water development. Of these, the Gumal River reentrant in the vicinity of Kot Āzam is the most promising area. There, much of the fill consists of very coarse-grained debris derived from the boulder conglomerate, and large yields from wells are potentially available. From the standpoint of geological data, this area appears to be second to the flood plain of the Indus River in development potential.

Most other marginal areas are relatively narrow zones immediately adjacent to the mountains. The large alluvial fans at the mouths of the larger mountain streams are particularly promising. The compound fan at the mouths of the Khora River and Chaudhwān Zām is a good example.

Within the interior part of the piedmont plain, the one area that appears to contain sufficient coarse-grained fill to yield appreciable amounts of water to wells is the area of the trench of sand fill along the course of the Gumal River system of distributary nālas. This area by comparison to the thick clay elsewhere in the piedmont plain is relatively permeable, but the amount of sand present indicates that only moderate yields from wells might be expected.

WATER RESOURCES

D.I. Khān District can be divided with regard to water supplies into two parts in a manner that is similar and related to the geology. In the piedmont and near-mountain areas, water is derived directly from precipitation and from streamflow that originates from precipitation in the mountains to the west. Ground water in the area of the piedmont plain moves downslope through relatively fine-grained thin aquifers to a discharge area near the Indus River.

Beneath and adjacent to the Indus River, water is derived mainly from the Indus River which carries the accumulated runoff from a vast region in northern West Pakistan and northwestern India. In D.I. Khān District, ground water is derived from seepage from both the river and the Pahārpur Canal. Here the ground water moves through a thick permeable section of sand in a direction subparallel to the river toward a discharge area common with the upland aquifers. The District as a whole is deficient in usable water as a consequence of its climate and geology, but as the present study shows, those water supplies available have not been fully developed.

SURFACE WATER

The presently available data indicate that surface water is the main source of water in D.I. Khān District, both for direct use and for recharge to the ground-water reservoir. Although precipitation is the ultimate source, water from that source reaches the study area in the District mainly by overland flow.

INDUS RIVER

The Indus River is the master stream of the D.I. Khān region. Its drainage area above the District is greater than 100,000 square miles and has its main sources of water in the Himalayas that extend across northern India and West Pakistan. Records of discharge of the Indus River were not accumulated for this study; however, the magnitude of the flow near D.I. Khān District is indicated by the flow at Kālābāgh. There the average annual flow for the period 1921–46 (White House—Department of Interior Panel on Waterlogging and Salinity in West Pakistan, 1964, table 1.2) was on the order of 89 million acre-feet of which about 76 million acre-feet was discharged during the kharif season. The records of the Surface Water Circle (West Pakistan Water and Power Development Authority, 1962–64), for the calendar year 1962, indicate that the flow of the river before diversions at the Jinnah Barrage in the Kālābāgh-Miānwāli area was on the order of 73 million acre-feet. Despite the diversion of 2.5 to 3 million acre-feet of water into canals that irrigate lands in Thal Doāb and the losses due to evaporation, the average annual discharge of the river near D.I. Khān District probably exceeds 85 million acre-feet per year.

At low flow the river threads its way through several braided channels, and during most years many of the islands thus formed are inundated in the summer by floodflow which forms a sheet of water that may be 6 to 9 miles wide. (See figure 4.) During infrequent years of high flood, the inundated area may be 12 miles or more wide. Between the south end oi the District and Chasma Headworks at the north end of the District, the gradient of the river is 1 to 1.5 feet per mile.

The flow of the river characteristically is low during much of the fall, winter, and spring. Floodflow begins generally in April, as a result of snowmelt in the mountains, and peaks in June. High flow is sustained into September as a result of monsoon rains, and subsequently it decreases rather abruptly in October. River stage gages are maintained by the Irrigation Branch, PWD, at Chasma Headworks and at D.I. Khān town. Plate **2D** shows the annual lowest and highest gage heights for 1950–63, and figure 14 shows daily gage heights at D.I. Khān town for 1963.

The very size of the river interferes with transportation in the area. Owing to its width, shifting character, and the nature of its bed material, the river is not spanned by permanent roadways from Jinnah Barrage, near Kālābāgh, to Taunsa Barrage, between Taunsa and D.G. Khān—a distance of about 170 miles. The river's size also indicates that a substantial amount of water is lost by evaporation from this large stream. If the average width of the river is taken as 5 miles, the 80-mile reach adjacent to D.I. Khān District loses about 0.25 million acre-feet for each foot of water evaporated.

PAHĀRPUR CANAL

The Pahārpur Canal is the principal firm irrigation supply in D.I. Khān District, but as an inundation canal, its supply depends on the stage of the Indus River. In dry years, the canal supply may also be short at a time when it is needed most.

The canal main line is about 46½ miles long and extends from Bilot Headworks, at the east side of the Khisor Range, southward to the area immediately south of D.I. Khān town. Water is taken from the Indus River at Chasma Headworks and delivered to Bilot Headworks where the needed amount of water is diverted into the main line. The intake capacity is 480 cfs (cubic feet per second), and the main line capacity diminishes with distance from Bilot (fig. 10).

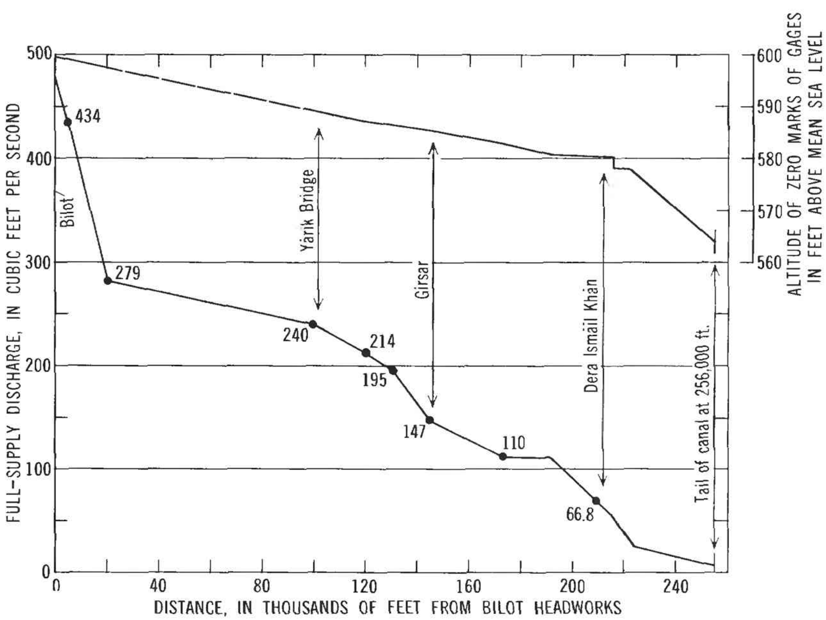


Figure 10—Discharge capacity and profile of Pahārpur Canal.

The canal can deliver water to about 100,000 acres of land through several large distributaries and many smaller ones. The spreading of water on the lands and leakage from the canal system has raised the ground-water level appreciably since the opening of the canal in 1934, as shown on plate 2G.

The quantity of water delivered through the canal depends both on the flow available in the Indus River and on the water requirements of the irrigators. Thus in wet years, canal flow may actually be less than during normal or exceptionally dry years. A partial record of canal flow during 1954-63 was obtained from the Irrigation Branch, PWD. The annual totals based on these data are as follows:

Year	Total canal flow (acre-ft)	Year	Total canal flow (acre-ft)
Mar.–Dec. 1954	238,800	1959	218,300
1955	163,300	1960	185,800
1956	104,200	1961	224,500
1957	161,700	1962	190,300
1958	212,700		

The total annual diversions, in acre-feet, for 1954 through 1963 are shown on plate 2*E*.

TRIBUTARIES FROM THE WEST

The streams that drain most of D.I. Khān District head in or close to the western border of the District. Several major streams, however, drain large areas of the western mountains and the areas west of them (fig. 11). All streams with small drainage basins are intermittent and flow only in response to local storms; a few that head in the foothills have continuous flow during most of the year but cease flowing during the hottest or driest periods.

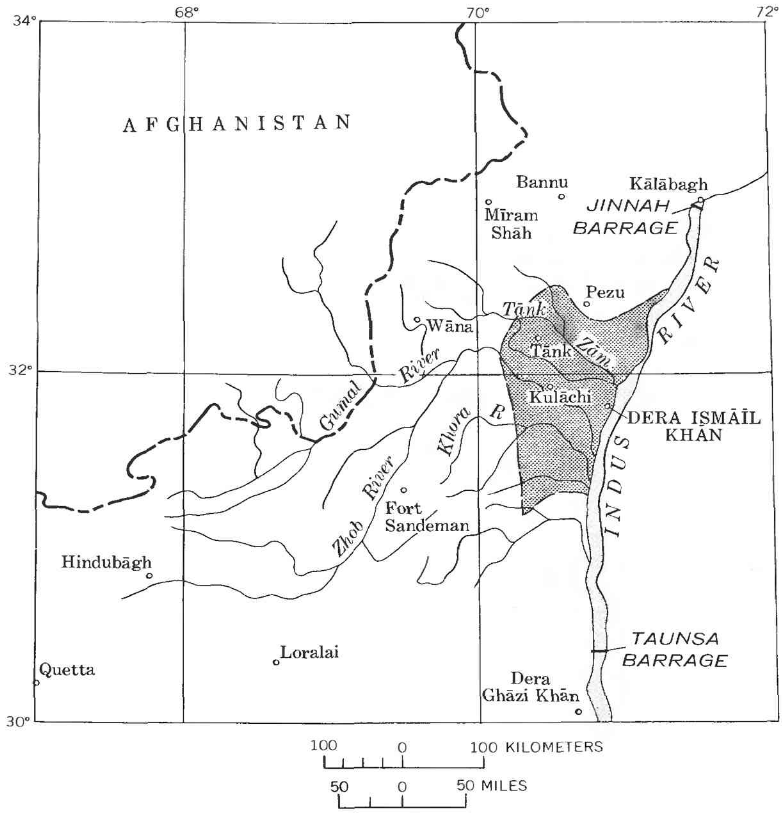


FIGURE 11—Major tributaries that drain through D.I. Khān District to the Indus River. Modified from "Map of Pakistan" (Survey of Pakistan, 1962).

At least three tributaries, however, have perennial flow and are the source of irrigation water to lands on the upper slopes of the piedmont plain. These are, southward, the Tānk Zām, the Gumal River, and the Khora River. The Tānk Zām and Khora River drain moderate-sized areas of the Bhittanni and Sulaimān Ranges, respectively, but the Gumal River carries the aggregate flow from a system that extends far to the west and south, into eastern Afghanistan and western West Pakistan. (See fig. 11.) Table 5

TABLE 5.—*Measured discharge of three streams that enter D.I. Khān District, 1962–63*

[Data reported by Surface Water Circle, WASID. WAPDA, Lahore]

Stream	Drainage area (sq mi)	Year	Discharge: Million acre-ft	Discharge: Mean cfs	Discharge: Cfs per sq mi
Tānk Zām at Jandola	840	1961	0.156	215	0.256
		1962	.115	159	.189
		1963	.170	234	.279
Gumal River at Khajūri Kach	11,200	1962	.337	466	.042
Gumal River near Kot Murtaza	13,870	1960	.385	531	.038
		1961	.418	574	.041
		1962	.289	400	.029
		1963	.391	540	.039
Darāban (Zām) at Zām Tower[1]	432	1961	.032	44.6	.105

1 Mouth of Khora River gorge west of Darāban.

summarizes the available data for the three stations, and plate 2F shows the monthly distribution of flow in the Gumal River and Tānk Zām for May 1961 through 1963. The response to fluctuations in precipitation is readily seen.

The instantaneous discharge of the perennial streams crossing D.I. Khān District varies through a wide range. Although the low flow is augmented early in the year by snowmelt from the uplands of the Sulaimān Range, most of the high discharge occurs in the summer in response to runoff from thunderstorms. Because of the source of runoff, streamflow can change very rapidly. As shown in figure 12, the flow of the Gumal River in June 1961 rose abruptly from about 85 cfs to nearly 450 cfs within 24 hours and to about 3,200 cfs by the following day. Annual extremes vary in a similar fashion. For example, in 1962 the Tānk Zām had a flow of 44 cfs on June 29 and an instantaneous peak of 12,600 cfs on July 29. In the Gumal River at Khajūri Kach, the lowest flow was 71 cfs on June 1, 1962, and the highest was 34,100 cfs on July 31. The Khora River in 1961 had a low of 1 cfs on April 22 and a high of 11,000 cfs on April 13.

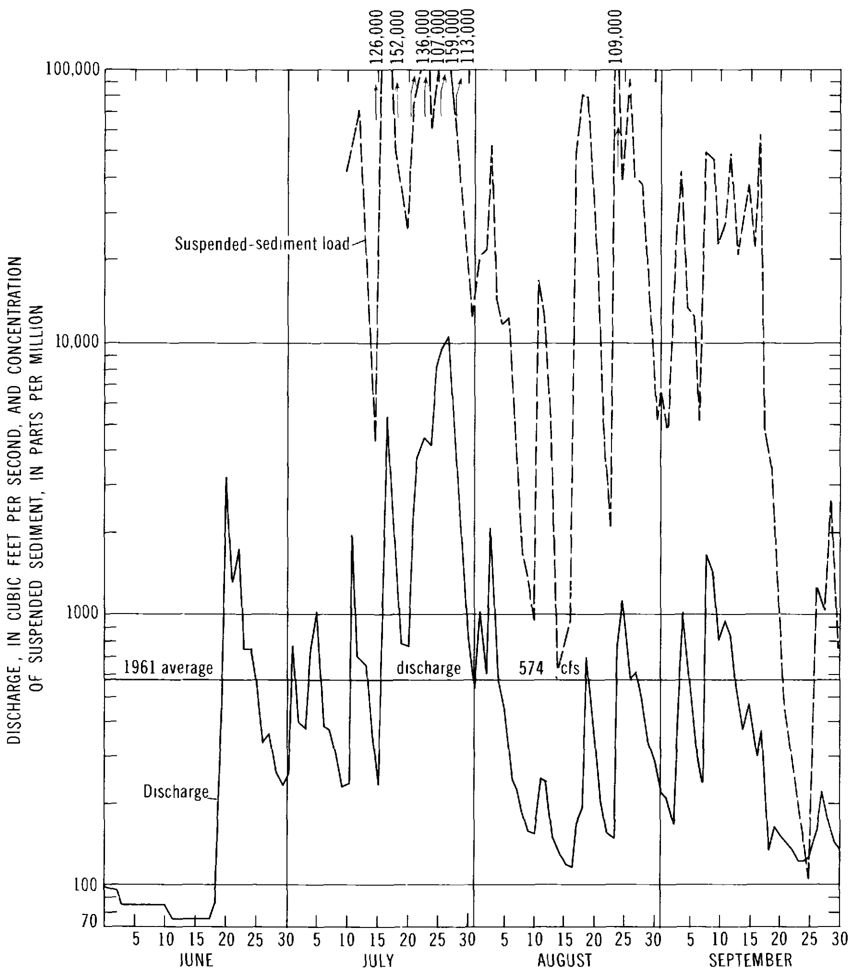


FIGURE 12—Discharge and suspended-sediment concentration of water in Gumal River near Kot Murtaza, June–September 1961.

The source of much of the fine-grained fill in D.I. Khān District can be seen in the sediment suspended in the modern streams. The Gumal River, for example, receives the flow of the Zhob River. J. C. Ringenoldus (oral commun., 1963) reports that the Zhob drains through large stretches of fine-grained deposits that are easily eroded. From his description, these fine-grained deposits are apparently similar to the loess-like beds found near Drazinda and Kot Āzam in D.I. Khān District. Figure 12 shows the concentration of suspended sediment in water of the Gumal River during June through September 1961. During peak floods in that period, measured concentrations exceeded 150,000 ppm (parts per million). Using 1 year of record of streamflow, engineers of Energoprojeckt (written commun., 1963) estimated that the Gumal River carries an average of 4 percent, by weight, of suspended sediment. Figure 13 shows the concentration of suspended sediment in water at the gaging station near Kot Murtaza.

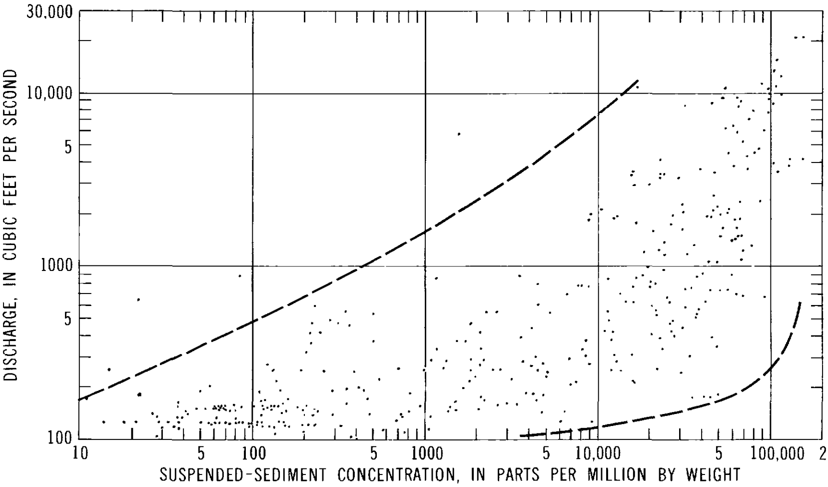


FIGURE 13—Relation of suspended-sediment concentration to rate of discharge in Gumal River near Kot Murtaza, 1961 and 1963.

GROUND WATER

The largest reserve of water in D.I. Khān District, other than water of the Indus River, is ground water, and at the time of this field study ground water was the least developed. Although the use of ground water in the District is widespread (pl. 1), the quantities used are small compared to those taken from surface-water sources. The small development of ground water apparently is due to the relative cost of installing wells. Until the mid-1950's, most wells in use were shallow dug or driven wells. The recent expansion in use of large-diameter drilled wells reflects an increasing prosperity—the result of government-supported development—and the growing pressure to develop lands that have no assured surface-water supply.

OCCURRENCE

The principal ground-water reservoir in the District is the unconsolidated fill of Quaternary age, and the reservoir system may include adjacent coarse-grained parts of the Siwalik Group. The upper limit of this reservoir is marked by a water table, below which the fill is saturated to known depths as great as 1,500 feet at the town of D.I. Khān.

In the upland recharge areas, at shallow depths beneath the water table in the piedmont plain, and in most of the thick sand section adjacent to the Indus River, water in the fill generally is unconfined. At greater depths, however, water is confined in permeable beds of sand and gravel beneath semipermeable beds of silt and clay. Where such confined conditions occur, the difference in head between the deep and shallow zones generally is only a few feet, but in the western edge of the piedmont plain head differences of 30 feet or more were found. Water in test holes 27, 2, 2A, and 15 flowed from beds 400 to 700 feet below the land surface. In test hole 2A, for example, the water in the zone from 94 to 114 feet had a head 16.5 feet below the land surface but that in the zone from 642 to 662 feet rose to 23 feet above the land surface. Similarly, the shallow ground water in test hole 12A had a level 44 feet below land surface, but the water level in the zone from 425 to 445 feet rose to 11 feet below the land surface.

The tentative inclusion of the uppermost coarse-grained part of the Siwalik Group in the reservoir system in western D.I. Khān District is based partly on theory and partly on observed data. It was observed that the boulder and gravel beds of the group dip beneath the piedmont deposits and that, although they are cemented, the boulder beds appear to be appreciably permeable. They are thus in a favorable position to receive water from rain and streamflow and to transmit that water beneath the fill. The fill adjacent to the Siwalik rocks, moreover, is coarse grained compared to the fill in most of the piedmont area. In addition to these data, samples of water from zones deep in the fill adjacent to the western foothills have a chemical quality that appears to indicate that the Siwalik rocks are the source.

SHAPE AND DEPTH OF WATER TABLE

The shape of the water table in D.I. Khān District in June 1964 is shown on plate 6 by means of contours that have a 50-foot interval in most of the map but a 10-foot interval in the area closest to the river. Contouring is based primarily on measurements of water-table altitude in 75 observation wells, but control also was estimated from the altitude of water surface of the river, reported altitudes of water levels in wells where no other control was available, and measured water levels for other dates in wells where the water level could not be measured in June 1964. Sea-level datum for the main control points was determined by spirit leveling and, for auxiliary control points, was carefully estimated from topographic maps that have a scale of 1 : 50,000.

Plate 6 shows that in the western part of the District the water table slopes generally east-southeastward from an altitude of about

900 feet near the center of the Gumal River reentrant west of Ama Khel to a trough that represents the discharge area. The trough extends from near Yārik, parallel to the Pahārpur Canal, southward to near the southern boundary of the District. Water-level altitudes in the trough range from about 600 feet to the lowest point of about 490 feet in the south end of the District. East of the trough, the water level slopes away from the river and toward the trough, both in the area served by the Pahārpur Canal and in the area south of the canal.

The depth to the water table in June 1964 is shown on plate 6 by means of lines that represent equal depth to water; the lines have an interval of 10 feet. The measured depths are those used in constructing the water-level contour map on plate 6, and the interpolated points of control were obtained by comparing the water-level contours with topographic contours. The depths shown at points of measurement, are accurate, but interpolation between points or contours will yield the approximate depth to water within about 20 feet.

FLUCTUATIONS OF WATER LEVELS

In D.I. Khān District, water levels are known to fluctuate in response to variation in the stage of the Indus River, infiltration from rainfall and stream runoff, discharge by evapotranspiration, and withdrawal from wells. These fluctuations were observed by means of a network of observation wells established in the District in November and December 1962. The wells were measured at biweekly to monthly intervals until June 1964. Forty-seven wells were chosen in both the piedmont plain and the flood plain. Of these, 18 wells in the vicinity of the Pahārpur Canal had been measured by the Irrigation Branch, PWD, since 1934, and those records were obtained (pl. 2G). Observation pipes were installed at most of the test holes as they were completed. Measurements were made in 32 of these, and fairly long records were obtained for some. At 20 of the test holes, observation pipes were installed in the shallowest water-sampling zone and in one or more of the deeper zones to permit the measurement of pressure differences between the shallow and deep zones. Representative short-term hydrographs of both observation-well and test-hole water levels are shown on plate 2H.

Water-level records show that ground-water levels in the Indus River lowland below the Pahārpur Canal from 1934 to 1964 generally rose from 1 to 6 feet, presumably as a result of canal operation. Initial rises of as much as 8 feet were reported, but these reported rises are not supported by the data supplied by the Irrigation Branch. Superimposed on the small general rise are secular fluctuations of 4 to 8 years in length, which reflect alternating series of dry and wet years; and throughout the record, fluctuations due to seasonal changes from dry season to monsoon are apparent. Water levels close to the Indus River are affected by the river stage (fig. 14), and the hydrographs of such wells show a generalized but much subdued replica of the trend in river stage.

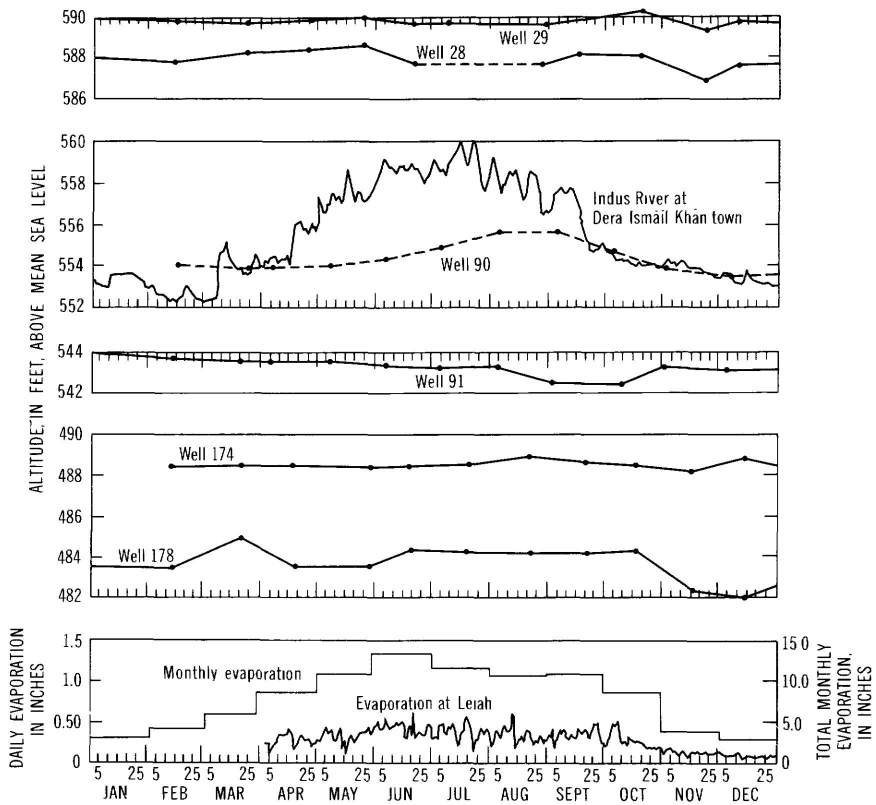


FIGURE 14—**Daily Indus River stage at D.I. Khān, daily and monthly total evaporation at Leiah, and water levels in selected wells in and near river lowlands, 1963.**

At well 90, whose hydrograph is shown in figure 14, the effects of changes in river stage lag by about 1 month. Comparison of plate 2D (annual high and low stages of the Indus) with the long-term hydrographs (pl. 2G) also shows this general lag relation.

The short-term hydrographs show a number of significant features. Some measurements in shallow wells doubtless were affected by withdrawals from wells, but the majority of the fluctuations are due to natural phenomena. Most fluctuations in the test-hole observation pipes are due to natural causes. In the upland areas, observation wells near streams and ditches show a seasonal rise due to infiltration from flooding; the deep artesian or semiartesian water levels show the same effects. Those observation wells ending in fill of low permeability generally show only small month-to-month fluctuations.

In the Indus River lowland, however, the fluctuations in some shallow wells apparently are modified by the effects of evapotranspiration, as for example wells 28 and 29 in figure 14. The water-level rise that would be expected at the onset of the monsoon is subdued, and in several wells, the decline of the water level during the hottest part of the year completely offset the effects of rise in river stage and heavy rains. The effects of evapotranspiration are most conspicuous where the depth to water is small and where there is either abundant vegetation or no surface water applied to the immediate area.

The principal fluctuations due to pumping in D.I. Khān District are in the area west of the Pahārpur Canal, west and southwest of D.I. Khān town. In that area, pumping has caused a persistent downward trend in water levels at times when wells elsewhere show a pattern that can be correlated with weather conditions. The effects of pumping are noticeable in the long-term hydrographs for wells 90, 91, 116, 119, and 120, beginning about 1958–59 (pl. 2G), and appear to be present in the records for wells as far west as well 107 and as far south as well 149. The hydrographs for wells 90 and 91 show that the effects of pumping reach across the Pahārpur Canal, but the effects east of the canal are much subdued.

The downward trend in water levels will continue as long as the large-yield irrigation wells are operated, and the area thus affected will enlarge with time. Moreover, the decline in water levels due to pumping can be expected to accelerate, and the area affected can be expected to increase as the area commanded by tubewells is extended. In the years immediately preceding 1964, a considerable number of private and government tubewells were installed, and it is noted that the use of these has extended to the south end of the District and beyond, into the river flood plain north of D.I. Khān town, and probably will be extended later into parts of the upper piedmont plain. Because the decline of groundwater levels has altered and will further alter the flow pattern in the aquifer, general conditions in the pumped areas have changed and will change still more. In those areas where the original water level was deep, the decline of the water level will increase the cost of pumping water by requiring more power to lift the water. Some of the settings of pumps may have to be lowered in the future. The main effect of water-level decline, however, is a change in the chemical quality of the pumped water.

AQUIFER TESTS

On the basis of the results of test drilling, 10 sites were selected for aquifer tests in areas where conditions seemed favorable for ground-water development and where it was considered necessary to determine the permeability of the fill. The tests were performed and analyzed by personnel of the General Hydrology Circle, WASID, WAPDA. The tests involved arrangements that ranged from simple recovery measurements in the pumped well to measurements in elaborate arrays of observation wells during periods of 12 to 96 hours of pumping. Not all the tests yielded data commensurate with the preparations made.

Table 6 gives the results of the aquifer tests in D.I. Khān District. Of the data, those for test well DIK–3 must be used conditionally because the observation wells for the test were installed at

TABLE 6.—*Results of aquifer tests at tubewells in D.I. Khān District*

[A, approximate value, or value subject to question; B, well pumped by airlift method at low rate of discharge; C, value derived by using only the discharge through the increment of well screen opposite the screens of the deeper observation wells; WT, water-table conditions; SA, semiartesian conditions; Art, artesian conditions]

Tubewell	Total depth	Total screen length (ft)	Length of test (hrs)	Yield (gpm)	Specific capacity (gpm per ft of drawdown)	Coefficient of transmissibility (gpd per ft)	Permeability (gpm per ft): Vertical	Permeability (gpm per ft): Lateral	Type of condition	Storage coefficient (S), or specific yield (S_y)
Tubewells in piedmont plain and near western mountains										
DIK–1	208	128	96	934	81 A	310,000	2,390	323	WT	Sy=0.18
–3	353	152	48	224B	3.6A	2,950–5,890	19.4–38.8	0.26–0.71	SA(?)	----------
–4A	390	150	96	337B	6.7	19,400–96,900	129–646	--------	Art(?)	S=0.00005–0.001
–8	315	50	96	211B	5.4	6,470	129	--------	SA	----------
GZ–2	525	89	96	449	10.8	104,000–391,000	1,160–4,390	--------	Art	----------
						38,000–153,000C	969–3,810C			
–3	305	115	12	154B	31.4	74,300A	646A	--------	SA(?)	----------
Tubewells in the Indus River lowland										
DIK–2	300	195	96	1,330	148	315,000	1,620	97	WT	S_y=0.14
–5	250	135	96	1,160	81	148,000	1,100	65–194	WT	S_y=0.05–0.07
–6	505	162	96	1,200	67	136,000	840	22	WT	S_y=0.19A
–7	302	160	96	1,120	85	238,000	1,490	14.2	WT	S_y=0.14

inappropriate depths. Four wells were pumped by the airlift method, and therefore their yields do not show that large amounts of water were produced. Potential yields at those sites can be evaluated by inspection of the column that shows specific capacities. Of these four, three were pumped by airlift because of the large amounts of sand that passed through the screen. Well GZ–3, however, was pumped by airlift because a suitable turbine pump was not available at the time of testing. Therefore, the well may not have been fully developed, because part of the development generally is done with the pump. At sites DIK–1, 5, and 6, recharge from adjacent surface-water sources produced results that interfered with the analyses of test results. Therefore, the specific yields shown for those tests were approximated by the analyses, and the figures cited are in the right order of magnitude.

The results of the program of aquifer testing in general confirm the results of the test-drilling program and point to the fact that by far the most extensive aquifer of permeable sand in D.I. Khān District is beneath the lowland of the Indus River. Only in the Gumal River reentrant in the bordering hills did aquifer testing indicate water-bearing material with aquifer cofficients comparable to those in the Indus River lowland.

The yields of all the test wells in the lowland were large, as were their related specific capacities. The coefficients of transmissibility were 60 times or more greater than those determined from the three test wells in the piedmont plain. Although the test results showed that the aquifer beneath the lowland is, in general, under water-table conditions, the sands there are not completely isotropic. The ratios of lateral to vertical permeability ranged from about 15 at test wells DIK–2 and DIK–5 through about 40 at DIK–6 and reached a maximum determined value of 120 at DIK–7, which is in or at the edge of the transitional zone in the south end of the District.

In most of the piedmont plain, the lateral permeabilities of sand beds are about the same as those of the sands in the Punjab-type deposits of the lowland, but the thickness of sand beds in the piedmont deposits is smaller; therefore, yields of wells and determined transmissibilities are smaller. Near the mountains, however, intermediate values were obtained for the aquifer coefficient in areas where the piedmont deposits are coarser, as at test well GZ–2. The very high values obtained at DIK–1 suggest that large yields may be obtained from wells in highly permeable fill at the mouth of the other large mountain canyons, such as those of Tānk Zām and the Khora River.

RECHARGE

The altitude of the water table and the depth to water in D.I. Khān District are shown on plate 6. From this plate it is apparent that the water table slopes away from both the mountain area and the Indus River. In the upland area, recharge occurs mainly at the base of the mountain and hill area where the surficial deposits of the piedmont plain consist partly of permeable gravels and where the coarse-grained rocks of the Siwalik Group crop out. The largest part of the piedmont plain, conversely, has surficial deposits of silt and silty clay that have low permeabilities and do not transmit water from the surface to the water table. At some places in the plain, there are extensive sand dune areas, but most of the dunes seem to be underlain by the same clay section that forms the surface elsewhere in the plain.

Most mountain stream channels are dry during the greater part of the year, the only flow occurring in response to infrequent rains. Several streams, however, are perennial or nearly so. These streams discharge water across the coarse gravels and thence out onto the piedmont plain. A part of the water sinks into the gravels, and that part which is not returned to the atmosphere by evapotranspiration reaches the water table. In the piedmont plain, the return of water to the atmosphere by evapotranspiration is greater than in the gravelly areas, because the silt and clay have a greater water-holding capacity.

The amount of recharge depends in large measure on the rate at which water passes over the gravel fans. During low flow, there should be a continuous train of water moving down into the gravels. At greater flows the increase in the rate of recharge would depend on the duration of the larger flow. The response, however, to larger flow D.I. Khān District probably is poor, owing to the rapidity with which floods rise and fall in the upland areas. Because of the flashy nature of flooding in the District, it is probable that the quantity of recharge resulting from flooding in the piedmont plain is very small.

In the eastern part of the District, the ground-water reservoir is replenished by seepage from the Indus River. As indicated by the water-table contours (pl. 6), ground water moves from the river and adjacent lowlands toward the southwest through beds that predominantly are very permeable.

The actual quantity of recharge cannot be computed with the data on hand. A minimum value for recharge, however, can be estimated by using the aquifer-test data and the slope of the water table in a variation of Darcy's law:

$$Q = 0.0011\, T\, L\, I\,,$$

in which Q is the quantity of water moving through the section, in acre-feet per year; 0.0011 is a conversion factor; T is the coefficient of transmissibility of the aquifer, in gallons per day per foot; L is the width of the section, in miles; and I is the slope of the water table, in feet per mile. In each test the value for transmissibility is thought to represent that zone in which sand beds were screened, and therefore, the values for the coefficient of transmissibility are not directly comparable. For the purposes of estimate, however, the value for transmissibility at each of the test sites used here has been adjusted to the standard thickness of 200 feet. Data for the estimate of recharge are given in the following table:

Test site	Coefficient of transmissibility for assumed thickness of 200 ft	Water-table slope, in feet per mile	Acre-feet per year flow through section 1 mile wide
DIK–3	5,600	15.4	100
4A	78,000	8.3	730
8	25,900	9.1	260
GZ–2	280,000	11.9	3,670
Total (rounded)			4,800
Average for four tests			1,200

If the figure of 1,200 acre-feet per year per mile is extrapolated to the entire contour length, the amount of water that annually crosses the 600-foot contour, approximately 80 miles long, would be about 96,000 acre-feet. This amount, of course, is purely an estimated minimum value and, further, contains no adjustments for additions or losses of water during movement or adjustments for changes in permeability or thickness of the aquifer from the test sites to the 600-foot contour.

In comparing the nearly 100,000 acre-feet of estimated recharge to the 1 million acres or more in the District above the 600-foot contour and the several millions of acres in the mountain drainage basins west of the District, it appears that the annual rate of recharge is small—on the order of 0.5 inch or less. Because the annual precipitation in the District proper is small, the soil permeability also relatively small, and the potential rate of evaporation large, it seems evident that most of the recharge comes from precipitation in the mountains and subsequent runoff west of the District.

In the Indus River lowland, the quantity of water that seeps from the river to recharge ground water in the District also can be estimated, but here, as in the piedmont plain, there are unknowns that preclude any accurate figure. Assuming that the water-table contours on plate 6 represent the direction of flow in the entire aquifier and that the minimum effective thickness of the aquifer is 500 feet, the adjusted coefficient of transmissibility at tubewell 6 is about 420,000 gpd per ft (gallons per day per foot). The average slope of the water table from the flood plain toward the discharge area is about 2 feet per mile. Thus the discharge across the 550-foot contour is about 920 acre-feet per year per mile, and an estimated 15,000 acre-feet per year moves across the 16-mile stretch of the contour from the river to the center of the trough that marks the discharge area west of the Indus River. The aggregate section through which seepage moves to the District is about twice the length of the 550-foot contour as described, and, therefore, the estimate of total seepage from the river is on the order of 30,000 acre-feet per year. This figure is low because the effective thickness of the aquifer exceeds 500 feet.

The total minimum recharge to the District then is the sum of estimated seepage from the river and infiltration from precipitation in the western and northern parts of the District, or an estimated minimum of about 120,000 to 130,000 acre-feet per year.

DISCHARGE

The apparent discharge area in D.I. Khān District is shown on plate 6 by the lowest area in the water table, which appears as a trough, from 4 to 14 miles west of the Indus River. The trough is perennial—that is, seasonal fluctuations of the water table are not large enough to eliminate the trough at any time during the year. The trough also is a natural phenomenon. Although withdrawal of water from tubewells in the area of D.I. Khān town is deepening it slightly, the trough reaches its lowest altitude in an area where there are little or no artificial withdrawals of any significance. The occurrence is similar to that of the troughs beneath the several doābs in the Punjab region in preirrigation times. (See Greenman and others, 1967.) Water-level records indicate that the trough once was more extensive than it presently is. The opening of the Pahārpur Canal in 1934 created a new source of water that leaked into the aquifer. This leakage offset evapotranspirational losses and raised water levels beneath the area adjacent to the canal. Initially, the trough extended as far north as the Khisor Range, and despite the raising of water levels, it still exists as a shallow depression in the water table west of the canal. The trough is again deepening as a result of operation of the tubewells that have been installed since 1958. The south end of the trough is defined by closed contours near the boundary between D.I. Khān and D.G. Khān Districts in an area where the Sulaimān Range is comparatively close to the Indus River. The existence of the trough does not imply that all discharge occurs at the deepest parts but does imply that water moving toward the trough is lost to the extent that little water reaches the lowest part.

Beneath large parts of the District, the water table is from 10 to 40 feet below land surface (pl. 6), and therefore, discharge occurs both by transpiration of phreatophytes and by direct evaporation from the soil. The persistence of shallow water levels is due in part to an eastward reduction of grain size in the unconsolidated rocks and thus an eastwardly increasing impedance of ground-water flow. The ground water upgradient, therefore, backs up behind a partial "dam." A part of the effect, however, is due to the upward component of ground-water flow in the western part of the District. As a result of artesian pressures in the deeper sands, some water leaks upward to the shallowest part of the saturated section. If water were not dissipated by evapotranspiration from the water table, the upward leakage would probably supply adequate water to raise the water table to the land surface.

Likewise, in the area between the river and the bottom of the trough, substantial losses must occur; otherwise, the river seepage would have no place to go and the water level would approximate that of the river. In the river flood plain and in the modified, or abandoned, flood plain, water levels are on the order of 10 feet below the land surface, and the lower part of the area supports a dense growth of grasses and other phreatophytes. In this area, as in the piedmont plain, soils are relatively fine grained, which leads to a large capillary rise from the water table and makes ground water available for evaporation from the soil surface. Small water losses by evapotranspiration appear to occur even where the water table is 40 to 80 feet deep. These losses apparently result both from the large capillary rise occasioned by the fine-grained character of the deposits and by the transpiration of hardy phreatophytes.

Data with which to estimate the water losses from the District by evapotranspiration are inadequate to arrive at any firm quantitative figure. Phreatophytic grasses and cattails, open-water areas, and other sources of continuously available water very likely lose several feet of water annually by evapotranspiration. The annual rate of discharge from areas of bare soil, where the water table is deep, probably ranges from nothing to a small fraction of an inch. If, however, the average annual loss from 1.5 million acres, which is less than three-fourths of the District, were only 1 acre-inch per acre, the annual ground-water loss would amount to 125,000 acre-feet of water, a figure on the same order as the estimated minimum recharge to the District.

CHEMICAL QUALITY OF WATER

The development of ground-water supplies in large parts of D.I. Khān District has been a difficult problem for the residents because of the existing natural distribution of ground water of poor quality. Broad areas contain water of good chemical quality, but this water is commonly overlain at shallow depth by water of poor quality.

Dug wells, the most common means of obtaining water, have penetrated only into the shallow water. This condition, coupled with the lack of adequate precipitation and the intermittent character of most streams in the District, has created the general impression that almost all the area of the piedmont plain lacks adequate supplies of water of usable quality. The results of test drilling and sampling of existing water sources, however, demonstrate that both the river lowland and the marginal parts of the piedmont plain are underlain by a substantial quantity of fresh, or at least usable, ground water.

SOURCES OF DATA

A part of the program of investigations in D.I. Khān District included sampling of water from representative existing wells, springs, and streams. Also during test drilling operations, permeable zones were selected on the basis of the lithologic and electric logs for water sampling and water-level measurements. Surface water was sampled at several locations and, additionally, the records of analyses for samples taken by the Surface Water Circle, WASID, WAPDA, were obtained for Tānk Zām, Gumal River, and Khora River. These data together were for 437 samples from 309 individual sources, which include several sampling zones in each individual test hole. From these, representative analyses were chosen and are given in table 7 for surface-water sources and in tables 8 and 9 for ground-water sources. Data from all sources are summarized on plate 6, which shows the amount of dissolved solids in water from individual sources. The amount of dissolved solids shown for each test hole is the average concentration for all samples from the water table down to a depth of 300 to 400 feet, depending on the availability of samples from the 300- to 400-foot intervals. On the basis of the data from spot sampling sites, the

TABLE 7.—*Chemical analyses of selected surface-water samples from streams that flow into D.I. Khan District*

[Analyzed at the Quality of Water Laboratory, WASID, WAPDA, Lahore. See pl. 1 for location of sampling sites]

Sampling site	Stream	Date sampled	Milliequivalents per liter				
			Calcium (Ca)	Magnesium (Mg)	Sodium + potassium (Na+K)	Carbonate (CO_3)	Bicarbonate (HCO_3)
1	Alīwāla Nāla	11- -62	0.97	1.35	40.66	1.40	6.00
3	Tānk Zām at Jandola.	12- 6-61	.58	.18	.41	0	.75
		8-19-62	1.75	3.61	5.58	0	2.90
		2-19-63	2.16	.54	.20	0	2.62
10	Gumal River	12- 6-61	3.30	3.74	7.75	0	3.62
		9-14-62	2.50	4.21	7.04	0	2.30
		4-21-63	2.24	5.96	12.97	0	4.96
14	Khora River	4- -62	3.02	3.34	3.42	0	3.66
15	Khora River	12- 7-62	4.02	4.75	1.61	0	3.95
21	Khuiwāli (Nāla)	1963	4.41	9.07	3.03	0	7.12

distribution of water of different chemical-quality ranges was delineated by the patterns shown on plate 6. Graphic representation of the several chemical types of surface and ground waters is given in figures 15 and 16, respectively.

DISTRIBUTION OF CHEMICAL TYPES OF WATER

Direct precipitation contributes some small amount of recharge that contains little mineral matter, but the main sources of recharge are the surface waters that are already mineralized when they reach the recharge areas in the District.

Surface waters in D.I. Khān District contain small to moderate quantities of dissolved solids that may be divided into several types. The Indus River is the source of the best quality water. About 80 percent of its flow occurs during the kharif season when runoff occurs from snowmelt and monsoon rains. During this season, the river carries a calcium bicarbonate water that contains 150 to 170 ppm of dissolved solids (Greenman and others, 1967). During the winter, however, the return of bank storage into the Indus and into the larger tributaries, such as the Kurram River in Bannu District to the north of the project area, modifies the quality of water. A sample taken at D.I. Khān town in November 1962 showed that the Indus River water at that point and time was a calcium magnesium sulfate water (fig. 15).

The western tributaries also carry water of low dissolved-solids concentration in the sporadic periods of flooding during the summer monsoon and occasional storms at other times in the year. Tānk Zām, for example, carried a calcium magnesium bicarbonate water on Dec. 6, 1961, during floodflow (fig. 15). During most of the year, however, the western tributaries carry water during low flow that contains 300 to 1,000 ppm of dissolved solids and that generally is

TABLE 7.—*Chemical analyses of selected surface-water samples from streams that flow into D.I. Khān District*—Continued

Milliequivalents per liter				Parts per million			Specific conductance in micromhos per cm at 25°C	pH	SAR
Chloride (Cl)	Sulfate (SO_4)	Nitrate (NO_3)	Total cations or anions	Silica (SiO_2)	Boron (B)	Total dissolved solids, by evaporation			
2.32	33.26	----	42.98	----	----	2,860	4,000	8.5	36
.24	.18	----	1.17	----	----	76	110	7.0	.7
1.04	7.00	----	10.94	----	----	650	1,000	7.4	3.6
.18	.10	----	2.90	----	----	176	270	7.5	.17
2.81	8.36	----	14.79	----	----	944	1,400	7.9	4.1
1.45	10.00	----	13.75	----	----	825	1,260	7.7	3.7
4.36	11.80	0.05	21.17	17	0.25	1,360	2,100	7.2	6.4
.62	5.50	----	9.78	----	----	580	900	7.2	1.9
.63	5.80	----	10.38	----	----	660	1,000	8.0	.77
.76	8.51	.12	16.51	26	0	1,000	1,530	7.2	1.2

TABLE 8.—*Chemical analyses of ground water from selected test holes in D.I. Khān District, 1962-64*

[Analyzed at the Quality of Water Laboratory, WASID, WAPDA, Lahore. Tr, trace]

Test hole	Date sampled	Depth (ft.)	Milliequivalents per liter: Calcium (Ca)	Magnesium (Mg)	Sodium + potassium (Na + K)	Carbonate (CO_3)	Bicarbonate (HCO_3)	Chloride (Cl)
2A	5-21-63	94-114	21.63	53.67	449.07	0	3.86	104.00
		483-513	4.22	1.41	10.64	0	2.81	1.30
		642-662	6.90	2.60	10.86	0	1.52	1.20
6A	1-24-63	168-178	8.61	8.19	12.30	0	5.87	5.30
		515-525	4.41	3.81	4.35	0	4.68	1.75
7	12-26-62	120-147	27.19	82.96	209.25	0	2.75	134.00
		460-481	22.66	10.22	16.70	0	1.70	3.40
8	3-25-63	154-170	5.39	4.79	20.48	0	2.75	4.17
		242-260	8.59	8.01	27.14	0	1.69	12.22
		635-653	6.19	6.81	16.64	0	1.36	6.21
14	4-30-63	84-105	2.50	6.80	9.38	0	5.60	3.20
	4-29-63	174-195	1.74	8.66	8.93	0	5.21	3.10
	4-30-63	275-295	2.26	5.04	5.31	0	4.82	1.70
	4-29-63	420-441	1.17	1.78	1.94	0	3.14	.60
	4-29-63	632-653	.69	.66	3.08	0	2.91	.55
	4-27-63	1,300-1,320	.85	.70	2.51	0	2.63	.45
16	8-26-63	127-147	19.89	19.81	31.76	0	2.10	8.12
		216-236	23.46	19.19	47.92	0	1.99	14.65
		298-318	21.73	25.57	96.62	0	2.68	28.51
	8-25-63	440-460	11.51	23.87	29.27	0	1.42	5.54
	8-24-63	920-940	18.38	10.92	21.37	0	1.62	3.36
18	11-27-63	256-271	5.63	4.17	6.34	0	1.89	1.86
	11-26-63	319-334	5.66	4.24	6.28	0	2.07	1.37
	11-26-63	414-429	3.83	6.47	2.88	0	3.20	1.18
21	9-23-63	125-145	5.46	12.84	11.25	0	8.00	1.53
22	8-26-63	47-70	24.58	18.54	49.66	0	2.20	19.01
		100-111	24.79	26.16	75.08	0	3.20	33.46
		175-215	22.23	21.37	38.07	0	1.00	17.62
		378-401	26.11	21.44	85.20	0	1.63	38.02
	8-25-63	524-547	23.15	18.00	48.43	0	2.00	20.59
	7-29-63	650-680	22.18	15.79	58.49	0	1.90	20.24
	8-25-63	767-790	24.38	13.35	57.66	0	1.47	23.56
	8-19-63	963-988	10.50	5.88	26.53	0	1.31	3.76
26	3- 1-64	180-190	.95	19.80	149.83	0	1.89	130.34
	1-24-64	570-585	8.43	9.81	29.19	0	1.08	10.30

of mixed types—calcium magnesium sulfate, sodium sulfate chloride—depending on the relative amounts of water contributed by the several branches of each tributary, the amount of runoff from snowmelt or precipitation in the water, and the amount of evapotranspiration along the mountain reaches of the streams.

In the District, ground water beneath the piedmont plain generally is more uniform as to chemical type. In the greater part of the District, the sodium and sulfate ions dominate among the dissolved solids in the ground water. Along the margins of the District there are areas of bicarbonate waters, and along the western margin ground water with low dissolved-solids concentration is generally a calcium magnesium type, in which magnesium is, in some cases, a dominant constituent.

North of D.I. Khān town in the thick Punjab-type sand deposits near the Indus River, ground water with as little as 240 ppm of dissolved solids extends as deep as 1,300 feet. Water in these sand deposits is mainly a calcium bicarbonate type derived from the river but changes to a sodium type as it moves through the aquifer and away from the river.

TABLE 8.—*Chemical analyses of ground water from selected test holes in D.I. Khān District, 1962–64*—Continued

Milliequivalents per liter				Parts per million					
Sulfate (SO_4)	Nitrate (NO_3)	Fluoride (F)	Total cations or anions	Silica (SiO_2)	Boron (B)	Total dissolved solids, by evaporation	Specific conductance in micromhos per cm at 25°C	pH	SAR
416.30	0.19	0.02	524.37	16	0	28,300	41,000	7.4	89
12.13	.01	.02	16.27	16	.10	1,070	1,550	7.3	6.5
17.64	Tr	Tr	20.36	16	.15	1,330	1,950	7.1	4.9
17.93	----	----	29.10	8	1.1	1,800	2,700	7.8	4.2
6.14	----	----	12.57	8	.20	730	1,100	7.6	2.1
132.65	----	----	269.40	----	----	14,500	22,000	7.9	38
44.48	----	----	49.58	----	----	3,090	4,700	7.8	4.1
23.64	.06	.04	30.66	8	.57	1,940	2,900	7.2	9.0
29.68	.10	.05	43.74	7	1.37	2,840	4,300	6.8	9.4
22.04	.03	Tr	29.64	6	.54	1,850	2,800	7.3	6.5
9.86	.02	0	18.68	10	.25	1,240	1,850	7.7	4.3
11.00	.02	0	19.33	12	.15	1,170	1,750	7.7	3.9
6.08	.01	0	12.61	12	.05	770	1,160	7.7	2.8
1.13	.01	.01	4.89	10	0	290	460	7.5	1.6
.97	0	0	4.43	8	.15	260	400	7.3	3.7
.98	0	0	4.06	9	0	240	380	7.6	2.9
61.20	Tr	.04	71.46	15	1.15	4,270	6,400	7.8	10
73.90	Tr	.03	90.57	20	.42	5,630	8,400	7.5	10
112.65	.05	.03	143.92	12	1.15	9,100	13,600	7.5	20
57.66	Tr	.03	64.65	10	.47	4,020	6,000	7.1	6.9
45.64	Tr	.05	50.67	13	.47	3,150	4,700	7.4	5.7
12.15	.24	Tr	16.14	Tr	.32	965	1,550	7.2	2.9
12.46	.28	Tr	16.18	5	.30	970	1,510	7.2	2.8
8.57	.12	Tr	13.07	5	.25	770	1,200	7.2	1.2
20.01	.01	Tr	29.55	12	.35	1,880	2,800	7.6	3.7
71.30	.21	.04	92.76	13	.47	5,760	8,600	7.4	10
89.26	.07	.04	126.03	20	.80	7,640	11,400	7.4	14
63.00	.03	.02	81.67	17	.52	5,230	7,800	7.6	7.9
93.00	.07	.03	132.75	16	.77	7,500	11,200	7.6	18
66.83	.10	.04	89.58	11	.47	5,560	8,300	7.3	11
72.70	1.60	.02	96.46	11	0	5,300	8,000	7.2	13
70.30	.05	.01	95.39	16	.52	5,900	8,800	7.3	13
37.30	.02	.02	42.41	12	.42	2,680	4,000	7.7	9.3
36.45	1.90	Tr	170.58	1	.57	9,230	14,000	7.5	46
36.01	.04	0	47.43	1	.42	3,000	4,500	7.3	9.7

At the northern edge of the District and in some other areas, in rocks of the Siwalik Group, and in fill immediately derived from those rocks, bicarbonate concentrations of as much as 16 epm (equivalents per million) occur in waters containing from about 1,200 ppm to as much as 14,000 ppm of total dissolved solids. The high concentrations, of course, are extreme values and were found only in a few samples. Many of the water samples from the immediate derivative of the Siwalik rocks contained less than 1,000 ppm of dissolved solids and were predominantly sodium bicarbonate waters.

In the remainder of the District—the larger central part—sulfate waters are dominant, and wherever the ground water is usable with respect to sulfate, it generally is usable with regard to the other anions. A statistical sampling of the chemical analyses of ground water from test holes points out the prevalence of sodium and sulfate in the District.

The following table shows the distribution of ionic concentrations of 50 percent or more of the total cations or anions in 128 samples from test holes:

Ion	Number of samples	Percent of total
Sodium	87	68
Sulfate	89	70
Bicarbonate	18	14
Chloride	5	4
Calcium	2	2
Magnesium	1	1

In the remaining analyses the more uniform distribution of ionic concentration led to classification of the waters as "mixed." In 56 of the 128 samples magnesium exceeded calcium, again a condition that would appear anomalous in most ground-water provinces. The relatively high magnesium concentrations are possibly derived from poorly flushed marine rocks of Tertiary age whose debris makes up a part of the unconsolidated fill.

With respect to minor constituents, among those analyses which included fluoride determinations, no sample considered to be fresh

TABLE 9.—*Chemical analyses of ground water from selected shallow wells, tubewells, and springs in D.I. Khān District*

[Analyzed at the Quality of Water Laboratory, WASID, Lahore. Tr, trace; OW, open well; HP, hand pump; TW, tubewell; IBTW, Irrigation Branch (PWD) tubewell; PW, Persian well. For locations of wells and springs see pl. 1]

Well	Date sampled	Depth (ft.)	Milliequivalents per liter: Calcium (Ca)	Magnesium (Mg)	Sodium + potassium (Na + K)	Carbonate (CO_3)	Bicarbonate (HCO_3)	Chloride (Cl)	Sulfate (SO_4)	Nitrate (NO_3)
1	11–62	10	0.54	1.08	4.00	0	4.10	0.19	1.33	----
4	11–62	50	.12	1.09	18.67	0	11.10	.67	8.11	----
6	11–62	Spring	2.78	.98	1.86	0	2.50	.24	2.88	----
7	1963	----	3.47	.11	1.51	0	2.88	.40	2.56	.05
9	1963	----	1.01	.97	3.79	0	3.62	.95	1.19	.01
11	11–62	Spring	3.56	7.57	11.27	0	3.80	1.84	16.76	----
12	11–62	60	16.45	11.73	47.59	0	3.70	9.02	63.05	----
17	11–62	10	3.74	5.23	5.96	0	3.70	2.63	8.60	----
21	11–62	34	8.06	.70	5.04	0	4.09	1.90	7.81	----
23	11–62	32	40.00	11.88	55.37	0	15.37	16.68	75.27	----
27	12–62	20	3.28	3.63	2.27	0	5.82	1.35	2.01	----
37	12–62	20	4.60	1.46	4.56	0	5.46	1.56	3.60	----
42	12–62	180	4.64	6.45	11.68	0	4.85	2.82	15.10	----
53	12–62	200	4.20	3.73	4.15	0	4.60	1.19	6.29	----
73	12–62	----	5.78	7.78	8.06	0	6.37	3.64	11.61	----
78	12–62	236	1.29	2.62	2.76	0.10	3.95	.72	1.90	----
99	11–62	237	3.14	5.49	23.65	1.20	2.30	6.25	22.53	----
105	11–62	30	----	----	----	----	----	----	----	----
107	11–62	115+	20.80	23.10	15.05	0	9.28	12.90	36.77	----
108	11–62	84	24.00	17.66	51.09	0	7.37	22.90	62.48	----
112	12–62	----	2.34	3.30	1.86	0	1.55	1.10	4.85	----
129	12–62	177	2.35	5.50	1.87	0	4.00	1.06	4.66	----
135	12–62	180	5.33	8.47	8.30	0	3.82	4.10	14.18	----
154	12–62	171	5.62	4.42	11.68	0	4.20	3.25	14.27	----
155	12–62	25	4.23	1.95	7.94	0	4.70	1.26	8.16	----
160	12–62	----	13.79	18.54	15.55	0	9.10	5.33	33.45	----
162	12–62	174	13.06	4.44	9.02	0	5.50	3.49	17.53	----
166	12–62	----	26.49	25.71	3.55	0	9.60	12.22	33.93	----
172	12–62	191	3.26	2.80	5.29	0	4.50	.87	5.98	----
175	8–19–63	105	8.01	9.93	13.04	0	4.68	1.68	24.22	.40
179	3–16–64	32	16.48	11.92	5.02	0	3.49	1.86	28.07	Tr
180	3–16–64	18	2.78	2.82	3.00	0	4.41	1.27	2.82	.1

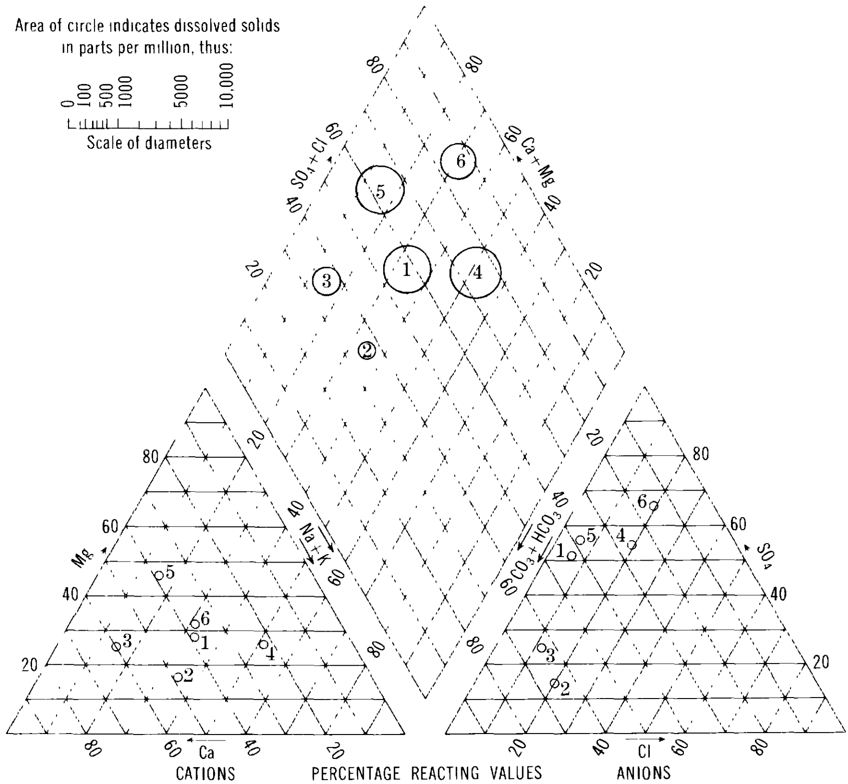
or usable for domestic purposes contained large amounts of fluoride. Some of the samples from shallow wells and some from shallow zones in the test holes contained nitrate in excess of 0.3 epm, which generally is considered to be indicative of contamination by organic sources. Among those analyses that included boron determinations, most showed low concentrations, but a few samples contained boron in excess of 1.0 to 1.5 ppm, the concentration at which damage begins in boron-sensitive crops. Sources that showed rather high boron concentrations included the Tānk Zām and the Gumal River and tubewells in a part of the area along the Indus River lowland south of D.I. Khān town.

In a belt that trends southward and is roughly alined with the ground-water discharge area, all or most of the ground water sampled is too poor in chemical quality for any present use.

Marked changes in water-quality type and in total dissolved solids within short distances, both horizontally and vertically, are

TABLE 9.—*Chemical analyses of round water from selected shallow wells, tubewells, and springs in D.I. Khān District*—Continued

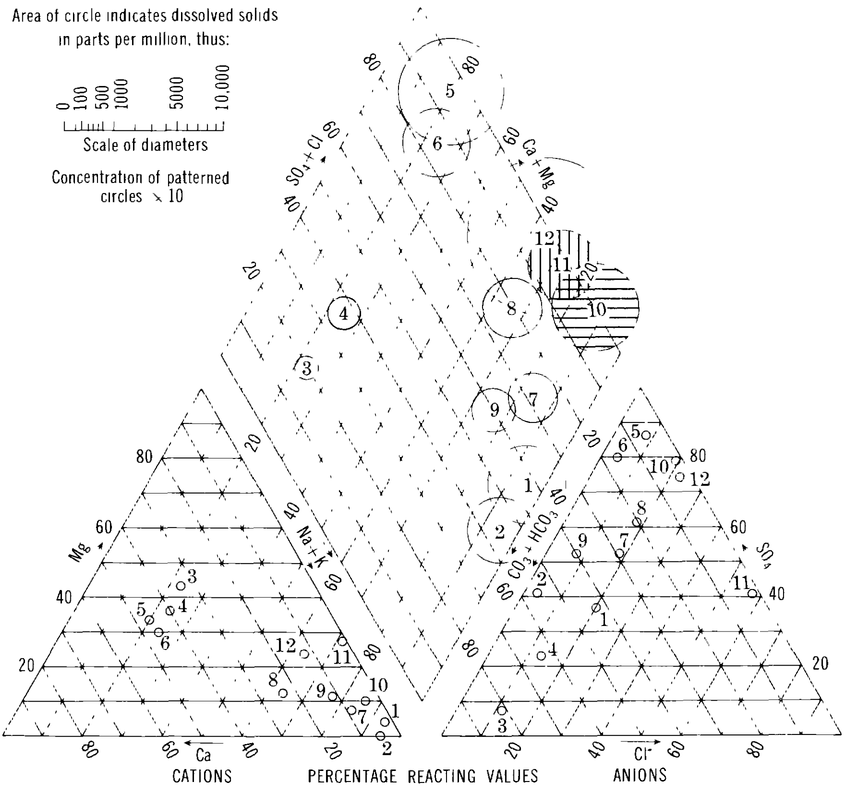
Milliequivalents per liter		Parts per million			Specific conductance in micromhos per cm at 25°C	pH	SAR	Remarks
Fluoride (F)	Total cations or anions	Silica (SiO_2)	Boron (B)	Total dissolved solids, by evaporation				
----	5.62	----	----	360	525	8.1	3.7	Frontier Constabulary Post at Bain.
----	19.88	----	----	1,220	1,900	8.2	24	OW at Ama Khel.
----	5.62	----	----	340	525	7.6	1.4	Spring near Pezu.
0	5.89	17	0	368	570	7.2	1.0	HP at Kot Shaikh Budīn.
0	5.77	16	0	345	530	7.3	3.8	HP at Chasma Headworks
----	22.40	----	----	1,360	2,050	7.8	4.4	At Paniāla. From pipeline
----	75.77	----	----	4,840	7,250	7.7	13	HP at Gul Imām.
----	14.93	4	1.80	960	1,450	7.9	2.8	OW at Kaur Post.
----	13.80	----	.80	860	1,300	7.6	2.4	OW at WAPDA Rest House Kot Murtaza.
----	107.25	----	----	6,900	10,500	8.1	15	OW at Garah Muhammad Akbar.
----	9.18	----	----	512	900	8.1	1.3	HP at Kotla Rest House.
----	10.62	----	----	612	1,000	8.2	2.6	HP at Pahārpur.
----	22.70	----	----	1,430	2,200	8.0	4.9	TW 1 mile west of Kech.
----	12.08	----	----	710	1,150	8.2	2.1	IBTW 1–B.
----	21.62	----	----	1,280	2,150	8.2	3.1	HP at Himmatwāla.
----	6.67	----	----	370	600	8.3	1.9	IBTW 16–B.
----	32.28	7	1.52	2,100	3,000	8.3	1.5	IBTW 6–C.
----	----	----	----	----	1,080	8.2	----	OW at Frontier Constabulary Post at Darābn.
----	58.95	----	----	3,540	5,500	7.9	3.0	OW at Sheru Kohna.
----	92.75	----	----	5,460	8,500	7.7	11	OW at Zindāni.
----	7.50	----	----	446	700	8.1	1.1	HP at Bridges and Roads Rest House in D.I. Khān
----	9.72	----	----	620	900	8.1	.90	IBTW F.A.
----	22.10	----	----	1,328	2,075	7.8	3.2	IBTW 2–A.
----	21.72	----	----	1,290	2,000	8.1	5.2	IBTW 16–A.
----	14.12	----	----	845	1,300	8.1	4.5	PW at Kacha Babar.
----	47.88	----	----	3,000	4,500	7.6	3.8	HP at Paroa.
----	26.52	----	----	1,680	2,600	8.1	2.9	IBTW 19–A.
----	55.75	----	----	3,330	5,200	7.5	1.0	HP at Māhrān.
----	11.35	----	----	675	1,050	7.9	3.0	IBTW 27–A.
0	30.98	14	.37	1,980	3,000	7.5	4.2	OW 100 yards east of rest house at Kirri Shamozai
----	33.42	19	.42	2,080	3,200	7.2	1.3	OW in Triman village, D.G. Khān District.
----	8.60	19	.05	550	850	8.1	1.8	OW in Bukhāra villge, D.G. Khān District.



Number and locality	Date	Dissolved solids (ppm)	Stream stage
(1) Tānk Zām at Jandola	12–24–61	536	Low flow.
(2) Do	12– 6–61	76	Flood flow.
(3) Gumal River near Kot Murtaza	3–21–63	220	Flood flow.
(4) Do	12–23–61	948	Low flow.
(5) Khora River at Zām Tower	12– 7–62	660	Low flow.
(6) Indus River at D.I. Khān	11– –62	354	Low flow.

FIGURE 15.—Chemical character of selected surface-water samples.

common in D.I. Khān District. This occurrence is illustrated in the tables of analyses of ground water (tables 8, 9, and 10), the composite logs and geologic sections (pls. 3 and 4), and the map of chemical quality (pl. 6). Immediately west of the area of tubewells west of the town of D.I. Khān, highly mineralized water adjoins and underlies the fresh water in the Punjab-type sands. In almost all the District, ground water of poorest quality occurs in the shallowest zone, and the quality improves with depth. In test holes 9A and 15, however, the deepest sampled zone has water of poorer quality than that from zones of a shallower depth. In the area of highly mineralized water, the deepest water samples had the least dissolved solids, but the shallower highly mineralized water is overlain by a thin zone of water of slightly better chemical quality. The zoning of quality with depth is related to the pattern of flow of the ground water from the eastern and western recharge areas toward the discharge area. At great depth beneath the main zone of active ground-water circulation, it is probable that the ground water is again highly mineralized. Such poor-quality water probably occurs at relatively great depths—more than 1,500 feet below the flood plain of the river and more than 1,000–1,200 feet below the piedmont plain.



Number	*Date*	*Dissolved solids (ppm)*	*Depth in aquifer (ft)*
(1) TH–1	2–21–63	2,070	97–117
(2) Well 4	11– –62	1,220	50
(3) TH–9	3–16–63	205	569–589
(4) TH–14	4–29–63	290	420–441
(5) TH–6B	2–11–63	3,330	90–100
(6) TH–15	10–30–63	1,500	638–661
(7) TH–4	4–13–63	740	396–416
(8) TH–7A	4–16–63	1,100	84– 99
(9) TH–21	9–19–63	600	710–731
(10) TH–2A	5–21–63	28,300	94–114
(11) TH–11	4–21–63	15,400	332–352
(12) TH–19	6–26–63	9,250	196–216

FIGURE 16.—Chemical character of selected ground-water samples.

TABLE 10.—*Specific conductance, in micromhos at 25°C, of ground water from three irrigation tubewells in D.I. Khān District, 1958–62*

Well	Depth (ft)	Specific conductance						
		1958(?)[1]	Jan. 1960	May 1960	Apr. 1961	Apr. 1962	June 1962	Dec. 1962
99 (IB 6C)	60	585	----	----	----	----	----	----
	85	1,525	----	----	----	----	----	----
	145	900	----	----	----	----	----	----
	220	2,200	----	----	----	----	----	----
	237	2,900	4,810	5,190	4,700	3,200	----	3,000
109 (IB 7C)	80	1,600	----	----	----	----	----	----
	145	870	----	----	----	----	----	----
	165	1,850	----	----	----	----	----	----
	240	4,900	----	----	----	----	----	----
	260	5,750	3,000	4,480	4,470	----	----	----
117 (IB 10C)	45	1,700	----	----	----	----	----	----
	80	1,600	----	----	----	----	----	----
	145	1,600	----	----	----	----	----	----
	180	2,000	----	----	----	----	----	----
	230	2,300	3,820	4,480	4,470	4,000	3,700	4,500

[1] Record from time of installation.

SOURCES OF MINERALIZATION

The dissolved solids in ground water in D.I. Khān District are derived from the rocks through which the water moves and also from streams recharging ground water. The process of evapotranspiration also contributes markedly to progressive concentration of dissolved solids in the ground water.

The contribution of soluble minerals from the rocks to the water moving through them is readily apparent from the observed lower concentrations of dissolved solids in recharge waters and the increase in mineralization in ground water deep within the unconsolidated rocks, well removed from the immediate effects of evapotranspiration. Recharge water from direct precipitation has little mineral content, but the recharge water from streams already is somewhat mineralized. Water from the Indus River generally contains less than 200 ppm of dissolved solids. Recharge water from Tānk Zām and the Gumal and Khora Rivers contains dissolved-solids concentration in the order of 600 ppm. Although the tributaries contain water of low mineralization during periods of flood, the bulk of recharge water from them is derived from the low flow that is more mineralized.

In addition to the immediate surface-water sources of recharge, it appears that the unconsolidated fill receives some water by interformational leakage from the older semiconsolidated rocks of the Siwalik Group. The older rocks are partly coarse grained and permeable and, therefore, are susceptible to recharge in their outcrop area by direct precipitation. In zones deep within the unconsolidated fill in test holes near the western boundary of the study area evidence for interformational leakage is the presence of bicarbonate water of lower mineralization than the waters in the western tributaries. In test hole 21, for example, water from the zone 965–985 feet contained only 380 ppm of dissolved solids but contained 3.45 epm of bicarbonate and 2.95 epm of sodium. Similar conditions were noted in test holes 6, 6A, and 15, all near outcrops of the Siwalik Group.

Within the unconsolidated fill, water from the recharge sources moves through predominantly fine-grained deposits which contain some soluble mineral matter, of which sulfate minerals are an important part. Bedded sulfate minerals were found in the rocks of Tertiary age in the mouth of the Khora River gorge, and detrital fragments of gypsum were found near the gaging station near Kot Murtaza (surface-water site 10, pl. 1). W. R. Hemphill and A. H. Kiawai (written commun., 1964) also report the presence of sulfate minerals in the shale of Tertiary age south of Drazinda. Debris from these sources make up a part of the unconsolidated fill. Inspection of the clay samples and cores from such test holes as TH–13 showed that they contained discrete crystals and fragments of sulfate minerals, some of which appear to have grown *in situ.*

The recharge water along the western side of the District enters the unconsolidated fill as, or becomes, a calcium magnesium sulfate water at low concentrations. As the water moves farther through the reservoir, it becomes a sodium water, probably mainly by base-exchange reaction, and acquires an increasing concentration of sodium and sulfate. That sulfate is the dominant anion is shown by the fact that chloride exceeds sulfate only in a very few samples; these anomalies were mainly in very highly mineralized water from the center of the District.

The relatively high mineralization in much of the shallow ground water is due not only to the acquisition of soluble mineral matter from the rocks but also to the effects of evapotranspiration. Interpretation of conditions in the District indicates that evapotranspiration occurs in most of the District, even where the water table is 50 to 80 feet deep. As a result of this process, the mineral content of the shallow water becomes concentrated to a level several times greater than that of water a few feet to a few tens of feet deeper. The higher concentrations in the shallow ground water also are due in part to irrigation. The mineral content of surface water used for irrigation is concentrated by evapotranspiration at the land surface and by leaching of salts accumulated in the soil profile. The flushing of salts to the water table takes place chiefly during occasional flooding and excessive applications of water, but in most areas flushing is negligible because applied water is directly dissipated by evapotranspiration in the soil zone. In areas of large-capacity tubewells and a few surface-supplied ditches in the western part of the District, flushing of salts to the shallow ground water is continuous, owing to the large amounts of water available and used for irrigation.

In part of the tubewell areas, where all the ground water is known to be fresh, an increase in mineral content of the pumped water has been noted. This increase in mineral content is interpreted as the result of recent leaching of soils and other unconsolidated deposits by return irrigation water. Although the soils are water laid and are occasionally flooded, substantial amounts of soluble mineral matter are still available for solution and transport to the water table.

The occurrence of the belt of saline ground water along the central part of the District is due not only to the ready availability of soluble mineral material in the silty clay that predominates there but also to slow ground-water circulation. The slow circulation in turn is due both to the low permeability of the clay and to near stagnation of the water because of the balance between recharge and natural discharge on either side of the belt of saline water. Thus the ground water in the saline belt is in contact with the sources of mineral matter much longer than is the ground water in the more permeable deposits on either side.

The occurrence of the highly saline waters in some of the sand beds east of the main belt of saline water appears to indicate that stagnation is not complete and that a small part of the water in the District may be discharging slowly south-southeastward toward the Indus River or into the area of Thal Doāb. The water in the sand beds in the saline belt, as for example near test holes 11 and 23, is the source of the saline water obtained from tubewells along the western edge of the tubewell development west of D.I. Khān town. There, drilling by the Irrigation Branch, PWD, has shown that wells put down to depths of about 200 feet or more pass into sands that contain more highly mineralized water (table 10).

WATER DEVELOPMENT AND POTENTIAL CHANGES IN QUALITY

Because most surface-water sources are now fully utilized insofar as is now feasible, water-quality problems resulting from further development of these sources are not likely in the immediate future. When the Gumal River Development Scheme becomes operative, however, and if a barrage is installed at the site of Chasma Headworks, changes in the quality of both ground and surface water are likely to result.

The presence of saline ground water also eliminates a rather large part of D.I. Khān District from immediate consideration for ground-water development. All the north-central part of the District and a belt through the central and southern part, extending to the flood plain of the Indus River in the southern part, contain poor-quality water to depths of 400 to 500 feet. In the poorest quality areas, the shallow water contains 2,000 to 4,000 ppm of dissolved solids, and this water overlies water of still poorer quality, containing as much as 10,000 ppm of dissolved solids. Below this general zone, the quality of water improves with depth. These areas are delineated on plate 6.

In the northern two-thirds of the Indus River flood plain and adjacent terraces, most of the ground water available for development has the Indus River as its source and is of suitable quality for both irrigation and domestic supply.

Elsewhere in the District, good-quality water that is suitable for both irrigation and domestic supply is available, but to obtain such water uncontaminated by the saline water in the shallow zone, it is necessary to drill wells to the zones containing fresher water and to case off tightly water in the shallow zone. The installation of such supply wells should do much to alleviate the scarcity of good-quality water in areas where some villagers now must travel several miles or more on foot or by animal transport to obtain potable domestic water.

Changes in the quality of water in D.I. Khān District are likely to result from three sets of conditions: (1) Pumping from wells in areas adjacent to those containing saline water, (2) irrigation by Indus River water of additional lands from expanded canal systems, and (3) operation of the Gumal River Development Scheme.

With respect to the effects of pumping, such changes already are in progress, and additional changes may occur in the future. Table 10 shows the specific conductance of water from three wells west of D.I. Khān. It shows that the water near the bottoms of the wells is more mineralized than that water in the upper part of the aquifer. After completion of the wells, the quality of the pumped water proved to be worse than that of most of the samples taken while drilling. This resulted from the movement of highly mineralized water into the wells, because pumping created hydraulic gradients toward the wells and thus drew the mineralized water in from the west and from below. As pumping continued, however, differences appeared in the water quality of all three wells. Water from well 99 at first deteriorated and later apparently improved slowly. Water from well 109 progressively deteriorated over a period of several years, and eventually the well was abandoned. In well 117, the water quality at first deteriorated and then stabilized on a fluctuating base. Because part of the present area of tubewell development and parts of other areas of potential development are close to the areas of saline ground water, it can be expected that dissolved-solids content of water from some wells will gradually increase. This increase will occur because the pumping of water creates steeper hydraulic gradients from the saline-water areas toward the wells. On the other hand, the quality of water from some wells that are now saline can be expected to improve, because pumping also increases the gradient from the Indus River, and thus the river-water recharge will move toward the wells at an increased rate. Such changes generally will be slow.

Additional canal water from the Indus River will probably flush the deeper aquifers during a period of decades. The principal effect, however, will be the probable development of waterlogging and concurrent salinization of soils in low areas due to the rising water levels that would result from the additional canal supplies. Such conditions already have been amply demonstrated in the main part of the Punjab Plain.

The effect of the Gumal River Development Scheme on the quality of ground water beneath the piedmont plain will probably be more complex because of several additional factors involved. First, the impoundment and mixing of the Gumal River water in most years would lead to a better average quality of recharge water from the river, but on the other hand, the rate of ground-water recharge may be considerably reduced by (1) the diversion of the water past the intake on the gravel fans at the mouth of the Gumal River gorge and its vicinity, and (2) the spread of water from a few established channels where excess water provides recharge to a broad area of fields where most if not all water is consumed. The latter condition also would result in even more saline water in both the shallow and deep zones. These are only a few of the potential changes that can occur in the area of development, but they are sufficient to indicate that further water-quality studies are necessary to assess the direction and magnitude of potential changes in the chemical quality of ground water there and, therefore, to assess the potential for ground-water development in all the D.I. Khān District.

CONCLUSIONS

The hydrologic studies in D.I. Khān District have identified the areas in which ground water of usable chemical quality is available in quantity and quality adequate for tubewell development and for domestic supply. These areas are shown on plate 6 and are described in greater detail in the following paragraphs.

Generally, in the District, surface-water supplies are as fully developed as present economic limitations permit. Available perennial supplies are completely utilized and probably are applied to more land than can be adequately irrigated with the water available. Floodflow also is utilized, but the uncontrolled nature of the flow frequently creates widespread damage that offsets much of the economic gain from use of the floodwater.

The future control and use of surface water from the western tributaries, such as in the Gumal River Development Scheme and from the proposed Indus River Barrage, will change the hydrologic and water-quality regimens of parts of the District. Future studies will be needed to evaluate the probable changes in these regimens in order to mitigate the adverse effects that would tend to offset the benefits of development works.

Ground water in the District is second only to the Indus River as a source of water. Within the ground-water reservoir the only existing and anticipated changes are those that can or will result from saline-water migration into wells from nearby source areas. Otherwise, conditions in the District are stable. The following discussion describes the areas shown on plate 6.

In area 1, extending along the Indus River lowland, ground water occurs in a thick section consisting almost entirely of sand in which most, if not all, of the ground water contains less than 1,000 ppm of dissolved solids. The permeability of the sand approximates that of similar sections in the main part of the Punjab Plain, and owing to the thickness of the sand section in D.I. Khān District, a large quantity of water is therefore available to wells. Test tubewells and tubewells of the Irrigation Branch have shown that a tubewell, 200–300 feet deep, in area 1, can yield 2 to 3 cfs with only moderate drawdown. Development of ground water from this area could, if proper well spacing were observed (1) control or diminish possible future waterlogging and salinization of soils in area 1, (2) provide adequate supplemental water supplies to lands now irrigated from the Pahārpur Canal, (3) provide adequate supplies to lands not irrigated from the canal or now receiving water from the canal only during wet years, (4) and possibly provide some water for export by canal to the south end of the District where most ground water is saline.

Adjacent to area 1, in area 1A, the occurrence of highly mineralized ground water at depths of 200 to 300 feet excludes the potential development of tubewells deeper than about 200 feet. Because the depth to water increases westward and the chemical quality of water deteriorates rapidly in that direction also, the amount of usable ground water in the area is definitely limited, and intensive development is not desirable. In this area it has been demonstrated already that pumping from wells with accompanying decline of water levels will lead to gradual deterioration in water quality. It should be kept in mind, however, that water of marginal quality from this area, if used in an integrated system, could be mixed with water from area 1 or with river water to provide a composite water of usable quality.

The second best area for development in the District is area 2, from the mouth of the Gumal River gorge to the vicinity of Kot Āzam. Here the chemical quality of water is moderately good; the water contains from 500 to 1,500 ppm of dissolved solids, as indicated by test-hole samples; and the aquifer consists mainly of gravel and sand. Wells in area 2 should, therefore, be capable of yielding from 1 to as much as 3 cfs of usable ground water. Depths to water in much of area 2 are about 30 to 50 feet below the land surface, but the depth may be substantially greater beneath the steep alluvial slopes at the foot of the adjacent mountain slopes. In this area, some water samples from both surface and ground-water sources contain moderate amounts of boron; therefore, the boron tolerance of crops is to be considered when crops are watered from those sources.

In area 3, at the base of the mountains near Darāban, and in the central Gumal River drainage near Kulāchi, depths to water are relatively shallow—on the order of 20 to 50 feet. However, to obtain adequate ground water of moderately good chemical quality, it is necessary to drill tubewells to depths of 300 to 400 feet. In the vicinity of Kulāchi, moreover, it is necessary to case off tightly the shallower sand which contains saline water. In the vicinity of Kulāchi and Rori and areas in a similar position, tubewell-construction experience has shown that the presence of fine sand in the aquifer makes the use of manufactured brass and other screen desirable and the careful selection of gravel for use in the gravel envelope essential. The potential yields of wells in area 3 are on the order of 0.5 to as much as 2.0 cfs in those parts of the area near the mountains where gravel beds are penetrated.

Area 4 yields supplies of moderately good to good-quality water, but the depth to water generally exceeds 100 feet. It probably would be necessary to drill to depths of 300 to 400 feet to obtain adequate supplies. Yields in this area, although not tested, probably would be on the order of 1 cfs.

Area 5 is a composite area comprising subareas of both shallow and deep water levels, but on the whole, water levels in most of the area do not exceed 100 feet. On the basis of aquifer tests, the permeability of the sand in area 5 appears to be low, but it is believed that wells yielding about 1 cfs can be installed in much of the area. On the basis of test tubewell-construction experience here, as in area 3, care should be exercised in the selection of well screens and gravel for the envelope of the well. In area 5, the chemical quality of water varies widely, but similar to conditions in area 3, it appears that the deeper sand yields the best quality water and that the shallow sand near the water table should be cased off. Care also needs to be taken in the use of water from area 5, because several analyses of ground water from that area indicate that the use of ground water there might lead to the accumulation of residual sodium bicarbonate in the soil and the development of the so-called black-alkali condition.

Area 6, near the Sūr Ghar Mountains at the end of the Khisor Range, appears to contain ground water of moderately good chemical quality, but the depth of water in much of the area is on the order of 200 to 300 feet. For this reason it does not appear feasible to put down tubewells for irrigation purposes in this area, but wells could be installed to supplement the meager domestic supplies now available. In the valley between the Khisor and Marwat Ranges, no test drilling was done, but the occurrence of springs at Paniāla and the geologic environment suggest that much of the lower valley of the Murin Wāh may contain water-bearing sand that is underlain by older consolidated rocks. This subarea merits further investigation.

It should be noted that the boundaries delineated on plate 6 are only approximate and that further exploratory drilling may reveal minor differences in the quality of ground water both within and outside the boundaries shown.

The remaining part of D.I. Khān District does not seem promising for the development of ground-water supplies of usable chemical quality. Most of the area east and southeast of Tānk contains few aquifers and the few contain highly mineralized water. South-southeast of Kulāchi in the broad area extending through the center of the District, as far south as test hole 22 near the Indus River, all ground water sampled was of very poor chemical quality. For this reason much of the area can be eliminated from consideration for ground-water development.

D.I. Khān District, then, is a broad area in western West Pakistan that has a climate and physiography much like parts of the southwestern United States. Like the southwestern United States, too, the water resources of D.I. Khān District have not been developed to their fullest potential. Unlike much of the Punjab Plain, the District has not yet had to cope in any great degree with the twin problems of waterlogging and soil salinization.

The data and the suggestions for further studies given in this report provide a basis upon which the further development of the District may be planned. Such development, if it is to be of greatest value to Pakistan, should be carried out in a careful, farsighted, and integrated manner that requires adequate planning and consideration of the geologic and chemical factors involved in the changes in the hydrologic regimen resulting from development.

SELECTED REFERENCES

Arif, Abdul Hameed, and Rehman, Ata-ur-, 1960, Analysis of aquifer tests in Rechna and Chaj Doabs: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div. Tech. Paper 2, 10 p.

Bakr, M. A., and Jackson, R. O., compilers, 1964, Geologic map of Pakistan: Quetta, West Pakistan, Geological Survey of Pakistan map.

Bennett, G.D. Rehman, Ata-ur-, Sheikh, I. A., and Ali, Sabir, 1967, Analysis of aquifer tests in the Punjab region of West Pakistan: U. S. Geol. Survey Water-Supply Paper 1608–G, 56 p. 1 pl. 23 figs.

Flint, R. F., 1957, Glacial and Pleistocene geology: New York, John Wiley & Sons, Inc., 533 p., 5 pls., 137 figs.

Fraser, I. S., 1958, Report of a reconnaissance survey of the landforms, soils, and present land use of the Indus Plains, West Pakistan; a Colombo Plan project by the Government of Canada in cooperation with the Government of Pakistan: Toronto, Resource Survey Div., Photographic Survey Corp., Ltd., 401 p., 111 pls., 27 maps.

Greenman, D. W., Swarzenski, W. V., and Bennett, G. D., 1967, Groundwater hydrology of the Punjab, West Pakistan, with emphasis on problems caused by canal irrigation: U. S. Geol. Survey Water-Supply Paper 1608–H, 66 p., 10 pls., 12 figs.

Hiatt, W. E., 1964, Potential evapotranspiration estimates for West Pakistan, *in* White House—Department of Interior Panel on Waterlogging and Salinity in West Pakistan, 1964, Report on land and water development in the Indus Plain: Washington, The White House, January 1964, p. 408–412.

Krishnan, M. S., 1960, Geology of India and Burma: Madras, Higginbothams, Ltd., 604 p.

Pakistan Meteorological Service, 1958, Isohyetal map of West Pakistan: Map H.Q. Met. N, No. 2, Lahore.

Sheikh, Ijaz Ahmad, and Hussain, Ansar, 1960, Analysis of precipitation data from Rechna, Chaj, and Thal Doabs: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div. Tech. Paper 1, 5 p.

Siddiqi, R., and Kazmi, S. A. T., 1963, Geology of Thal Doab: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div. Bull. 7, 33 p., 4 figs.

Survey of Pakistan, 1962, Map of Pakistan [1st ed.]: Rawalpindi, West Pakistan, Survey of Pakistan map, scale 1:2,000,000.

Swarzenski, W. V., 1968, Fresh and saline ground-water zones in the Punjab Region, West Pakistan: U.S. Geol. Survey Water-Supply Paper 1608–I, 24 p., 3 pls., 2 figs.

Thomas, H. E., 1962, The meteorologic phenomena of drought in the Southwest: U.S. Geol. Survey Prof. Paper 372-A, 41 p., pl., 39 figs.

——— 1963, Effects of drought in basins of interior drainage: U.S. Geol. Survey Prof. Paper 372–E, 51 p., 47 figs.

Trewartha, G. T., 1954, An Introduction to climate: New York, McGraw-Hill Book Co., 402 p.

Wadia, D. N., 1961, Geology of India: London, McMillan and Co., Ltd.

West Pakistan Director of Land Records, 1965, Gazette of West Pakistan: Lahore, Jan.–Dec. monthly issues.

West Pakistan Water and Power Development Authority, 1962–64, Annual reports of river and climatological data of West Pakistan, 1960–62: Lahore, West Pakistan, Water and Soils Inv. Div., Surface-Water Circle.

White House—Department of Interior Panel on Waterlogging and Salinity in West Pakistan, 1964, Report on land and water development in the Indus Plain: Washington, The White House, January 1964, 454 p., 31 figs., 5 maps.

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[Italic page numbers indicate major references]

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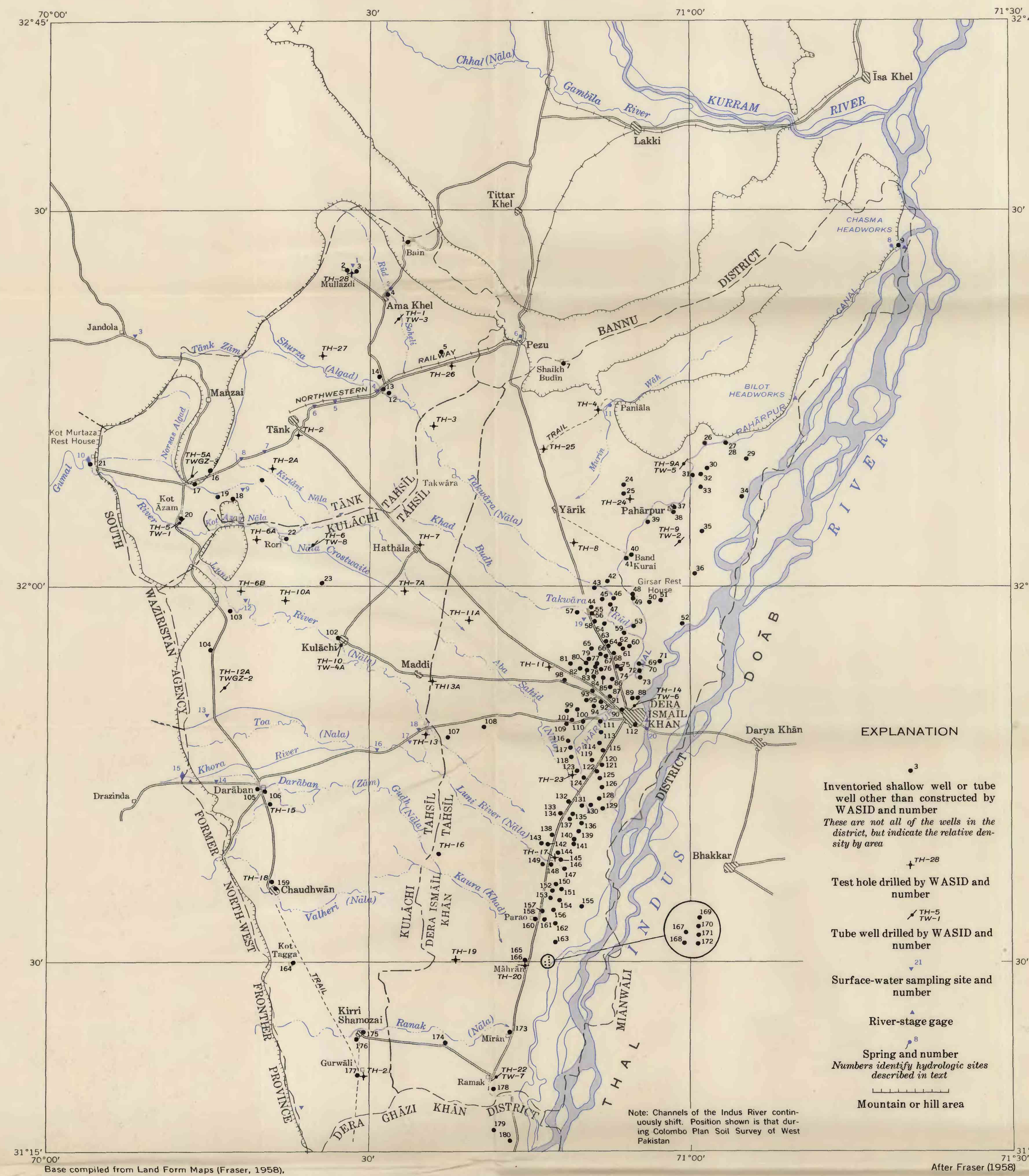
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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

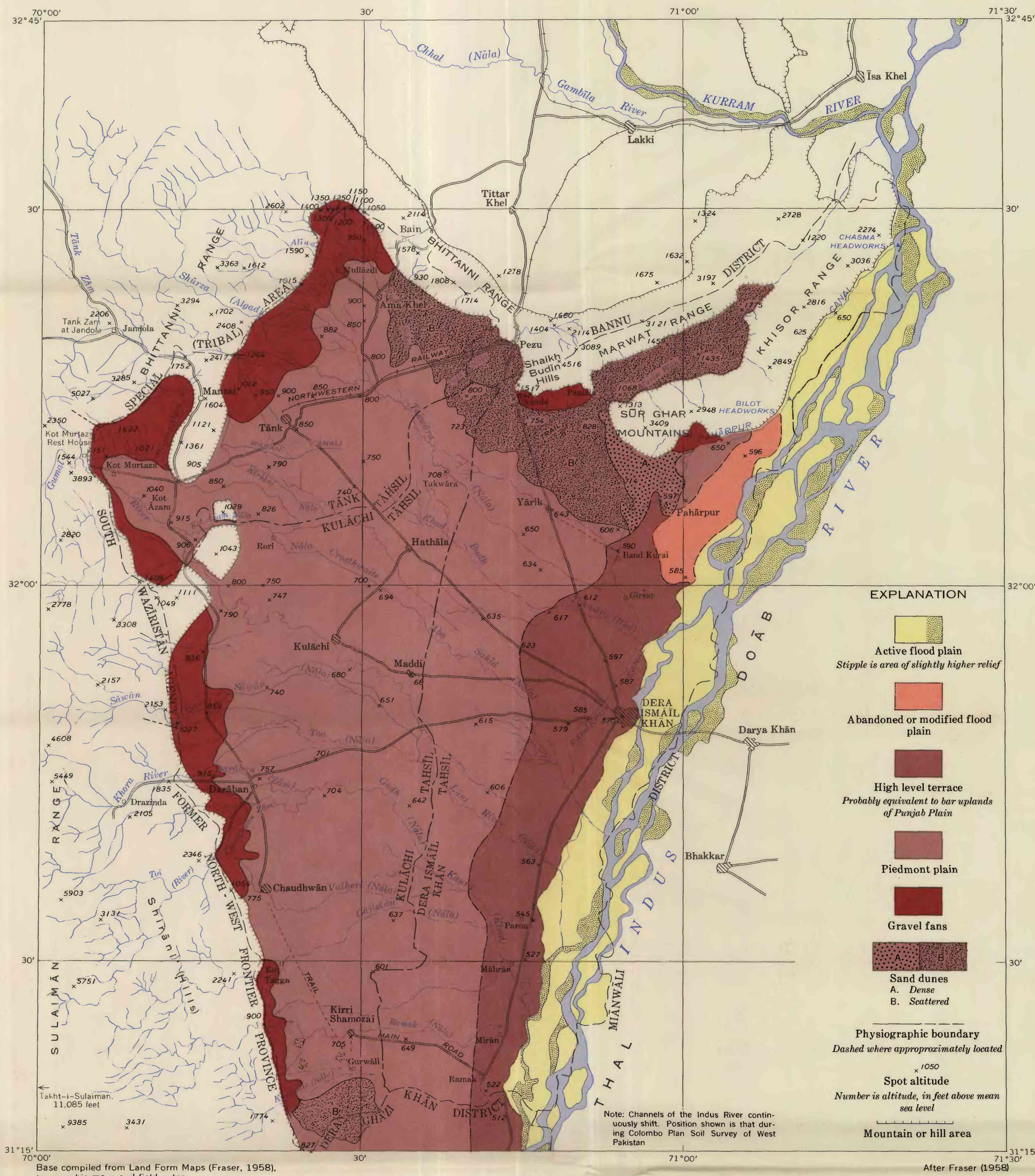
WATER-SUPPLY PAPER 1608-K
PLATE 1



Base compiled from Land Form Maps (Fraser, 1958), topographic maps and field notes

After Fraser (1958)

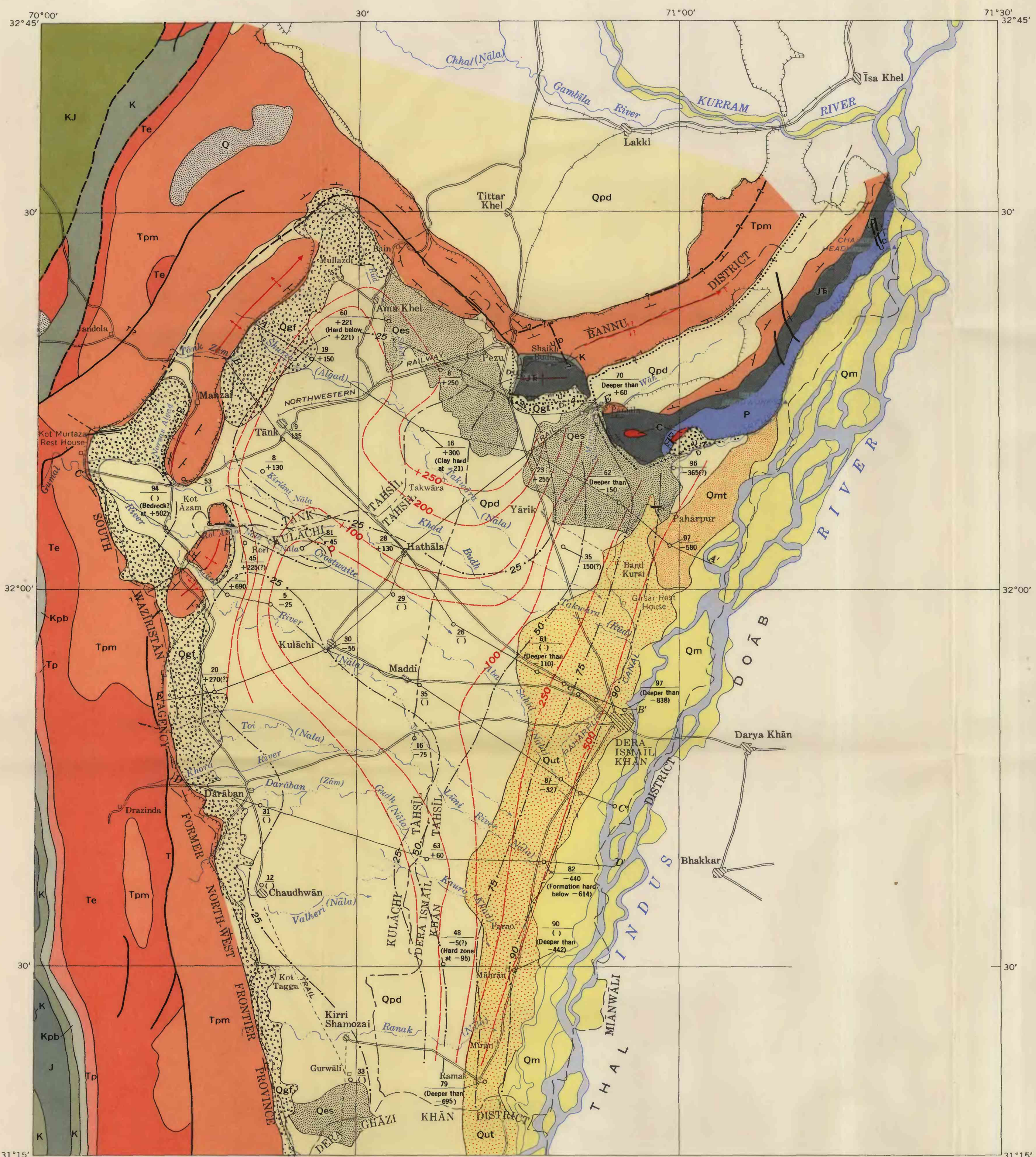
LOCATION OF HYDROLOGIC DATA SITES



Base compiled from Land Form Maps (Fraser, 1958), topographic maps and field notes

After Fraser (1958)

PHYSIOGRAPHY



Base compiled from Land Form Maps (Fraser, 1958), topographic maps and field notes

After Bakr and Jackson (1964) with modifications from Fraser (1958), W. R. Hemphill and A. H. Kidwai (commun.), aerial photographs, and field notes. Positioning of stratigraphic contacts and structural features in upland areas are not considered to be precise as shown on this map, but are included to provide information of the geologic framework in the areas adjacent to the piedmont plain and river lowlands, the principal study area.

GEOLOGY

EXPLANATION

QUATERNARY

Q

Alluvium

Unconsolidated surficial deposits of silt, sand, and gravel

Qm | Qmt | Qut

Stream deposits

Streambed and meander-belt deposits, Qm. *Deposits of the middle terrace,* Qmt; *and the upper terrace,* Qut. *Areas of outcrop are called the active flood plain; abandoned or modified flood plain which partly has been removed by recent erosion; and, following terminology in the Punjab Plain, the bar upland. In some areas, the deposits of the three levels are sharply divided by bluffs; at other locations the division between terrace deposits, especially between* Qut *and* Qpd, *is obscured by erosion in modern stream channels. Both* Qmt *and* Qut *are partly dissected and partly covered with alluvium locally*

Qpd | Qgf | Qes

Piedmont and related deposits

Piedmont deposits, Qpd: *coarse-grained detrital material derived from adjacent highlands; diminishes in grain size eastward toward Indus River. Gravel fan deposits,* Qgf: *small boulders, gravel and other very coarse grained material in that steeply sloping part of the piedmont plain immediately adjacent to the highland sources of the material. Eolian sand,* Qes: *mostly barchan-type sand dunes, ranging from scattered to very dense, as in area north of Paharpur*

TERTIARY

Tpm

Pliocene and Miocene sedimentary rocks

Siwalik Group and the inseparable Nari Formation (Oligocene) in the Sulaimān Range and areas to the northeast: mostly sandstone, conglomerate, and siltstone; also include inseparable conglomerate beds of Pleistocene age; thickness as much as 15,000 feet

Te

Eocene sedimentary rocks

*In the northern Sulaimān Range and Wazīristān, include the Ghazij Shale and overlying Baska**, Domanda**, and Drazinda shale members, and Habib Rahi* and Pir Koh limestone members*

Tp

Paleocene sedimentary rocks

In the Sulaimān Range, include the Dunghan Formation and equivalents: blue or grey limestone with some shale and sandstone in the basal part; mostly Paleocene in age but fossil evidence indicates Late Cretaceous to Early Eocene sedimentation; thickness as much as 2,500 feet

JURASSIC AND CRETACEOUS

Kpb | K | KJ

Cretaceous and Jurassic sedimentary rocks

Pab Sandstone, Kpb: *sandstone with marly limestone near base. Undivided rocks of Cretaceous age,* K, *in the Sulaimān Range, Wazīristān, and areas immediately to the east include Pab Sandstone, Mughal Kot Formation*, Parh Limestone*, Goru Formation*, Lumshiwal Sandstone, and Chichali and Sembar Formations (both former Belemnite beds***). Undivided rocks of Cretaceous and Jurassic age,* KJ, *include inseparable rocks of Paleocene age*

JURASSIC

J

Jurassic sedimentary rocks

In the Sulaimān Range, the Sulaiman Limestone Group [Takatu(Chiltan) Limestone*, Anjira Formation*, Loralai Limestone*] and the underlying Springwar Formation**

TRIASSIC AND JURASSIC

J$\overline{R}$

Jurassic and Triassic sedimentary rocks

*In the Shaikh Budin and adjacent uplands, include the Samana Suk Limestone and Datta Formation, both Jurassic in age; also include the Kingriali Dolomite of probable Triassic age and the Khatkiara Sandstone Member** and Landa **, Narmia** and Mittiwali** Members, the last equivalent to the former Ceratite beds***, all of Triassic age. Also may include narrow, inseparable outcrops of the Late Jurassic-Early Cretaceous Chichali Formation*

PERMIAN

P

Permian sedimentary rocks

*Include the Zaluch Group** (former Productus Limestone***): mostly limestone with some shale and sandstone beds in basal and upper parts. Also include the underlying Lower Permian Nilawahan Group (former Lavender clay***, Speckled sandstone***, Olive series***, and the basal Talchir boulder bed*** of possible Upper Carboniferous age). Thickness, about 1,300 feet*

CAMBRIAN

€

Cambrian sedimentary rocks

*Include the Jhelum Group (former Salt pseudomorph beds***, Magnesian sandstone***, Neobolus beds***, and Purple sandstone***), and the underlying Salt Range Formation** (former Punjab saline series***) of questionable Late Precambrian age*

Note: Stratigraphic names used above mainly follow the Stratigraphic Code of Pakistan. Specific names not followed by asterisks have been used in published reports and are believed to meet the requirements of the code. The status of other stratigraphic names, followed by asterisks, are as follows: *, Formal name used in reports and whose status was under examination in 1964; **, Formal name used in manuscripts being processed in 1964 for publication by the Geological Survey of Pakistan and believed to meet the requirement of the code; ***, Name does meet the requirements of the code, but has been used in published reports

Approximate contact

Strike and dip of beds

U
D

Fault

Dashed where approximately located. Dotted where concealed. Arrows indicate relative movement. High-angle fault— U, *upthrown side;* D, *downthrown side. Thrust fault—* T, *upper plate*

Anticline

Showing crestline and direction of plunge

Syncline

Showing troughline

Note: Use of query (?) with any of the above symbols indicates that feature shown is either doubtful or probable

Shallow well or tube well

$\frac{28}{+130}$

Test hole

Upper figure indicates percentage of permeable beds in first 500 feet below land surface. Lower figure shows altitude of top of "thick clay" section, in feet above (+) or below (-) mean sea level

25

Line of equal percentage of permeable beds in first 500 feet below land surface

Interval 15 and 25 percent

+100

Structure contour

Shows altitude of top of "thick clay" section. Interval, in feet, is variable. Datum is mean sea level

A — A'

Line of section

Sections shown on Plate 4

Mountain or hill area

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1969—W68274

MAPS SHOWING LOCATION OF DATA SITES, PHYSIOGRAPHY, AND GEOLOGY IN THE DERA ISMĀĪL KHĀN DISTRICT AND ADJACENT AREA, WEST PAKISTAN

SCALE 1:500 000

10 0 10 20 30 40 50 KILOMETERS

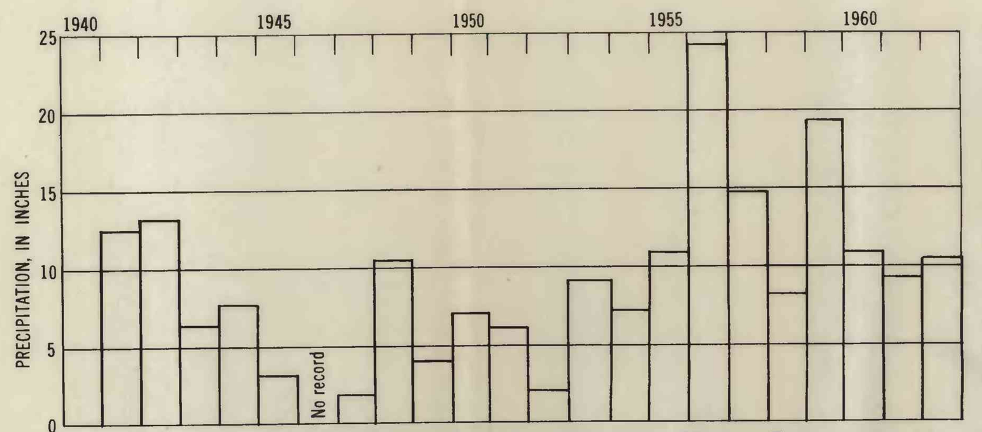
10 0 10 20 30 MILES

DESIGNATION OF STREAM TYPES

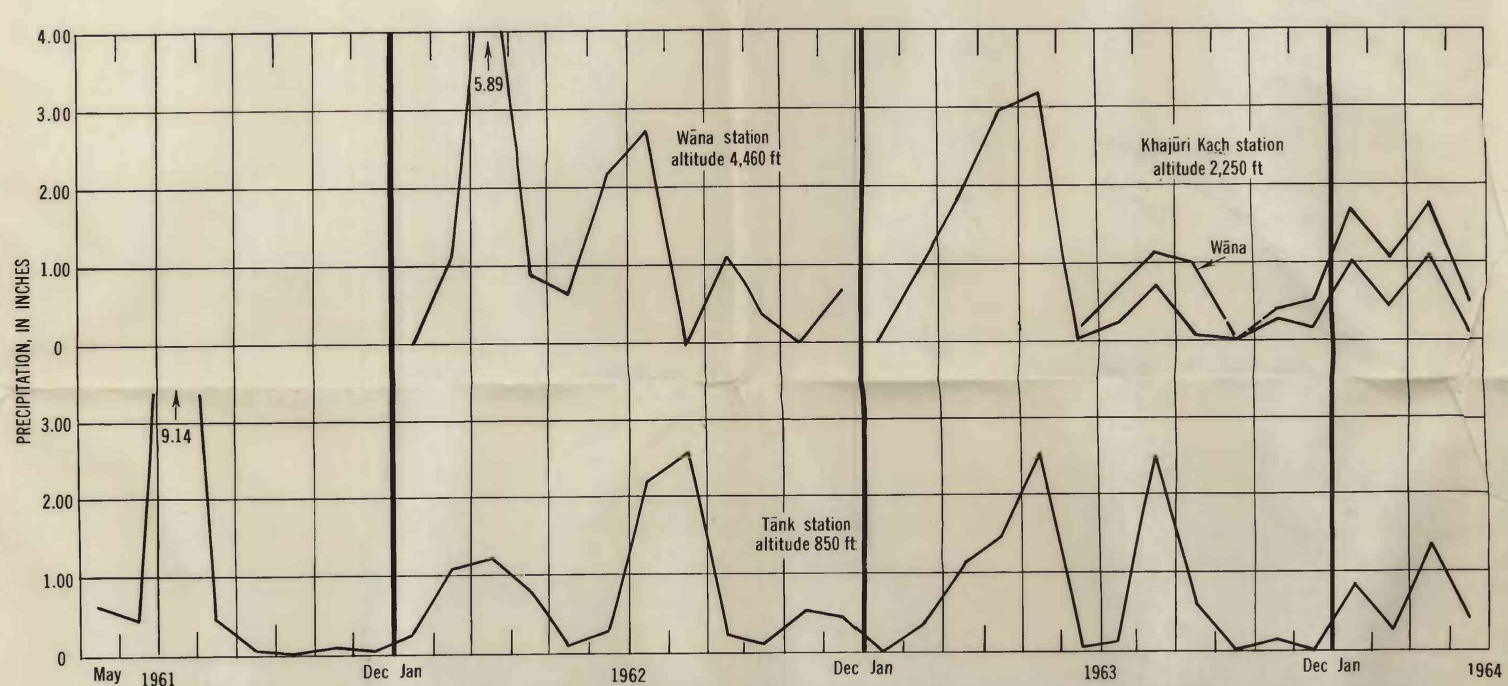
Stream names used on these maps generally follow spellings recommended by the U. S. Board on Geographic Names. Where a generic term indicative of the type of stream or drainage channel is not part of the BGN-approved name, one of the following terms has been added to the map

Algad, Toi, Zām — *Perennial streams*

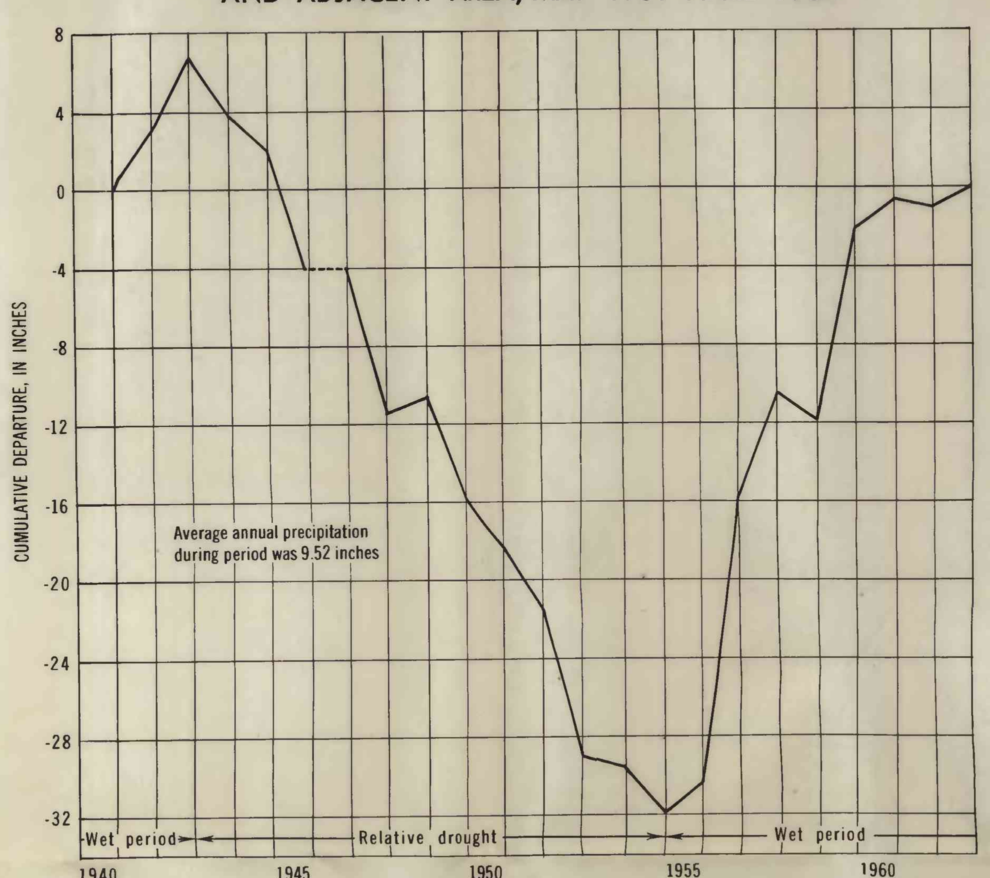
Khad, Kaur, Nāla, Rūd — *Intermittent streams, abandoned stream courses, or drains*



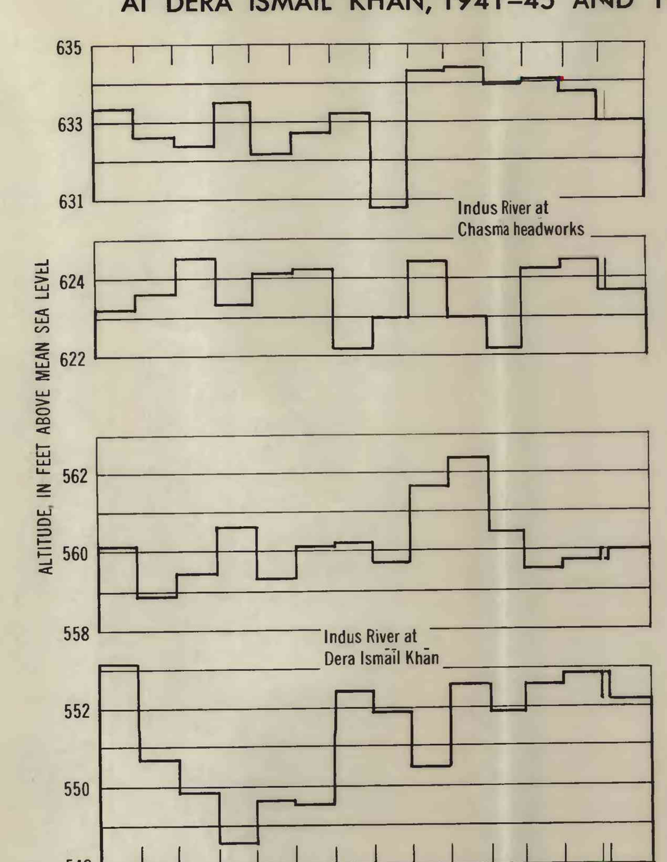
A. ANNUAL TOTAL PRECIPITATION AT DERA ISMĀĪL KHĀN, 1941–45 AND 1946–62, INCLUSIVE



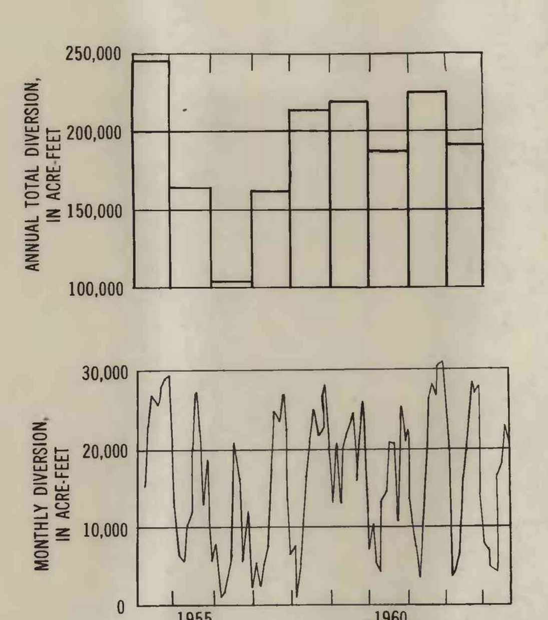
B. MONTHLY TOTAL PRECIPITATION AT THREE STATIONS IN WESTERN DERA ISMĀĪL KHĀN DISTRICT AND ADJACENT AREA, MAY 1961–APRIL 1964



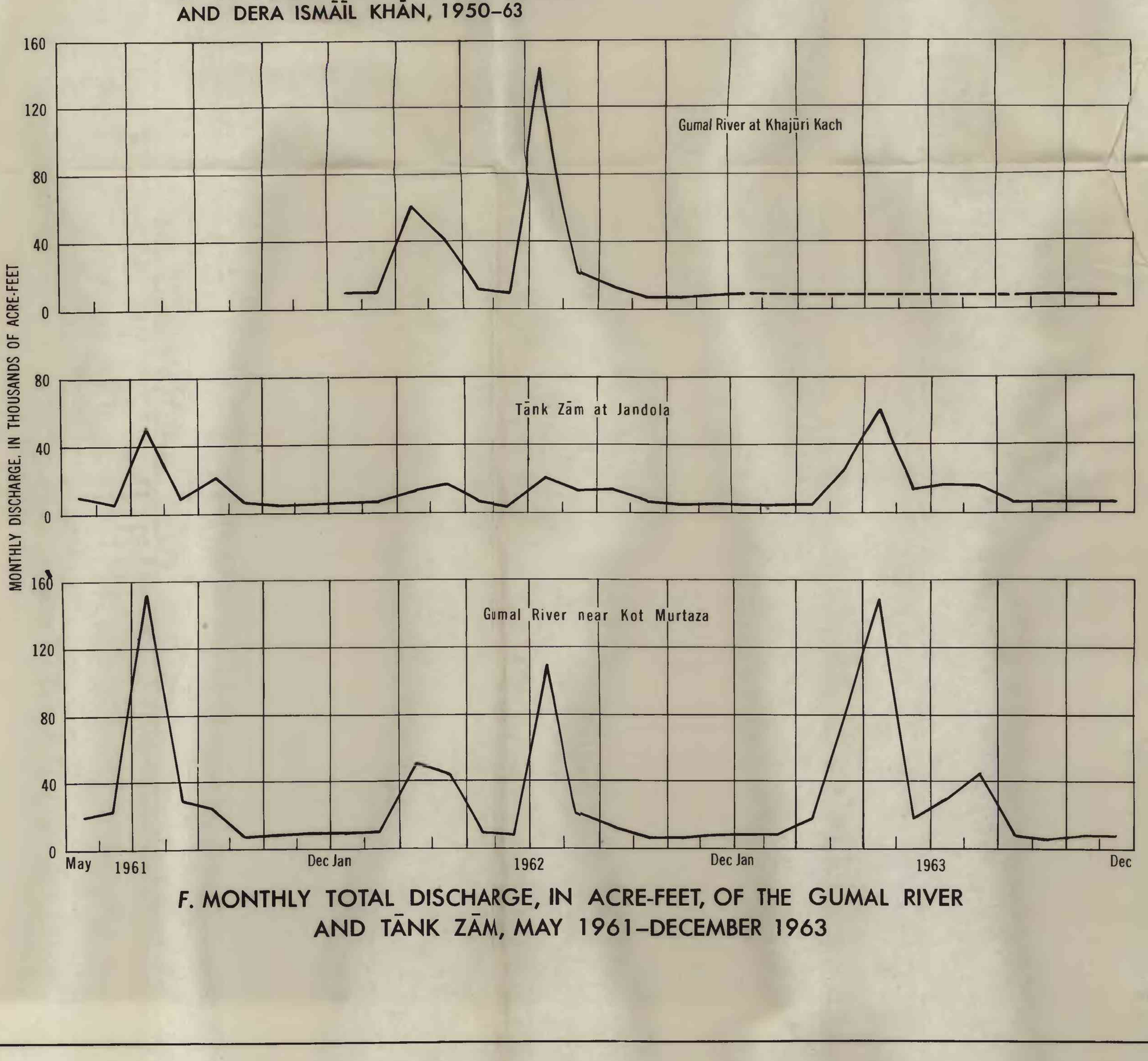
C. CUMULATIVE DEPARTURE FROM AVERAGE ANNUAL PRECIPITATION AT DERA ISMĀĪL KHĀN, 1941–45 AND 1946–62, INCLUSIVE



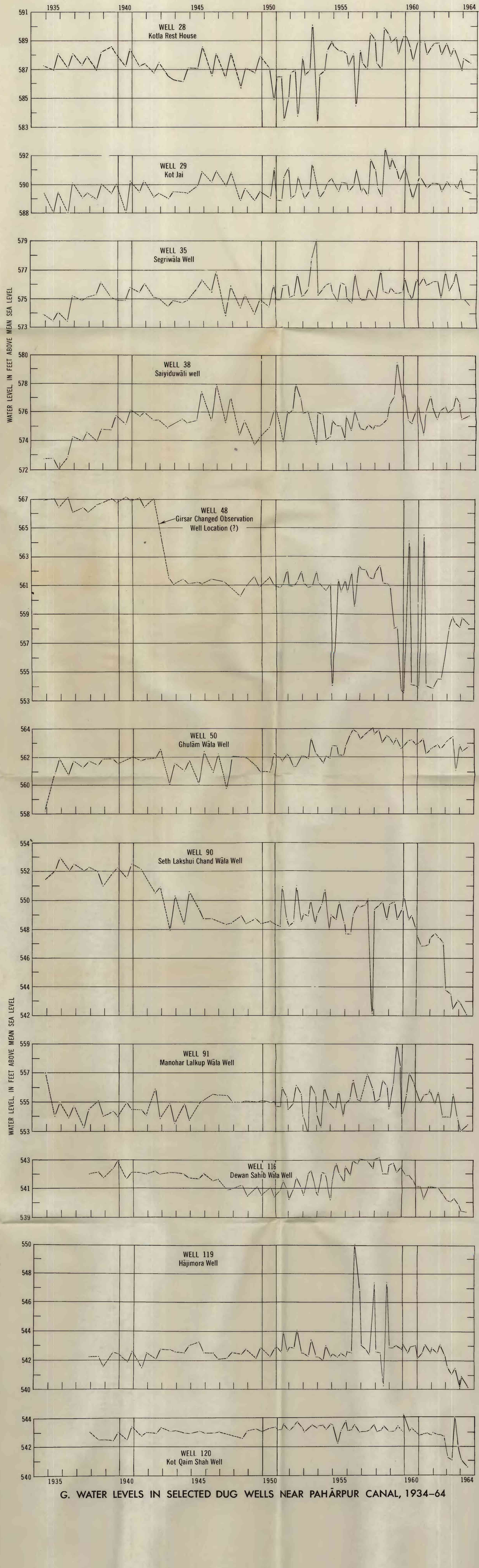
D. ANNUAL HIGHEST AND LOWEST STAGES OF INDUS RIVER AT CHASMA HEADWORKS AND DERA ISMĀĪL KHĀN, 1950–63



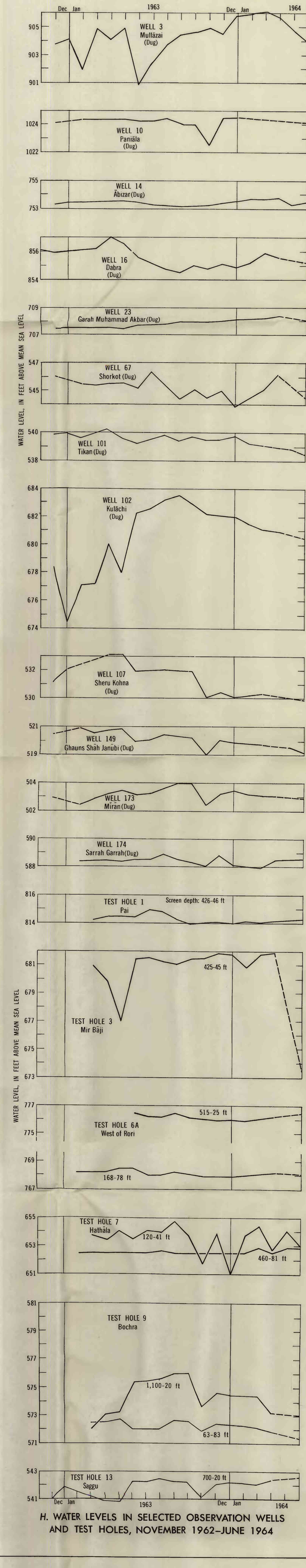
E. AMOUNTS OF WATER DIVERTED FROM INDUS RIVER, INTO PAHĀRPUR CANAL AT BILOT HEADWORKS, 1954–63



F. MONTHLY TOTAL DISCHARGE, IN ACRE-FEET, OF THE GUMAL RIVER AND TĀNK ZĀM, MAY 1961–DECEMBER 1963



G. WATER LEVELS IN SELECTED DUG WELLS NEAR PAHĀRPUR CANAL, 1934–64



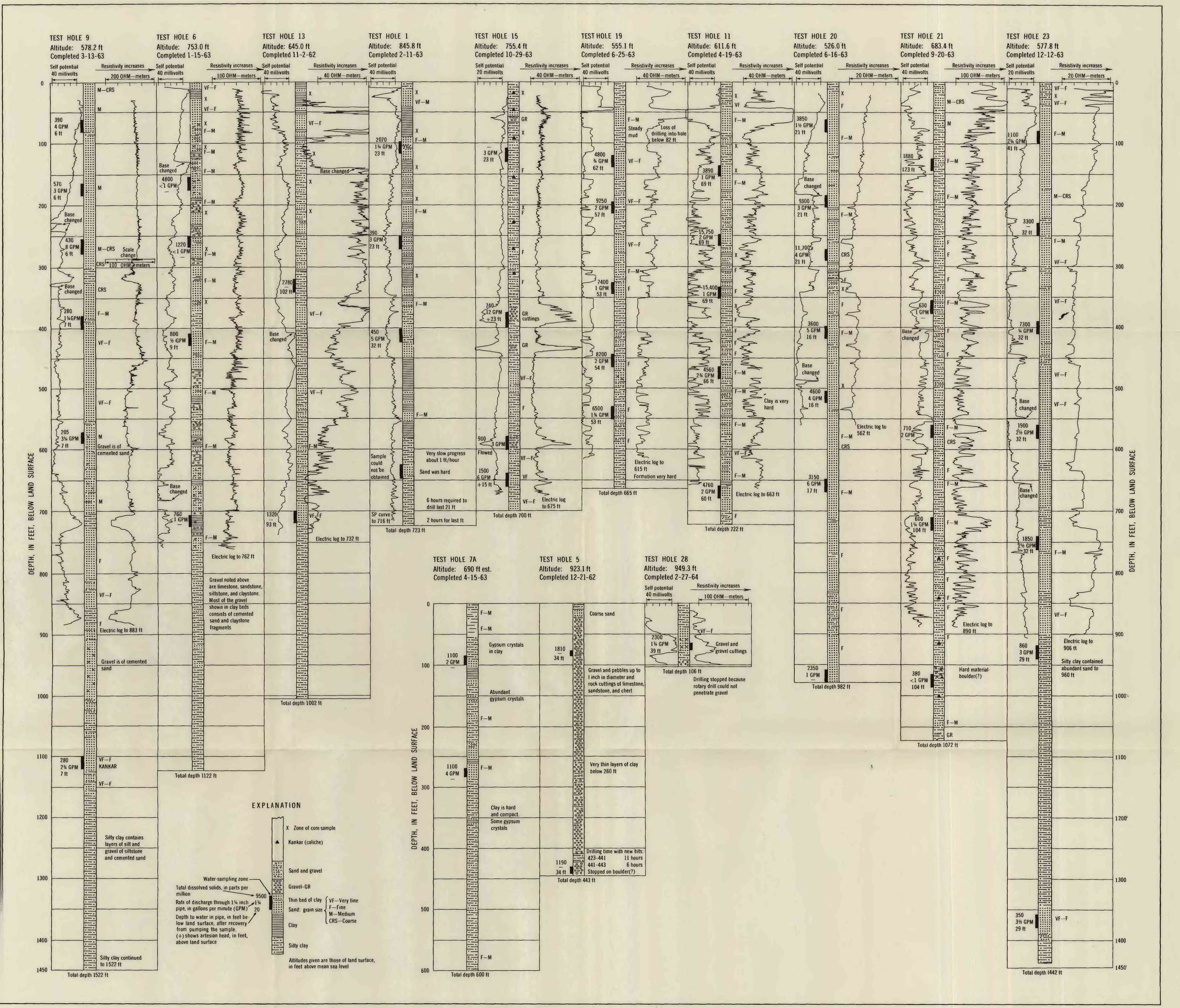
H. WATER LEVELS IN SELECTED OBSERVATION WELLS AND TEST HOLES, NOVEMBER 1962–JUNE 1964

GRAPHS SHOWING SELECTED HYDROLOGIC DATA FROM DERA ISMĀĪL KHĀN DISTRICT AND ADJACENT AREA, WEST PAKISTAN

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

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

WATER-SUPPLY PAPER 1608-K
PLATE 3



GRAPHS SHOWING COMPOSITE LOGS OF REPRESENTATIVE TEST HOLES DRILLED IN DERA ISMĀĪL KHĀN DISTRICT, WEST PAKISTAN, 1962–64

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

DIAGRAMMATIC SECTIONS OF UNCONSOLIDATED DEPOSITS BENEATH PIEDMONT PLAIN SHOWING SHAPE OF TOP OF "THICK CLAY" SECTION, RELATION OF WATER TABLE TO LAND SURFACE, AND VERTICAL DISTRIBUTION OF DISSOLVED SOLIDS AT TEST-HOLE SITES, DERA ISMĀĪL KHĀN DISTRICT, WEST PAKISTAN

SCALE 1:250 000

5 0 5 10 15 20 25 KILOMETERS

5 0 5 10 15 MILES

PREPARED IN COOPERATION WITH THE
WEST PAKISTAN WATER AND POWER DEVELOPMENT AUTHORITY
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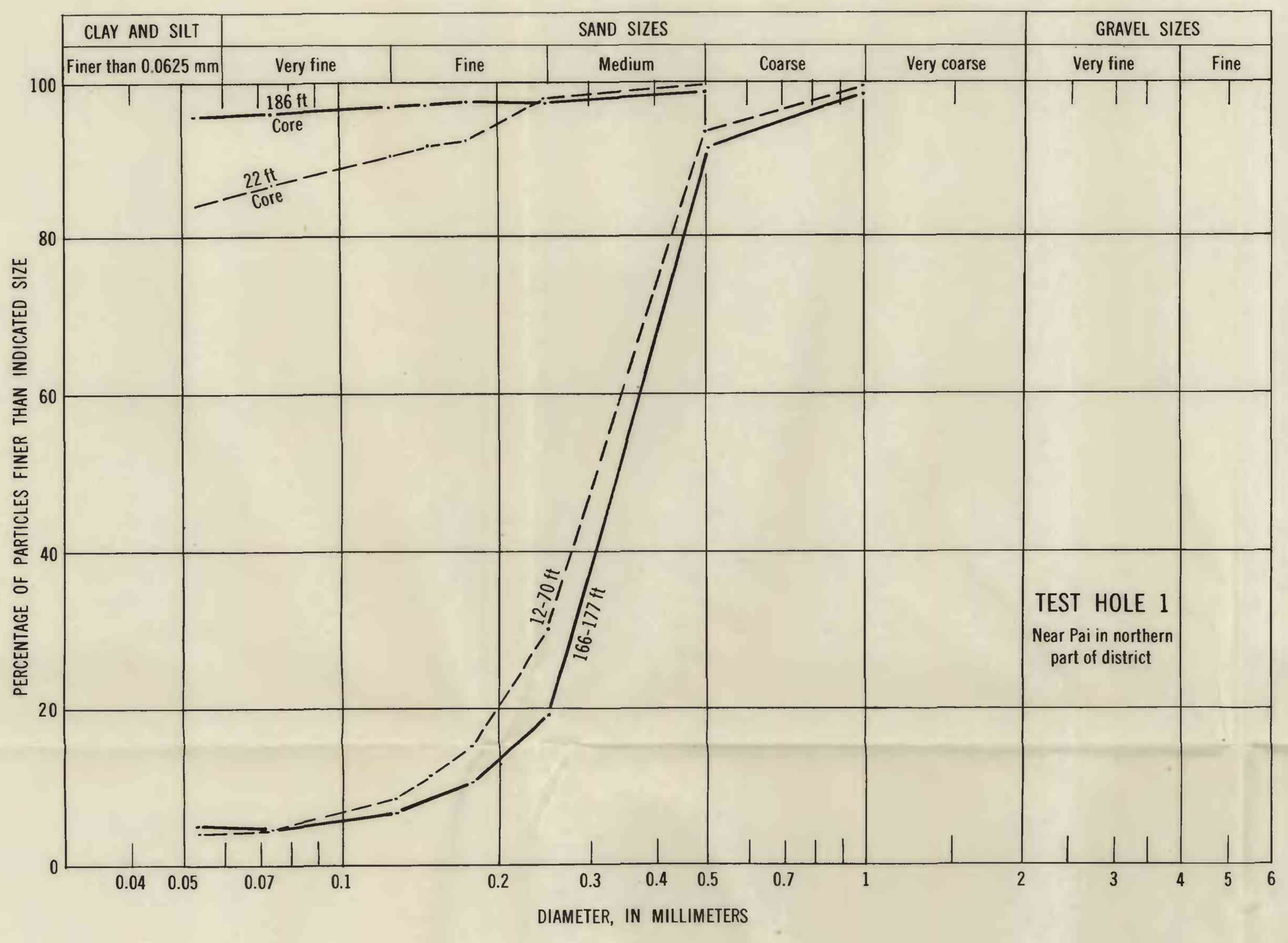
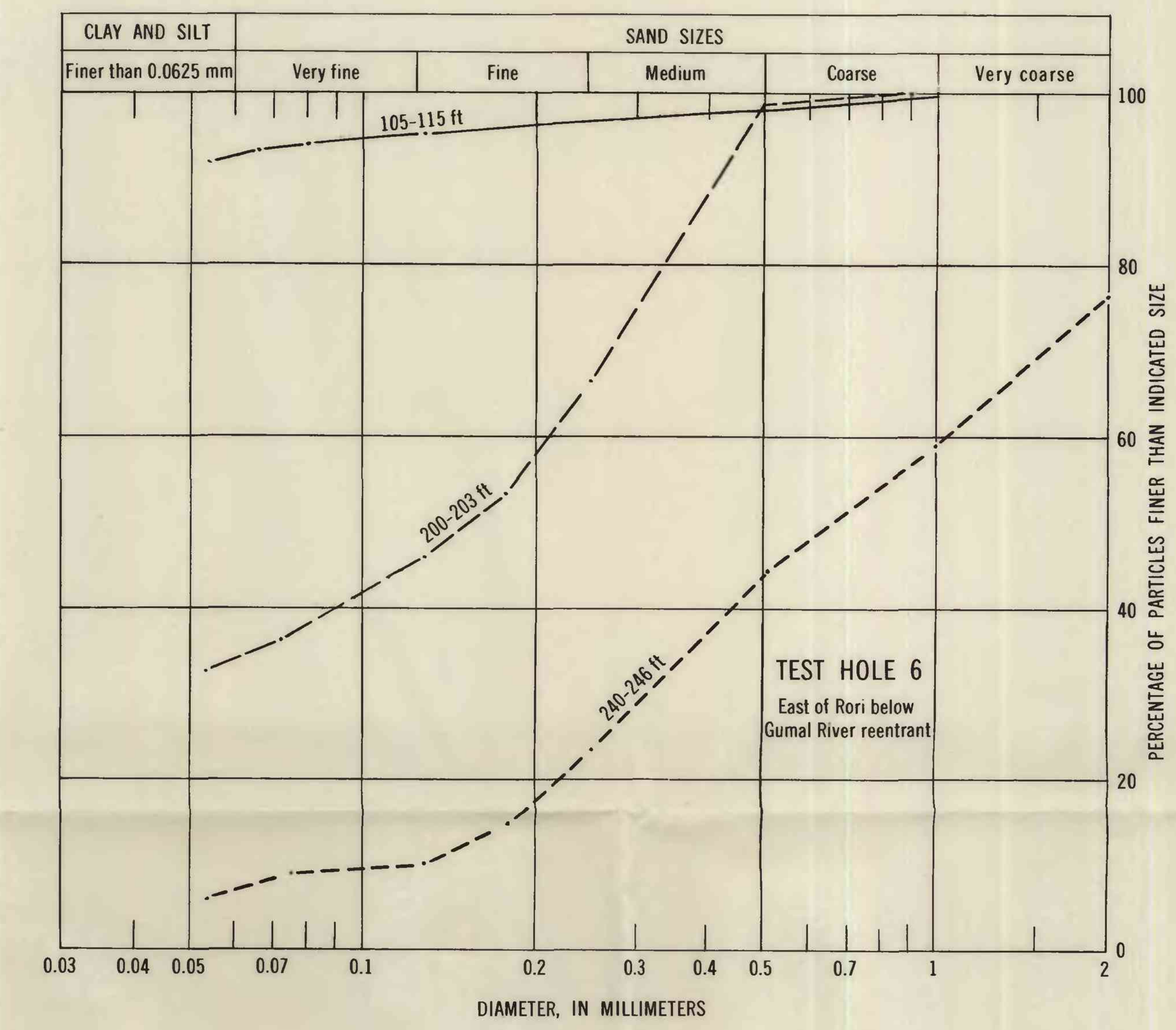
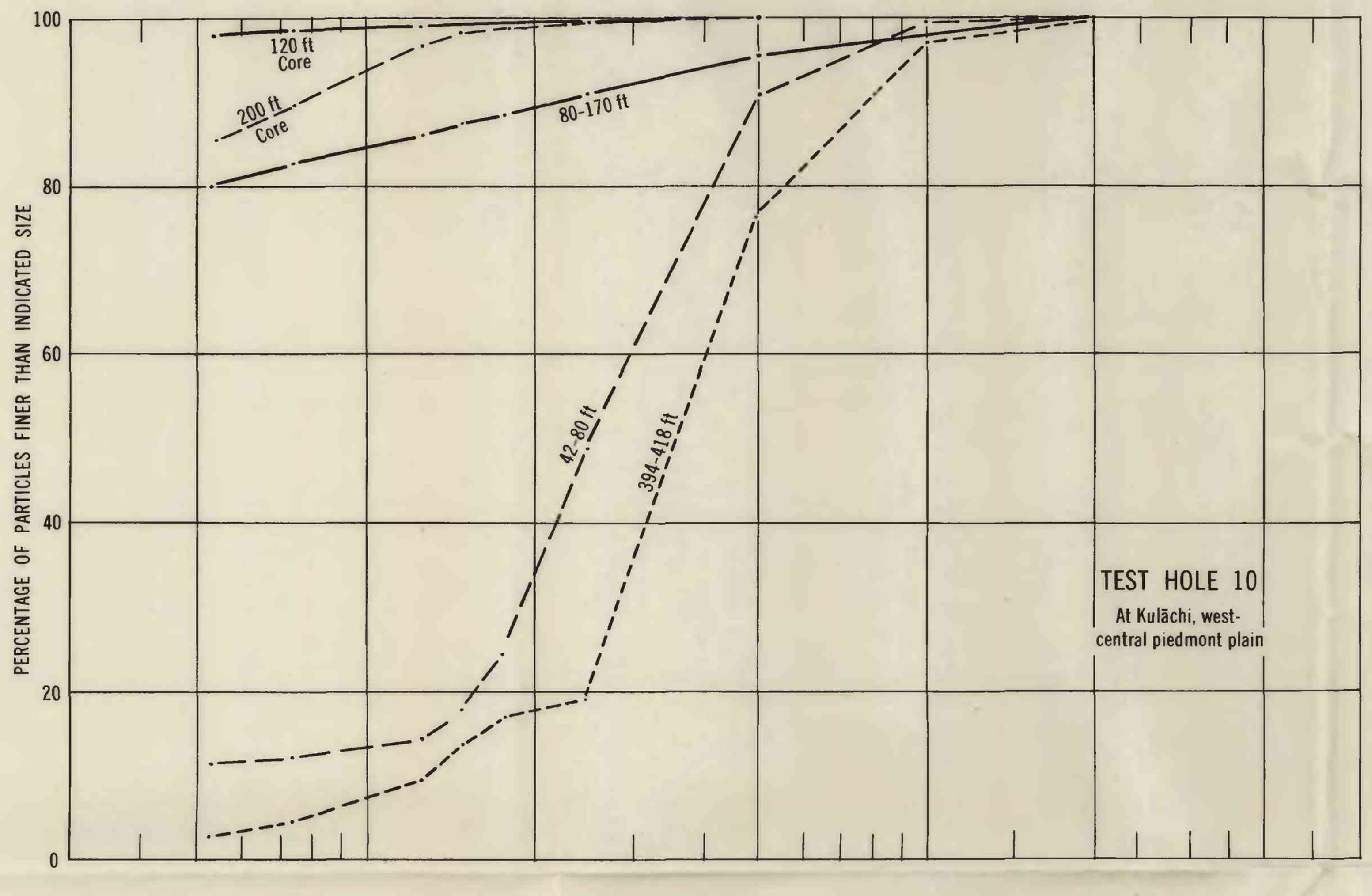
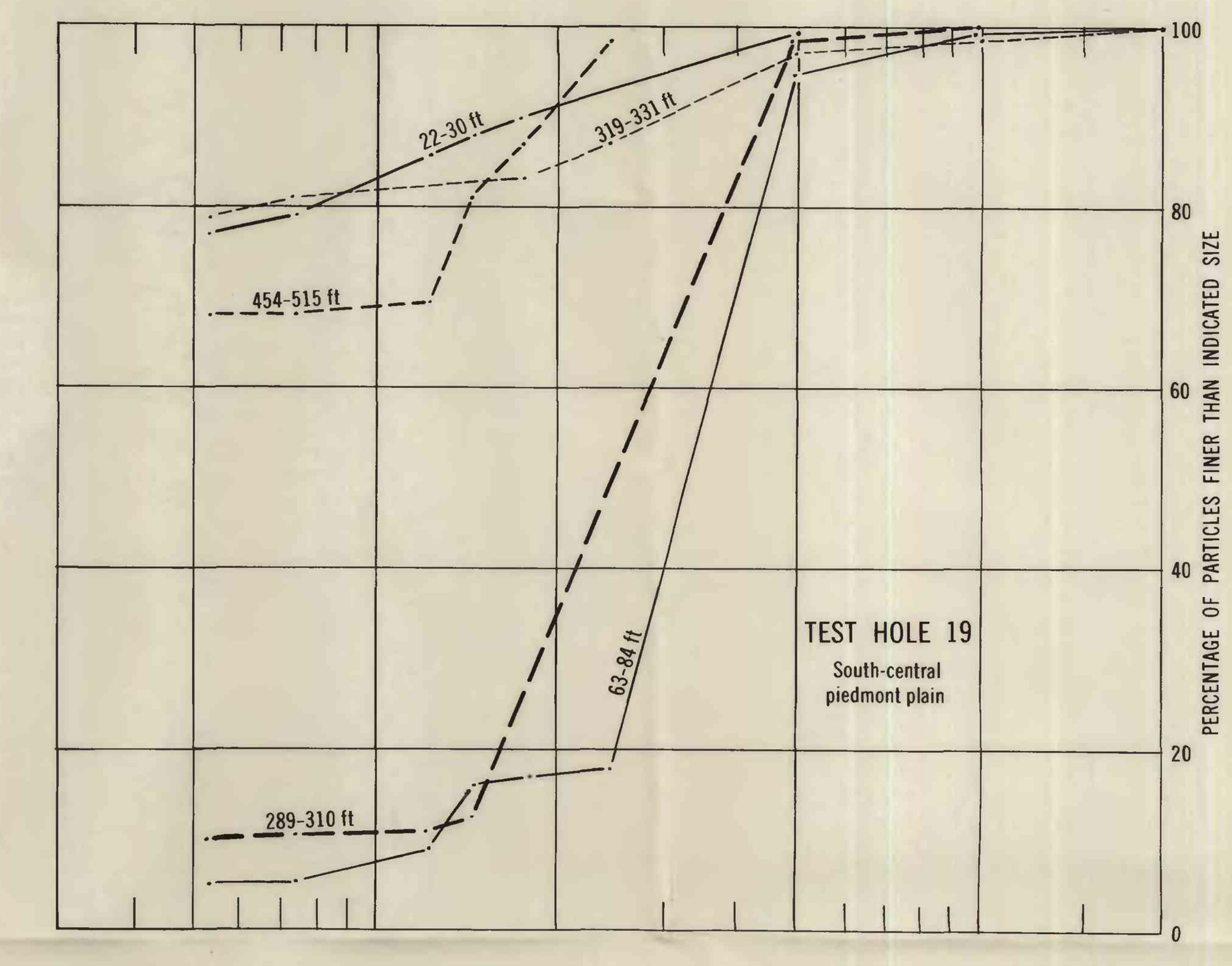
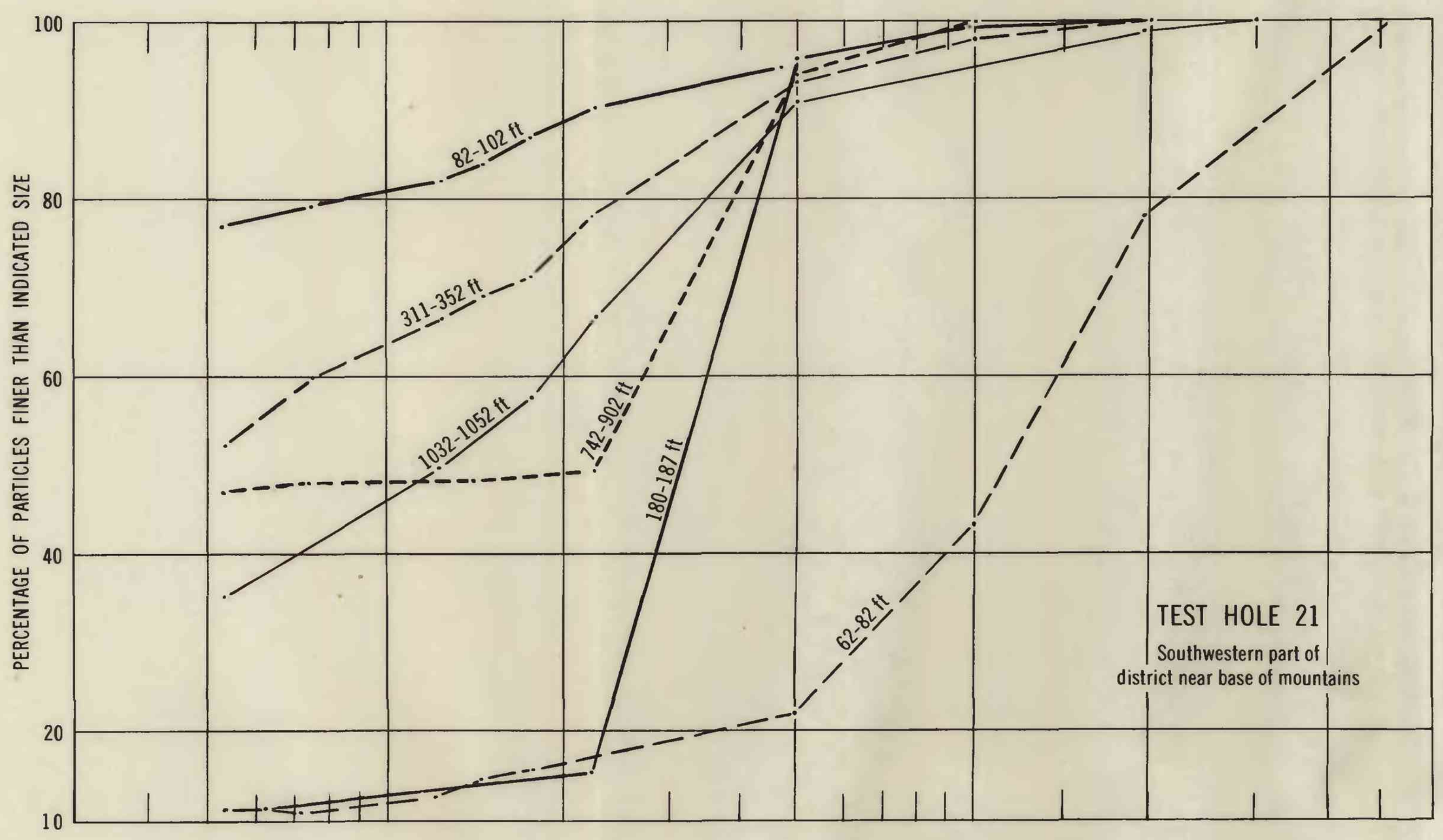
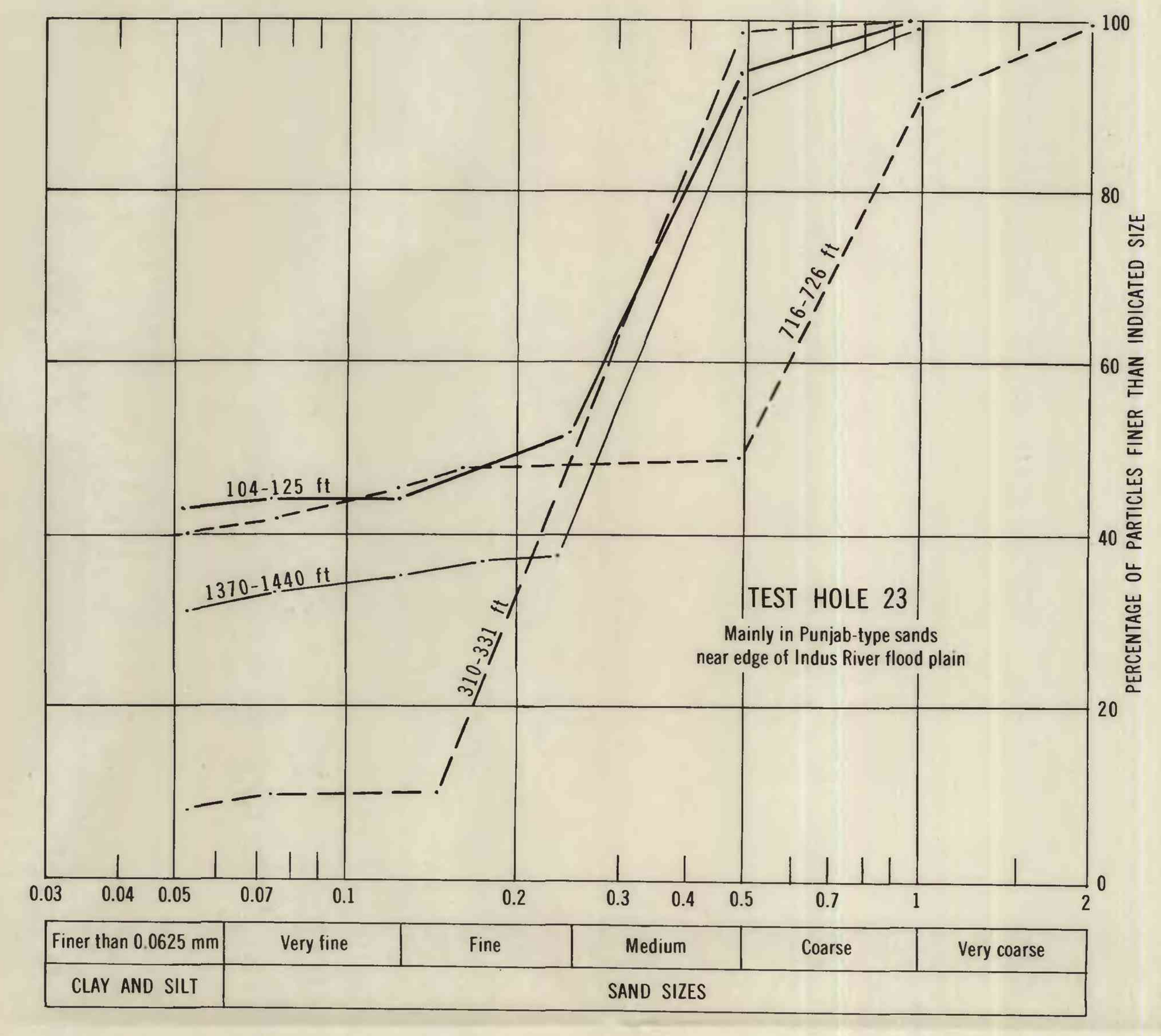


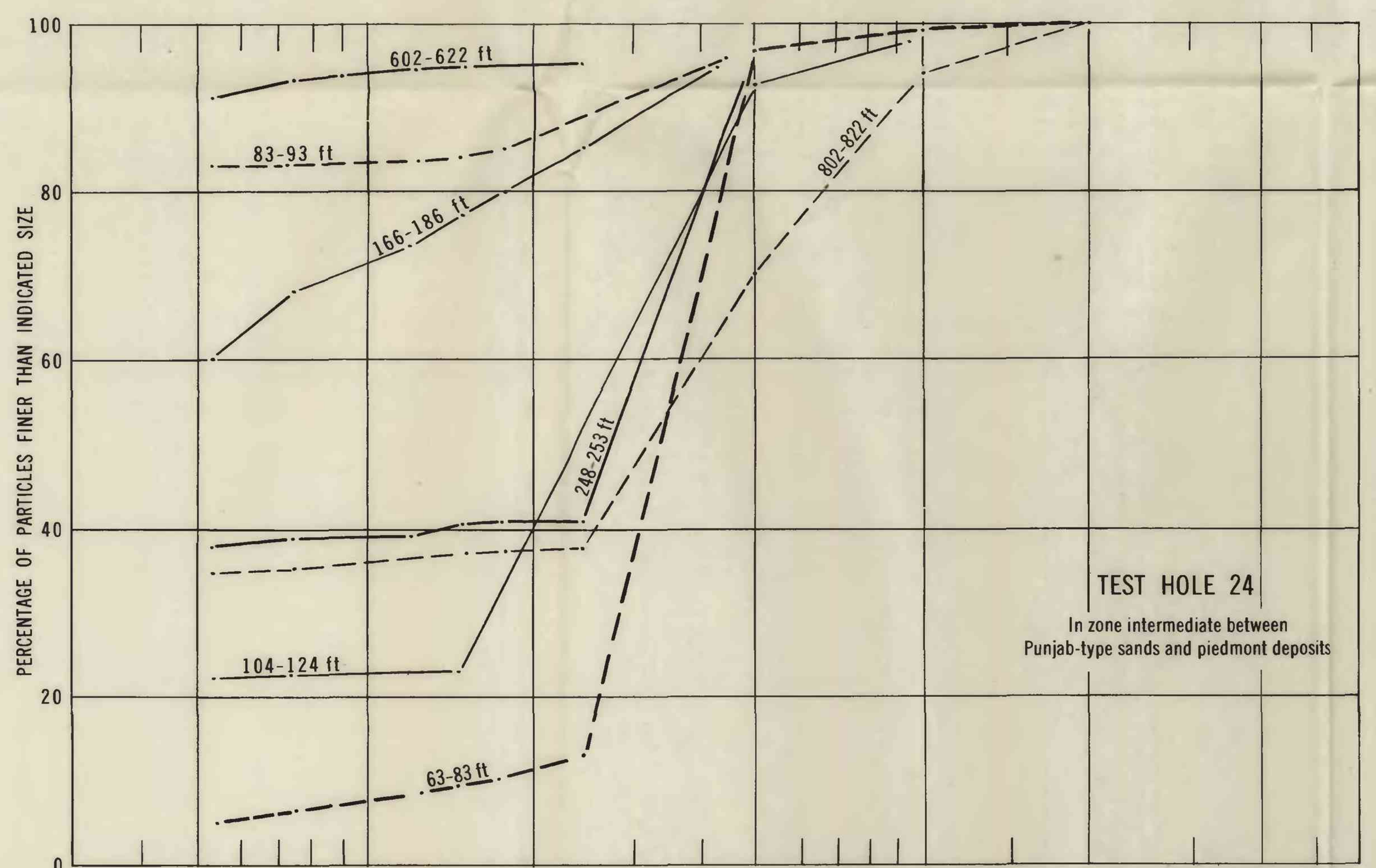






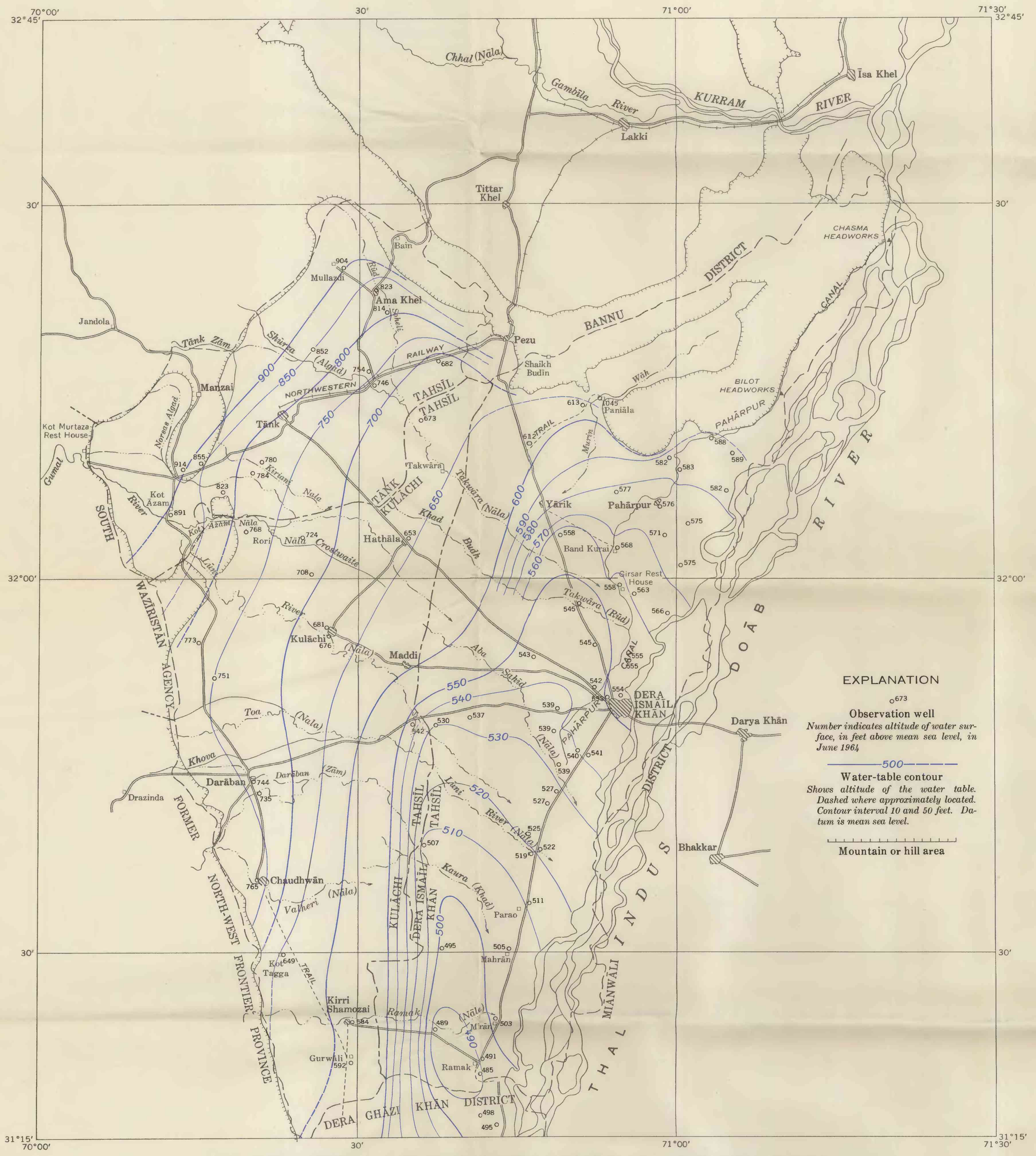




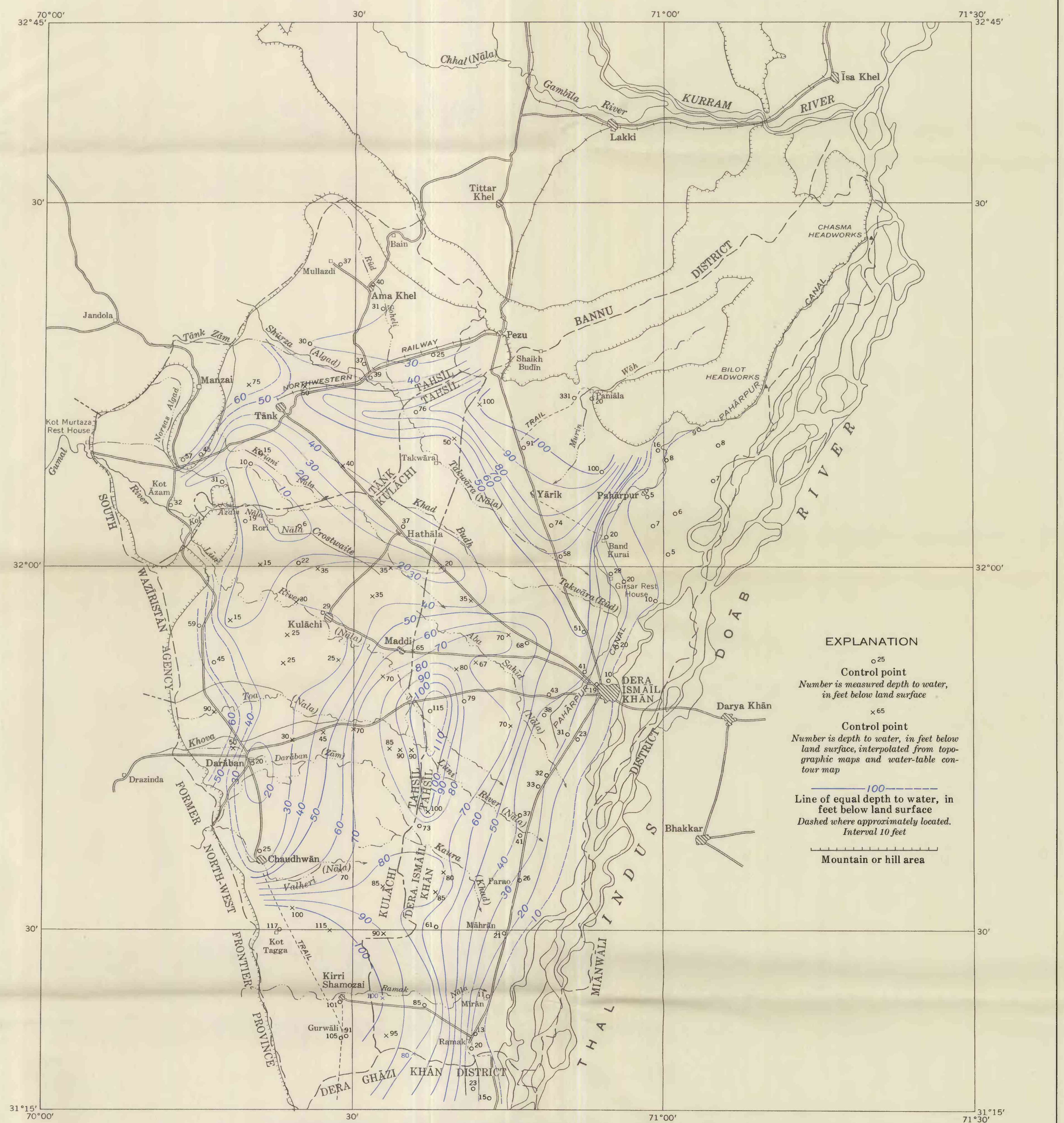


GRAPHS SHOWING GRAIN-SIZE DISTRIBUTION IN SELECTED SAMPLES FROM TEST HOLES IN DERA ISMĀĪL KHĀN DISTRICT, WEST PAKISTAN

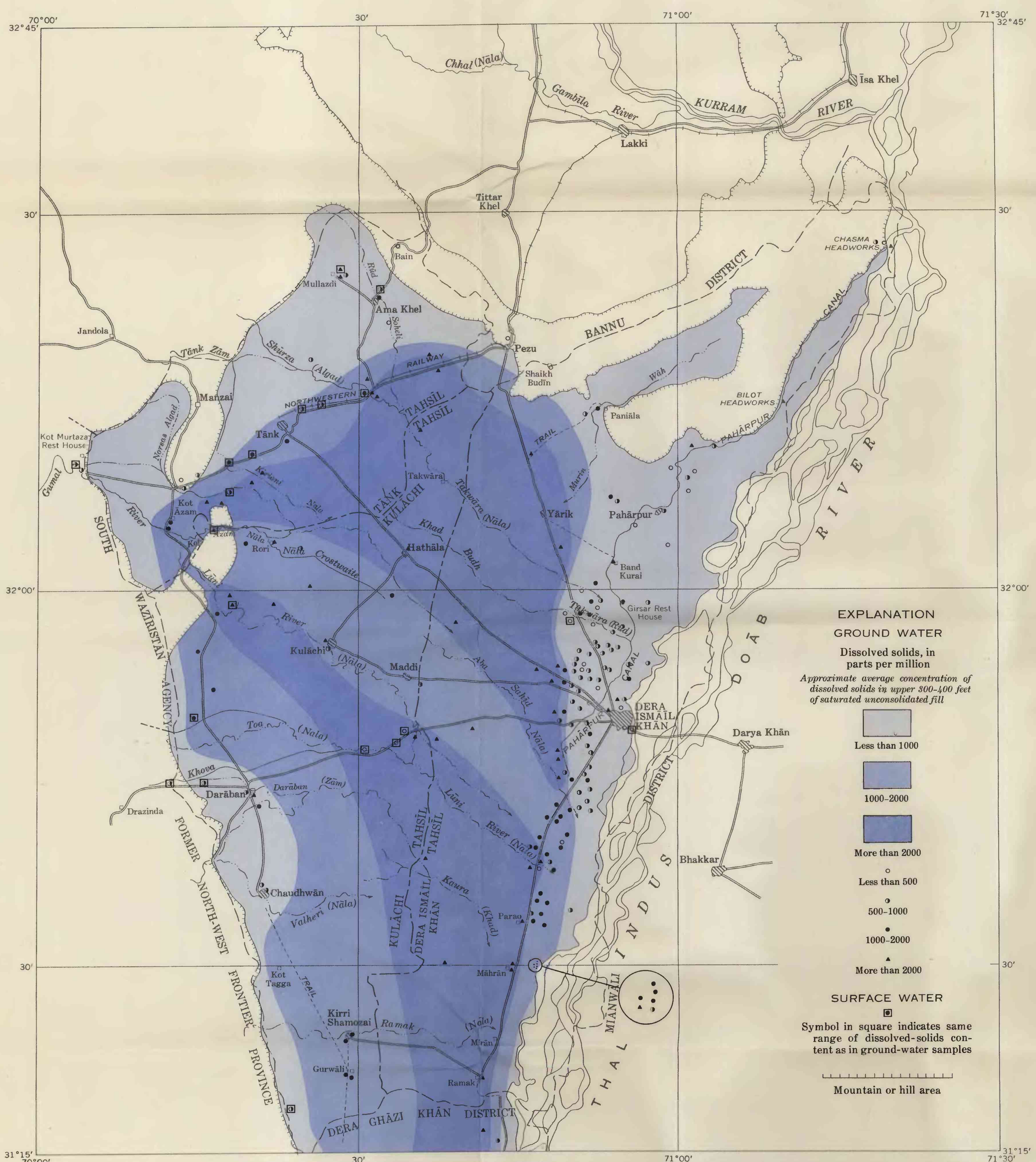
PREPARED IN COOPERATION WITH THE
WEST PAKISTAN WATER AND POWER DEVELOPMENT AUTHORITY
UNDER THE AUSPICES OF THE
U.S. AGENCY FOR INTERNATIONAL DEVELOPMENT



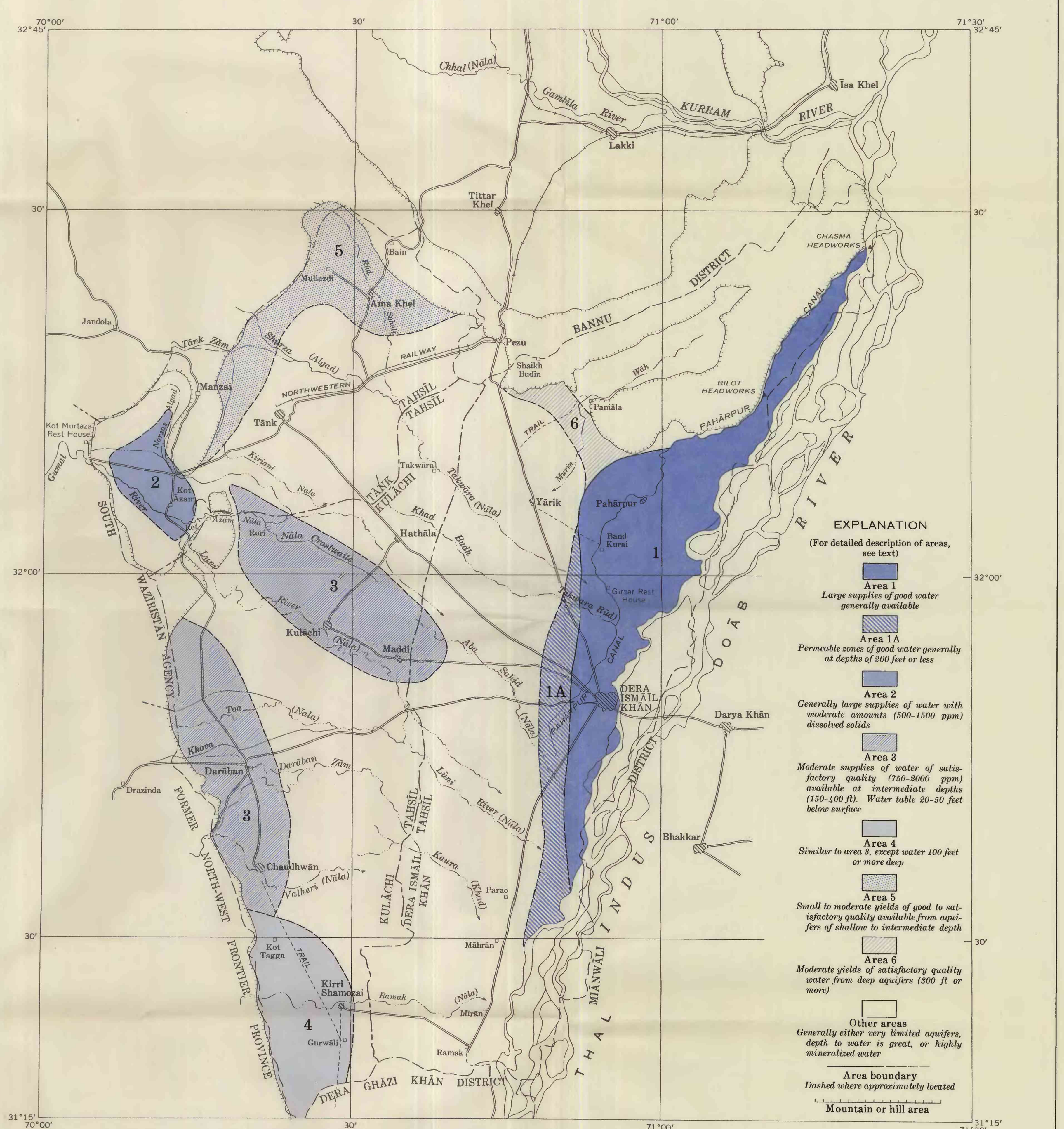
ALTITUDE OF WATER TABLE, JUNE 1964



DEPTH TO WATER, JUNE 1964



DISSOLVED SOLIDS IN WATER SAMPLES, 1962-64



AVAILABILITY OF GROUND WATER

Base compiled from Land Form Maps (Fraser, 1958), topographic maps and field notes

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1969—W68274

HYDROLOGIC MAPS OF THE DERA ISMĀĪL KHĀN DISTRICT, WEST PAKISTAN

SCALE 1:500 000

10 0 10 20 30 40 50 KILOMETERS

10 0 10 20 30 MILES

DESIGNATION OF STREAM TYPES

Stream names used on these maps generally follow spellings recommended by the U. S. Board on Geographic Names. Where a generic term indicative of the type of stream or drainage channel is not part of the BGN-approved name, one of the following terms has been added to the map

Algad, *Toi*, *Zām* — *Perennial streams*

Khad, *Kaur*, *Nāla*, *Rūd* — *Intermittent streams, abandoned stream courses, or drains*