Reclamation by Tubewell Drainage in Rechna Doāb and Adjacent Areas, Punjab Region, Pakistan

By GLENN T. MALMBERG

CONTRIBUTIONS TO THE HYDROLOGY OF ASIA AND OCEANIA

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RECLAMATION BY TUBEWELL DRAINAGE IN RECHNA DOĀB AND ADJACENT AREAS, PUNJAB REGION, PAKISTAN

By Glenn T. Malmberg

ABSTRACT

Around the turn of the century, a network of more than 40,000 miles of canals was constructed to divert water from the Indus River and its tributaries to about 23 million acres of largely unused desert in the Punjab region of Pakistan. The favorable climate and the perennial supply of irrigation water made available through the canals instituted the beginning of intensive farming. However, because of generally poor drainage and the high rate of canal leakage, the water table began to rise. As the population increased and agriculture expanded, the demand for irrigation water soon exceeded the available supply. Spreading of the canal supply to meet the expanded needs locally created shortages that prevented adequate leaching. Increased evaporation from the rising water table further contributed to the progressive accumulation of soluble salts in the soil. By the late 1930's the combined effect of waterlogging and salinity had reduced the agricultural productivity of the region to one of the lowest in the world.

In 1954, after several unsuccessful projects were undertaken to reclaim affected areas and to stop the progressive encroachment of waterlogging and salinization, the Government of Pakistan in cooperation with the U.S International Cooperation Administration undertook a study of the geology and hydrology of the Indus Plain that ultimately resulted in the formulation of a ground-water reclamation program. The principal feature of the program is the utilization of a network of deep wells spaced about a mile apart for the dual purpose of lowering the water table and for providing supplemental irrigation water. Through financial assistance and technical and engineering support principally from the United States, construction began in 1960 on the first of 18 proposed reclamation projects that eventually will include 21 million acres and more than 28,000 wells having an installed capacity of more than 100,000 cubic feet per second.

An area of about 1.3 million acres a few miles west of the City of Lahore was selected for the pilot project. The first Salinity Control and Reclamation Project (SCARP–1) was completed in 1962. Within the project area about 2,000 wells were drilled as deep as 350 feet and equipped with turbine pumps

having a capacity of up to 5 cubic feet per second each and a combined operating capacity of about 3.5 million acre-feet per year.

To July 1968 pumping from project wells and from private and other governmental agency wells supplied about 12 million acre-feet of water. This pumping more than doubled the available irrigation supply and lowered the water table to a depth of 10 feet or more below most of the project area. As a result, approximately 66 percent of the 400,000 acres of land damaged by waterlogging and accumulation of excessive salt was wholly or partially reclaimed. The cropping intensity was increased from about 77 percent in 1962 to 101 percent in July 1968, and the annual value of crops increased 186 percent over 1962.

Annual water budgets for the first 6 years of project operation indicate that pumping caused a decrease in annual ground-water outflow from the project area from about 57,000 acre-feet to 32,000 acre-feet, caused an increase in annual ground-water inflow to the project area from 35,000 acre-feet to 52,000 acre-feet, and depleted about 1.71 million acre-feet of ground-water storage. Net annual recharge to the ground-water reservoir during this same period ranged from a high of slightly more than 2 million acre-feet in 1964 to a low of about 1 million acre-feet in 1965. The budgets suggest that perhaps as much as half the net canal inflow to the project area is lost through leakage. This leakage is the principal source of recharge to the ground-water reservoir.

Pumping has caused widespread changes in the chemical quality of ground water by changing the rate and direction of flow, inducing infiltration from canals, and mixing of indigenous waters of different chemical quality. Water from many wells remote from canals and water from wells in the southwestern part of the project area increased in total dissolved solids and electrical conductivity and increased in sodium ion concentration. Use of ground water from some wells having the undesirable combination of relatively high conductivity and a high sodium content has reduced soil permeability and locally created a hard surface layer in soil that makes tilling by the usual method of oxen and wooden plow difficult. Reduction in soil permeability probably will become more pronounced with continued use of ground water, unless the well water is mixed with canal water, soil amendments such as gypsum or green fertilizers are used, or irrigation practices are changed. There is no evidence that recycling of irrigation water had affected the chemical quality of the pumpage from project wells up to 1967. Near the canals, total dissolved solids and the sodium-adsorption-ratio of most ground water has changed little since pumping began.

Drainage from the project area to the rivers and as underflow to adjacent areas is small. Consequently, pumping has created a circulation system in the ground-water reservoir that will cause a gradual increase in concentration of dissolved solids. Eventually it will become necessary to export or otherwise treat saline water if irrigation is to continue.

INTRODUCTION

Agriculture and associated activities engage about 80 percent of the national population, and the produce derived from these activities provides approximately 80 percent of the gross national product of Pakistan. Agricultural commodities produced in the

Punjab region provide a substantial proportion of this total national effort. Development of agriculture began in Punjab and Bahawalpur around the turn of the century when the first perennial canals were built. Since that time an elaborate system of canals more than 40,000 miles in length has been completed to divert water for irrigation from the Indus River and its tributaries. This vast distributary network commands an area of about 23 million acres and is the largest contiguous irrigated area in the world.

After the completion of the first large canal system, the water table beneath the irrigated areas began to rise. The accretion of ground-water storage caused principally by seepage from canals and by percolation of irrigation water, had no particularly adverse effects during the early years of development when the depth to the water table was as much as a hundred feet below land surface. Nevertheless, it was early recognized that remedial measures would eventually have to be initiated to control the depth of the water table. The rapid growth in population following the colonization of the canal-commanded areas created a continual demand for greater agricultural productivity. To meet this growing demand, it has been common practice to expand the irrigated acreage and to adjust the available water supply accordingly.

In many places the irrigation supply eventually was spread over large areas in amounts insufficient to satisfy the consumptive use of crops or to provide for adequate leaching of salts from the soil. As a result, a progressive accumulation of salt in the root zone of the plants reduced the fertility of the land and the agricultural productivity. As the water table approached the land surface, evaporation from the water table increased and the rate of salinization was intensified.

By the late 1930's and early 1940's, waterlogging and salinization had affected several million acres of land and was spreading at the rate of tens of thousands of acres yearly. During the early 1900's a succession of governmental agencies, commissions, and scientists made studies to determine the causes and to formulate preventive measures to combat the continuing encroachment of waterlogging and salinity. Most of the studies were too limited in scope and areal extent to evaluate all pertinent factors, and consequently the conclusions drawn were inconclusive or misleading. On the basis of these studies, various remedial measures were adopted with little or, at best, only partial success.

In 1954 the Government of Pakistan in cooperation with the

U.S. International Cooperation Administration (ICA), and later, its successor the United States Agency for International Development (AID), began a comprehensive study of the geology and hydrology of the Indus Plain. This study, which was begun under the direction of the Irrigation Branch of the West Pakistan Public Works Department and was supported by a team of technical advisors on loan from the U.S. Geological Survey, was aimed at assessing the ground-water potential of the northern Indus Plain in order to formulate reclamation measures that would solve the problems of waterlogging and salinity and restore the productive capacity of the land. An important part of the study included training of Pakistan engineers, geologists, and related scientists in hydrology in an effort to create a cadre of specialists with sufficient scientific and technical skills to independently carry out water-resources investigations. Field and laboratory equipment, vehicles, drilling rigs and other commodities, and technical advisors required in support of this study were provided by AID. Personnel to carry out the investigations, and field and office facilities, were supplied by the Government of Pakistan.

Because of the nature and urgency of the investigation, exploration of the alluvial aquifer was limited principally to its uppermost part. More than 1,400 test holes, totaling about a million feet, were drilled in an area of about 35 million acres. Lithologic and electric logs and data from more than 10,000 samples of material obtained from the test holes and analyzed in the laboratory helped to define the lithologic nature of the alluvial aquifer to depths of about 600 feet. Water samples obtained from tens of thousands of test holes and private wells were analyzed for their chemical composition, and the analyses have been studied to understand in more detail the vertical and areal distribution of the ground water. The results of nearly 200 aquifer tests were used to determine hydraulic characteristics of the aquifers. An elaborate array of observation wells was installed at each of the aquifer-test sites, and some of the tests were operated continuously for as long as 19 days' duration. An extensive and detailed soils-mapping program utilizing more than half a million soil samples obtained from auger holes to a depth of 6 feet furnished detailed information concerning soil types in an area of 27 million acres.

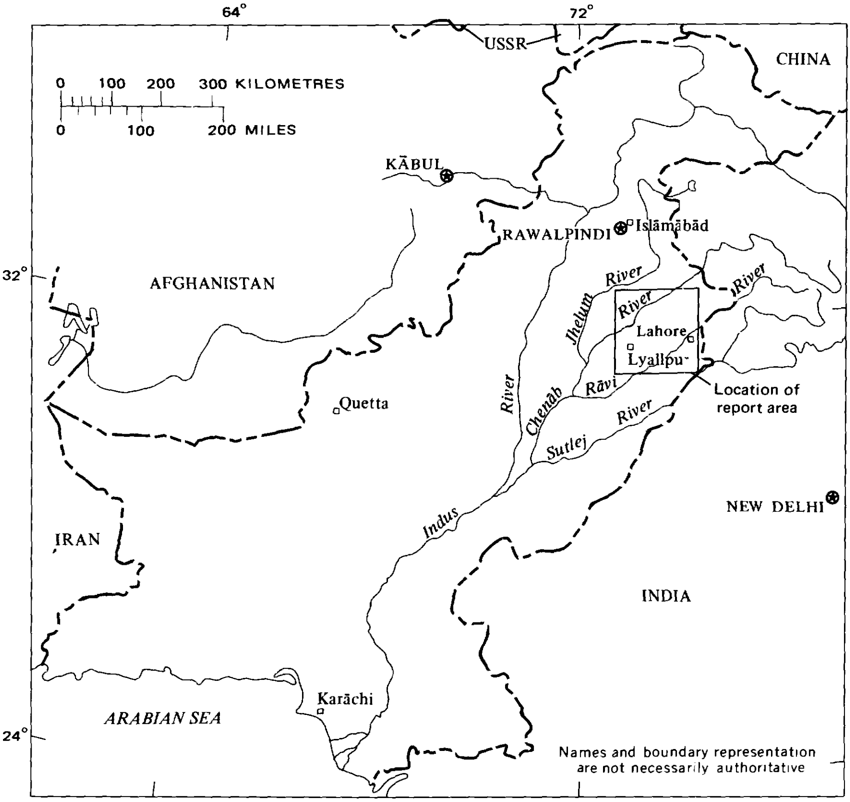
The results of these investigations, which appear in more than 60 published reports, provided the basis for the present reclamation projects utilizing deep tubewells to lower the water table and supplement the canal-irrigation supply.

Early in 1959, 15.2 million dollars in United States currency was made available to the Government of Pakistan by the United States Development Loan Fund to cover expenditures in foreign currencies for equipment, materials, and services required for construction. Work on the first Salinity Control and Reclamation Project (SCARP–1) was begun in 1960. In April of that year the administration of the project was transferred from the Irrigation Branch to the Water and Power Development Authority (WAPDA). The survey and investigational phase of the project was carried out by the Water and Soils Investigation Division (WASID) of WAPDA.

The project area selected for construction of SCARP–1 is in the center of the interfluvial area between the Rāvi and Chenāb Rivers, known as the Rechna Doāb (fig. 1). This project is the first of 18 planned reclamation projects in the northern Indus Plain that will ultimately include about 21 million acres and more than 28,000 drainage and production wells having a total installed capacity of more than 100,000 cubic feet per second (Tipton and Kalmbach, written commun., 1957).

The principal objective of the SCARP–1 project is to demonstrate the effectiveness of vertical drainage in reclaiming saline-affected soils in a large area. The plan is to lower the water table by pumping ground water to supplement the existing canal supply. The pumped water, which generally is of satisfactory quality for irrigation, provides additional water sufficient to supply the consumptive use of crops when the cropping intensity is increased to 150 percent; moreover, water is available to leach salts from the root zone of the soil. In effect the additional irrigation supply provides for increasing density of irrigation not only by the reclamation of lands gone out of production but also by bringing additional lands into cultivation.

Although the project is large and is a major undertaking requiring an international effort, the project area covers but a small part of the croplands in Pakistan that are being affected by a rising water-table salinization. Therefore, the project is in a sense a pilot project to gain experience and knowledge through the hydrologic monitoring of an experimental network of wells designed to salvage leakage of canals for recycling. The data should permit an analysis of the cause-and-effect relation between pumping and the various components of the hydrologic budget and will provide increasingly accurate criteria for the design and operation of future reclamation projects.



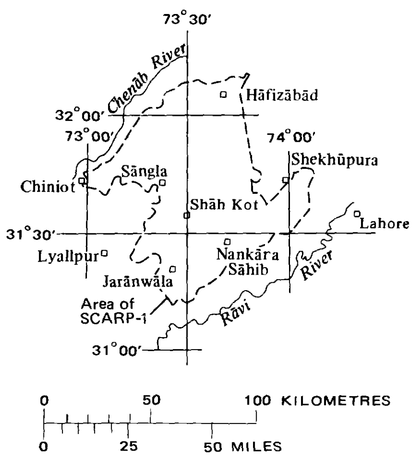


FIGURE 1.—Location of report area in Pakistan and site of Salinity Control and Reclamation Project 1 (SCARP-1).

PURPOSE AND SCOPE OF THE HYDROLOGIC MONITORING PROGRAM

The monitoring program is a continuing program for the collection and analysis of hydrologic data in the ground-water reclamation project areas. The purpose of the monitoring program is to observe, record, and analyze physical and chemical changes that occur in the ground-water system resulting directly or indirectly from ground-water withdrawals.

The objectives of the hydrologic monitoring program include both limited and long-range effects of pumping on the flow system in the ground-water reservoir and changes in magnitude of the various components of the flow system resulting from a lowering of the water table. Periodic quantitative analyses of the flow system have been prepared as an essential part of the continuing program of evaluating the effectiveness of the reclamation project in terms of design characteristics and operational procedure. The studies are designed to provide pertinent hydrologic data to agencies responsible for developing operational and management techniques and to provide data and interpretation that may be useful in planning future ground-water reclamation projects.

In addition to the analysis of the regional hydrology of the project area, tubewell performance is monitored in an effort to measure changes in well efficiency with time and to determine the merits of different types of well construction and constructional material. The chemical quality of ground water is monitored to determine the amount and areal distribution of change in chemical character of ground water in the project area. Knowledge of these changes will permit implementation of sound and efficient management of the ground water, including mixing and distribution of ground water of different chemical characteristics and conjunctive use of ground water and surface water; moreover, the monitoring will provide required data in the probable event that the transfer of water from one area to another becomes necessary.

Preliminary water-budget analyses describing the flow system and response characteristics of the ground-water reservoir have been prepared annually since water year 1962 (starting July 1). The principal objective of these studies is to determine the annual changes on the flow system in the SCARP–1 area resulting from pumping. These reports utilize data routinely collected by several governmental agencies including the Irrigation Branch, the Land and Water Development Board, the Meterological Department, and the Water and Power Development Authority to supplement the data collected by the Water and Soils Investigation Division. Included in these studies is an evaluation of (1) change in altitude of water table; (2) annual and long-term change in ground-water storage; (3) pumpage; (4) precipitation; (5) ground-water inflow and outflow; (6) surface-water inflow and outflow; (7) evapotranspiration; (8) ground-water recharge; and (9) changes in chemical character of the ground water.

The purpose of this report is to summarize and condense the hydrologic information available through water year 1967 and to refine the quantitative estimates within the scope of available data. Specifically, this report describes the change in water table that occurred during the first 7 years of project operation and presents the annual ground-water budget, including elements of inflow, outflow, pumpage, and changes in ground-water storage. It also describes the change in altitude of the water table since pumping began and the areal distribution of the cumulative decline. Estimates are given on precipitation and on surface-water diversions to and from the area. Analyses are made of the hydrologic budget utilizing all the increments of inflow, outflow, and change in storage to compute the total consumptive use of water. Changes in the quality of ground water resulting from recirculation of irrigation water, induced infiltration from canals, and the migration of deep-seated brines brought about by heavy pumping are described.

ACKNOWLEDGMENTS

The field and laboratory studies upon which this report is based were a part of the general program of ground-water investigations and of the subsequent hydrologic monitoring and research project and were carried out by the Water and Soils Investigation Division (WASID), West Pakistan Water and Power Development Authority (WAPDA), under the administrative direction of Mr. S. M. Said, Chief Engineer, and his successor, Mr. M. M. Ahmad. Technical guidance for the studies was furnished by a team of US AID advisors under the immediate supervision of Maurice J. Mundorff, Chief Technical Advisor, and his successor, Herbert A. Waite, and the author, all of the U.S. Geological Survey. The studies were under the general supervision of George C. Taylor, Jr., U.S. Geological Survey, Washington, D.C.

The author is indebted to many members of WASID's staff who assisted in the compilation and analysis of data and the preparation of illustrations. Supervision of the collection and analysis of data was provided by Mr. M. A. Lateef, Project Director, Central Monitoring Organization, Mr. Syed Amjad Hussain Shah, Superintending Hydrologist, General Hydrology Circle, Mr. Abdul Hamid, Superintending Research Officer, in charge of the Quality of Water Circle, and his successor, Mr. H. S. Zaidi. Mr. C. M. Umar, Project Director, and Mr. M. I. Varaich, Superintending Engineer, both of the Surface Water Hydrology Directorate, WASID, WAPDA, provided valuable assistance and technical guidance in establishing gaging stations on the drains in SCARP–1 and in checking the rating curves for the staff-gage sites at the points of inflow and outflow on the canals and drains.

The collection of field data and the office computation was carried out under the supervision of Mr. A. Rehman, Senior Hydrologist, Monitoring Studies Section (Northern Zone). Much of the work of tabulating data and of preparing maps and other illustrations during the last 4 years of the monitoring studies was performed by Mr. Ghazanfar Ali Awan, Assistant Hydrologist, of the Monitoring Studies Section.

All of the water-quality analyses used in construction of the maps on which all interpretations in this report are based were processed in the laboratory of the Quality of Water Circle. The collection of water samples in the field and their analysis in the laboratory involved the efforts of many men, it is likely that this is one of the world's largest and most detailed water-quality monitoring programs of its kind ever carried out. The combined field and laboratory staff of the Quality of Water Circle share the credit for collecting and analyzing the data used in the investigation of the quality of ground water in SCARP–1. Without the combined effort of the entire staff in collecting and processing the data, this report would not have been possible. Staff members deserving special credit for help in the preparation of data used in this report include Messrs. M. S. Randhawa and H. A. Shah, who tabulated many of the voluminous data required for the construction of isogram maps, and Messrs. Z. A. Khan, A. T. Khan, and A. Ghaffar, for their assistance in the preparation of preliminary drafts of some of the maps and other illustrations used in this report.

GENERAL FEATURES OF THE AREA

The Indus Plain is a vast alluvial plain that covers an area of about 80,000 square miles. It extends from the foothills of the Himalaya to the Arabian Sea, sloping southward at a low angle ranging from about a foot and a half per mile in the northern areas to less than a foot per mile in the areas adjacent to the sea. The plain is composed of alluvial deposits laid down by the Indus River and its tributaries and consists of two principal parts: (1) the Punjab region in the north and (2) the lower Indus Plain in the south.

The Punjab, meaning the land of five rivers, includes an area of about 40,000 square miles traversed by the Indus River and its principal tributaries, the Jhelum, Chenāb, Rāvi,[1] and Sutlej Rivers. The rivers separate the Punjab into four areas, each of which is bounded by two rivers and is locally called a "doāb." These four interfluvial areas are Thal, Chaj, Rechna, and Bāri Doābs.

The SCARP–1 area described in this report is in central Rechna Doāb. Rechna Doāb is bounded by the Chenāb River on the north and the Rāvi River on the south, and comprises an area about 70 miles wide and 250 miles long. The topography of the doāb is characterized by broad flood plains several miles wide along the bordering rivers. The center of the doāb is a broad flat upland plain that stands as much as 50 feet above the level of the active flood plains.

The climate of Rechna Doāb is typical of the Punjab and of the low-lying, interior part of the Indo-Pakistan subcontinent, and is distinguished by large seasonal fluctuations in both temperature and precipitation. Except in the northern and northeastern extremities of the doāb, precipitation is insufficient in amount and distribution throughout the year to sustain agriculture. About 70 percent of the annual precipitation occurs during the monsoon period in July and August, and during the rest of the year precipitation is scarce and sporadic.

The summer is long and hot with maximum daily temperatures of more than 90°F occurring almost uninterruptedly from April through September. Temperatures rarely fall below freezing in the winter. The growing season is sufficiently long for harvesting two crops a year, and, in the irrigated area, double cropping is widely practiced.

The soils of Rechna Doāb, like those of other areas in the Punjab, are composed of alluvial material of recent origin transported by the rivers draining the northern mountain ranges. They are mostly moderately coarse to medium textured soils having favorable permeability characteristics. Although they generally contain little organic matter, they are fertile soils with high po-

[1] Geographic names in this report are from Board of Geographic Names sources. Names are approved standard names where verified.

tential productivity, provided that adequate water can be applied to the land to sustain plant growth and to insure crop survival. Man's attempt to cultivate this land has resulted in a history of water-resource development in the Punjab that dates back several hundred years.

WATER RESOURCE DEVELOPMENT

Precipitation is insufficient for successful agriculture, except on a very limited scale, and, therefore, prior to the construction of canals, agriculture was confined largely to river flood plains where overbank flooding periodically provided irrigation water.

Construction of canals began about the end of the 17th century when water was diverted from the rivers during periods of relatively high flow to upland areas adjacent to the flood plain. The canals functioned only during periods of high streamflow following the monsoon rains, and, therefore, irrigation was restricted to a relatively narrow strip of land bordering the rivers and limited largely to the summer season.

Perennial irrigation water supplies became available to the central part of the doāb, including the SCARP–1 area, near the end of the 19th century only after the construction of the large diversion canals and permanent barrages and headworks on the Chenāb River. The water diverted through these canals and distributed through an extensive network of distributaries permitted vast areas of previously uncultivated land in the central part of the doāb to be irrigated on a perennial basis. The perennial canals still provide the principal sources of irrigation water to most of the Punjab.

Prior to the evolution of efficient well-drilling methods and before the development of deep-well pumps, the ground-water resources in the Punjab were little utilized except for a few scattered wells that provided limited quantities of water for domestic and irrigation use. Along the flood plain of the rivers, where the water table was within a few feet or a few tens of feet of the land surface, dug wells equipped with Persian Wheels, or with a leather bag (mote) attached to a rope and lowered and raised by bullocks or camels, provided water for limited irrigation. In the central part of the doāb, where ground water occurred at somewhat greater depths, a few scattered hand-dug wells at villages and places of religious worship and equipped with handlines and buckets, provided essential water supplies for domestic and livestock use.

For all practical purposes, however, ground-water underflow entering the area was discharged by evapotranspiration or moved beneath the study area to points of natural discharge downgradient. Recharge to the ground-water reservoir was principally influent seepage from the rivers and to a lesser degree precipitation; it was equal to the natural discharge of ground water by evapotranspiration and subsurface outflow. Under the conditions that prevailed, dynamic equilibrium had been established between all the various components of recharge, discharge, and ground-water storage. Within the study area seepage from the Chenāb and Rāvi Rivers generally moved away from the rivers towards the center of the doāb, and that portion which was not discharged locally by evapotranspiration eventually moved southwestward toward the Indus River. Except for a narrow strip adjacent to the river, the water table occurred at a depth in excess of 30 feet (Greenman and others, 1967) below land surface, and in the center of the doāb, ground water occurred at depths of 90 feet or more.

Following the construction of the perennial canals, seepage losses from the unlined canals contributed a significant increase in recharge to the ground-water reservoir. Because of the relatively flat topography, low hydraulic gradient, and generally poor drainage conditions in the doāb, the water table began to rise.

Simultaneously with the rise of the water table, the hydraulic gradient and consequent movement of ground water towards the center of the doāb decreased annually. By about 1930 the water table in the central part of the doāb had risen above the altitude of the adjacent rivers, thereby reversing the hydraulic gradient and direction of ground-water flow.

Many remedial steps were initiated to control the depth to the water table including closure of canals during the monsoon period, construction of drainage ditches, and planting phreatophytes along canals. Experience with open-ditch drains to control waterlogging and salinity showed that they were too expensive; moreover, they did not provide for the regulation of or for an increase in irrigation supply. As an alternative, experiments with vertical drainage by tubewells were begun.

The first attempt to stem the rising water table by pumping water from the ground-water reservoir was begun in the 1940's with the construction of about 1,600 tubewells (drilled wells). Wells drilled under this plan, which are known locally as the "Rasul wells," were part of a reclamation scheme designed to intercept leakage from the canals and to pump it back into the canals. The wells were drilled at distances of up to about 600 feet on both sides of the larger canals at intervals of about a quarter of a mile. The Rasul wells proved to be ineffective in bringing permanent relief. By 1960 the water table in Rechna Doāb had risen as much as 90 feet in the area southeast of Lyallpur, and in many areas it reached the land surface or was within a few feet of it.

The second use of tubewells to lower the water table in irrigated areas began in 1950 when the Irrigation Branch selected four separate areas in the central part of Rechna Doāb that were badly affected by waterlogging. These four areas or schemes, which include Chūhar Kāna, Jarānwāla, Pindi Bhattiān, and Chīchoki (Chīchoki Malliān), respectively, range in size from about 7,000 to 90,000 acres and have a total combined area of about 119,000 acres. Within these schemes, 190 project wells were constructed and placed in operation in 1954, 1957, 1958, and 1960, respectively. These schemes were later incorporated into Salinity Control and Reclamation Project One (SCARP–1), which is the first of several planned ground-water reclamation projects designed to lower the water table in a large area. Reclamation projects similar to SCARP–1, and of comparable or larger size, are planned eventually to control the depth of the water table and to regulate the irrigation supply for most of the Indus Plain.

The SCARP–1 area is a contiguous area of about 1.3 million acres. It includes the four reclamation schemes completed by the Irrigation Branch. For construction and operation, the remainder (about 1.1 million acres) of SCARP–1 was divided into eight schemes ranging in size up to about 255,000 acres (table 1).

TABLE 1.—*Statistical data for SCARP–1*

Scheme	Approximate area (acres)	Number of project wells	Length of canals (miles): Main canals and branches	Minor and distributary	Total
Pindi Bhattiān [1]	8,300	21	-----	8.40	8.40
Chīchoki (Chīchoki Malliān) [1]	7,000	12	-----	-----	------
Chūhar Kāna [1]	10.800	24	-----	-----	------
Jarānwāla [1]	93,100	133	40.00	72.85	112.85
Shāh Kot	254,900	384	8.20	160.33	168.53
Zafarwāl	243,600	390	50.17	133.02	183.19
Khāngāh Dogrān	115,300	209	26.80	73.33	100.13
Sāngla (Sangla Hill)	138,000	233	20.00	78.36	98.36
Berānwāla	104,600	126	30.00	59.35	89.35
Harse Sheikh	24,500	44	39.26	23.55	62.81
Hāfizābād	171,900	318	17.00	136.24	153 24
Shādmān	78,500	149	21.90	129.69	151.59
Total	1,250,500	2,043	253.33	875.12	1,128.45

[1] Schemes completed by the Irrigation Department and transferred from the Tubewell Circle to SCARP–1 in July 1963.

More than 1,800 tubewells drilled to depths of up to 350 feet and constructed with 16-inch housing pipe, 10-inch diameter screen surrounded by 6 inches of gravel shrouding, were completed and placed in operation by 1962. The tubewells are equipped with turbine pumps designed to pump from 1 to 5 cfs (cubic feet per second) and have a combined installed capacity of about 3.5 million acre-feet per year. Although the average density of tubewells in the project area is about one per square mile, they were positioned on the basis of irrigation requirements and available conveyance ditches and, therefore, are somewhat irregularly spaced (pl. 3).

Each year since the beginning of full-scale operation, the combined pumpage from project, private, and other wells has about doubled the amount of water supplied to crops in SCARP–1. As a result of the vertical drainage and increased water consumption by crops, the water table in the project area has been lowered about 5 feet. Of the total area of more than 400,000 acres that had been wholly or partially affected by waterlogging and salinity in 1950–60, about 66 percent of the damaged land was reclaimed as of June 1967. During the same period of time, the cropping intensity increased from about 77 to about 101 percent, which, together with increased productivity, resulted in an increase in annual value of major crops of about 186 percent over 1959–60 (West Pakistan Land and Water Development Board, 1966).

Although pumping has lowered the water table in the project area, the direction of ground-water movement remains generally the same as during the prepumping period. Continued pumping may continue to lower the altitude of the water table. However, under the present operating schedule, it appears that equilibrium between recharge and discharge may have been reestablished. As reclamation projects in adjacent areas become operative and as pumping in those areas begins, ground-water inflow from areas of recharge upgradient will be reduced. At that time the water table in SCARP–1 will decline to a new level until equilibrium is again established.

GROUND WATER

THE GROUND-WATER RESERVOIR

The alluvial material beneath SCARP–1 forms part of the extensive heterogeneous and anisotropic unconfined ground-water reservoir underlying the Indus Plain and is more than 1,000 feet thick. The upper 600 feet as described by Greenman, Swarzenski, and Bennett (1967), is composed of a thick sequence of alluvial sand, silt, and clay that has been laid down since late Tertiary time by the Indus River and its tributaries. Recurrent floods and frequent changes in rate of flow caused the streams to meander back and forth across the land surface in a braided pattern of irregularly shifting channels. Over a period of time a broad constructional plain was built up. The underlying deposits have little vertical or horizontal continuity. The bulk of the alluvium is composed of silt and fine sand or mixtures thereof. Lithologic logs of wells indicate the absence of thick layers of pure clay in the alluvium. Except for a few clay lenses, a few feet thick, clay usually occurs as a mixture with silt and sand. Material coarser than fine sand is practically nonexistent, except in the upper reaches of the doāb where the alluvial plain overlaps older rock formation. The bulk of the alluvium is unconsolidated except for an occasional zone where the deposition of chemical precipitates has formed calcareous concretions. Most of the alluvial material is highly porous and is capable of storing and transmitting water readily.

The water-bearing character of the ground-water reservoir in SCARP–1 has been evaluated largely on the basis of numerous pumping tests. Bennett, Ata-Ur-Rehman, Sheikh, and Ali (1967) listed the results of 49 pumping tests in Rechna Doāb and showed that horizontal permeability of the aquifer is considerably greater than vertical permeability. In the screened intervals in the wells tested, horizontal hydraulic conductivity (formerly designated the coefficient of permeability) averaged about 0.0038 cfs (cubic feet per second) per square foot. About 69 percent of the results fell in the range 0.0025 to 0.0053 cfs per square foot. The presence of clay and silt lenses within the reservoir retards the vertical movement of water and reduces the vertical permeability. Bennett, Ata-Ur-Rehman, Sheikh, and Ali (1967) have shown that the vertical hydraulic conductivity of a section of unconsolidated alluvium can be expected to fall in the range 10^{-5} to 10^{-3} cfs per square foot. Anisotropic ratios suggested by the tests range from about 3:1 to 195:1 and average about 76:1.

Despite the anisotropic nature of the alluvium, properly constructed wells can be developed almost anywhere in the area to yield 1.5 to 5 cfs. The average capacity of the project wells in SCARP–1 is about 2.8 cfs. Specific drawdowns in the project wells at the time of completion range from a maximum of about 28 feet per cfs to a minimum of 2.2 feet per cfs and average about 4.3 feet per cfs. Specific capacities of the project wells at the time of completion ranged from about 0.044 to about 0.4 cfs per foot of drawdown. The average specific capacity for all wells in SCARP–1 at the time of completion was about 0.22 cfs per foot of drawdown. Experience in SCARP–1 has shown that in some areas encrustation and corrosion of mild-steel well screen and casings has resulted in a marked reduction in the specific capacity of some wells in relatively short periods and have rendered some wells useless in the short period of 3 or 4 years. The problem has been minimized in more recently constructed ground-water reclamation projects by utilizing epoxy resin-bonded fiber-glass casing and screen.

SOURCE AND MOVEMENT

Replenishment to the ground-water reservoir in SCARP–1 is derived principally from ground-water underflow from adjacent areas updoāb, canal seepage, direct infiltration of precipitation, and percolation of irrigation water from conveyance ditches and irrigated fields. The direction of flow and the implied source is indicated by the water-level contour maps (pl. 1). Water moves downward and away from areas of recharge toward areas of discharge along curvilinear flow paths in response to differences in hydraulic head both vertically and horizontally. Vertical circulation of ground water in the study area can be defined only to a limited extent on the basis of available data. The lateral component of movement is in a direction normal to the water-level contours and indicates the source area and the cardinal direction of flow. Plate 1 shows the approximate altitude and configuration of the water table based on the average water levels in 1960–61, and the water levels in June 1968 in wells penetrating the upper few hundred feet of the zone of saturation. Many test wells drilled to a thousand feet or more indicate a small difference in head with depth, and, consequently, the maps do not necessarily reflect the exact hydraulic gradient and the precise direction of ground-water flow in the deep aquifers. However, inasmuch as the water contained in the ground-water reservoir generally is unconfined, the maps probably indicate the general horizontal component of regional movement of ground water at depth also. Contour maps based on the altitude of the water table in June for successive years since 1961 approximate the annual low water level, which usually occurs prior to the monsoons in July.

The configuration of the water table represented by the contour maps is intentionally generalized to show the regional hydraulic gradient. Ground-water mounds or ridges beneath the canals or depression cones around pumped wells generally are limited in areal extent and magnitude, and may be of temporary duration. These anomalies affect the direction and rate of ground-water movement locally, but have little effect on the regional movement of ground water, unless they persist over a prolonged period of time.

The regional water table in SCARP–1 is an irregular surface; it occurs at a depth of a few feet to a few tens of feet below the land surface and has a gradient of about 1.5 feet per mile to the southwest. It ranges in altitude from about 700 feet above mean sea level in the northeastern corner of the area to about 580 feet in the southwestern corner of the project. The altitude of the water table is generally from 10 to 20 feet higher in the center of the project area than along the bordering rivers.

As the water table rises or falls in response to recharge and discharge, the contour lines reflect the change. Consequently, the shape of the contours may change from day to day or from season to season. However, a comparison of the water-table maps for 1960–61 and June 1968 shows that the general shape of the contours has remained about the same, despite the fact that there has been a general lowering of the water table in the project area of about 5 feet. The main change in configuration has been a migration upgradient of the water-table contours in the center of the project area. The reduction in the lateral component of underflow toward the rivers is manifest in the progressive decrease in calculated underflow from the area (table 3).

INFLOW

Ground-water inflow to SCARP–1 from areas of recharge updoāb enters the northeastern tier of schemes including Hāfizābād, Khāngāh Dogrān, Chūhar Kāna, Shāh Kot, Zafarvāl, and Chīchoki (Chīchoki Malliān). It is calculated for each scheme along the northeastern edge of the project on the basis of (1) the length of the cross-section between limiting flow lines separating adjacent schemes, (2) the average hydraulic gradient between flow lines, and (3) an estimated value of transmissivity. Accordingly, the computed inflow represents an estimate of the total amount of ground water moving into the area from recharge areas up the hydraulic gradient.

The length of the cross section through which ground water enters SCARP–1 has increased since 1964 as the cone of depression expanded. Lowering the water table has caused a convergence of ground-water flow along the northeastern and southeastern corners of the project area. Consequently the potential area of recharge has been enlarged and the magnitude of the annual inflow increased.

The hydraulic gradients, on which the computations of ground-water inflow are based, are determined from water-table maps prepared from data on the altitude of the water table in several hundred observation wells in June of each year. The altitude of the water table in June approaches its annual minimum following a long period of pumping that begins in September or October of the previous year. Pumping usually is minimal during the monsoon season in July and August. The regional hydraulic gradients along the margin of the project area, as shown by the water-table maps for June, therefore, are steepest along the northeastern boundary where ground-water underflow enters the area, and they are flattest along the southwestern border of the project where ground-water underflow leaves the area. Computed ground-water inflow and outflow based on the altitude of the water table in June, therefore, represent the annual maximum and minimum flow, respectively. The hydraulic gradient of the water table along the northeastern edge of the area ranges from about 2 to 3 feet per mile.

The average transmissivity of the saturated sediments, determined by analyzing more than 140 pumping tests in partially penetrating wells, is on the order of 0.50 ft^2/sec, or about 300,000 gpd per ft (gallons per day per foot) (Bennett and others, 1967; Arif, 1966).

However, the transmissivity obtained from the pumping-test analysis may be in considerable error. The transmissivity used in calculating ground-water underflow was determined by methods developed by Theis (1935), Cooper and Jacob (1946), and Boulton (1963), which were the best methods available at the time. Because field conditions deviate from assumed physical conditions on which the methods of analysis are based, the calculated value of transmissivity may not accurately represent the transmissivity of the aquifer as a whole. The pumping tests were made in multiple-screen wells penetrating the upper 300–400 feet of an anisotropic aquifer that in most places exceeds a thousand feet in thickness. It is probable that the values obtained from the tests, therefore, are much less than would be expected in fully penetrating wells screened throughout their entire length. Because of the anisotropy of the alluvium, however, ground water in the lower part of the reservoir may be more or less stagnant and may be of little significance in the regional movement of ground water from one area to another. In this event, the transmissivity values indicated by the pumping tests may be representative of the upper part of the aquifer where ground-water circulation is most significant.

For lack of more accurate data on the transmissivity, Mundorff and Lateef (1963), and subsequent investigators, used the values determined from the analysis of the pumping tests to compute ground-water inflow and outflow from the project area.

The computations of ground-water inflow to SCARP–1 are based on a modified form of Darcy's Law which may be expressed by the equation $Q=0.00112\ TIL$, where Q is the quantity of water, in acre-feet per year, T is the transmissivity of the aquifer, in gallons per day per foot, I is the hydraulic gradient, in feet per mile, L is the width of aquifer, in miles, through which underflow is computed, and 0.00112 is the factor for converting gallons per day to acre-feet per year.

The calculated annual inflow to SCARP–1 is shown in table 2. It gradually increased since pumping began, from a minimum of about 35,000 acre-feet in water year 1960 to a maximum of about 52,000 acre-feet in water years 1966–67.

TABLE 2.—*Ground-water inflow to SCARP–1 (by water years starting July 1)*

Scheme	Inflow, in acre-feet							
	1960	1961	1962	1963	1964	1965	1966	1967
Hāfizābād	3,000	-----	8,000	8,000	7,000	8,000	11,000	10,000
Khāngāh Dogrān	13,000	-----	20,000	22,000	16,000	16,000	19,000	19,000
Chūhar Kāna	3,000	-----	4,000	3,000	1,000	3,000	4,000	4,000
Shādmān and Chichoki	13,000	-----	9,000	8,000	9,000	14,000	14,000	9,000
Zafarwāl	3,000	-----	3,000	5,000	4,000	4,000	4,000	10,000
Total	35,000	[1] 42,000	44,000	46,000	37,000	45,000	52,000	52,000

[1] Estimated.

OUTFLOW

Ground-water outflow moves generally southwest from the project area toward areas of natural and artificial discharge across a section about 70 miles in length extending from Hāfizābād and Pindi Bhattiān in the northwest to Zafarwāl in the southeast. Along the southern edge of the project area, ground-water underflow moves from the Zafarwāl Scheme towards Degh Nāla and the Rāvi River. Along the northwestern border, ground-water underflow from the project area moves from Hāfizābād, Pindi Bhattiān, and Harse Sheikh Schemes toward the Chenāb River. In the central part of the doāb, the general direction of ground-water underflow is toward areas of natural discharge southwest of the project area.

The hydraulic gradient along the project border where ground-water outflow occurs ranges from about one-half foot per mile to less than 2 feet per mile, and changes from year to year depending on the expansion or decay of the cone of depression under the project area.

Theoretically, ground-water outflow from the project should decrease as the depth of the cone of depression increases. As the cone deepens and as more water is removed from storage, the water table is lowered. Lowering of the water table in the project area will decrease the hydraulic gradient along the southwestern border of SCARP–1 and result in less ground-water outflow. The annual subsurface outflow from SCARP–1, calculated on the basis of the hydraulic gradient, the width of the cross-sectional area, and uniform transmissivity is summarized in table 3 for water years 1960 through 1967. During this 8-year period for which records are available, ground-water outflow from the project area decreased from a maximum of about 57,000 acre-feet in water year 1960 to a minimum of about 32,000 acre-feet in water year 1966.

Tabulation of the annual ground-water outflow from SCARP–1 (table 3), based on water-table maps for June of each year, shows a progressive annual decrease except in water year 1967. The increased outflow in 1967 is the result of a rise in the water table within the cone of depression and a corresponding increase in hydraulic gradient along the southwestern border of the project. The hydraulic gradient in June 1968 was approximately the same

TABLE 3.—*Ground-water outflow from SCARP–1 (by water years starting July 1)*

Scheme	Outflow, in acre-feet							
	1960	1961	1962	1963	1964	1965	1966	1967
Hāfizābād	11,000	-----	4,000	8,000	7,000	5,000	6,000	11,000
Harse Sheikh	10,000	-----	10,000	6,000	6,000	6,000	8,000	9,000
Berānwāla	3,000	-----	3,000	4,000	3,000	3,000	3,000	3,000
Sāngla	7,000	-----	4,000	3,000	4,000	4,000	4,000	4,000
Shāh Kot	4,000	-----	4,000	3,000	3,000	2,000	3,000	2,000
Jarānwāla	8,000	-----	6,000	5,000	6,000	5,000	4,000	4,000
Zafarwāl	14,000	-----	7,000	9,000	7,000	9,000	4,000	6,000
Total	57,000	[1] 48,000	39,000	37,000	36,000	34,000	32,000	39,000

[1] Estimated.

as in June 1963, and therefore the ground-water outflow from SCARP–1 during both years was about the same.

TUBEWELL PUMPAGE

Pumping in the area began in the Chūhar Kāna Scheme in 1954–55, in Jarānwāla in 1957, in Pindi Bhattiān in 1958–59, and in Chīchoki in 1960. Tubewells in the other eight schemes were completed and commissioned progressively beginning in September 1961. By July 1962, most of the wells had been placed in operation except in Shāh Kot and Zafarwāl Schemes, where full-scale pumping started in October 1962 and March 1963, respectively. Data on annual pumpage [by project wells] in each scheme area during water years 1960 through 1967 are given in table 4. Pumpage values shown in the table for water years 1961–66 were obtained by multiplying the number of hours of operation of each project well by the designed capacity of the pump. Higher pumping life, resulting from the lowering of the water table during the first few years of pumping, probably has caused the actual pump discharge to be somewhat less than the design discharge, and, therefore, the estimates of pumpage for the first 5 years of operation may be somewhat high.

Pumpage for water year 1967 is calculated on the basis of measured discharge at each well and on the number of hours of operation during the year, and, therefore, probably is more accurate than the estimates made in previous years.

The estimates of annual pumpage of project wells in SCARP–1 indicate that the pumpage increased rapidly in water years 1960 and 1961 and reached a maximum of about 2.8 million acre-feet in 1962. Since 1962 there has been an annual decrease in pumpage to a minimum of slightly more than 1.5 million acre-feet in water year 1966. Although electrical power shortages and above-average precipitation in 1966 (fig. 2) probably are the principal reasons for the low pumpage during that year, the progressive decline in annual pumpage is due to several other reasons as well. Part of the decline undoubtedly is due to a decrease in demand. During the initial phases of reclamation, when large amounts of irrigation water were applied to saline-affected areas to leach the salt from the soil profile, there was a high demand for irrigation water, but, as reclamation progressed, the demand decreased. Other causes cay be attributed to (1) the shutdown of pumps for maintenance and repair, (2) the abandonment of some wells producing highly mineralized water, and (3) reduction in pump discharge resulting

TABLE 4.—*Approximate pumpage in SCARP–1 (by water years*[1] *starting July 1)*

Scheme	Discharge, in thousands of acre-feet									
	1960	1961	1962	1963	1964	1965	1966	1967	Total	Average discharge, in feet per acre
Berānwāla	---	133	203	181	158	182	96	114	1,067	10.1
Hāfizābād and Pindi Bhattiān	[2] 18	36	532	464	453	489	290	312	2,594	14.4
Harse Sheikh	---	40	70	73	71	76	43	53	426	17.4
Jarānwāla	70	75	240	115	109	112	80	108	909	9.7
Khāngāh Dogrān	---	225	365	319	270	318	202	257	1,956	17.0
Sāngla	---	237	370	317	289	300	199	225	1, 37	14.0
Shādmān and Chichoki	9	[2] 19	169	180	138	163	90	105	873	10.2
Shāh Kot and Chūhar Kāna	18	[2] 33	435	423	339	420	245	266	2,179	8.0
Zafarwāl	---	---	380	508	480	293	301	386	2,348	[illegible].6
Subtotal [3]	[2] 115	[2] 98	2,764	2,580	2,307	2,353	1,546	1,826	14,289	
Rasul wells [2]	250	250	250	250	250	250	250	250	2,000	
Private wells [2]	---	50	50	50	50	50	50	50	350	
Total	[2] 365	[2] 1,098	3,064	2,880	2,607	2,653	1,846	2,126	16,639	34.3

[1] Water year as used in this report includes the 12 month period July 1 through June 30 and is designated by the calendar year in which it starts.
[2] Estimated values.
[3] Pumpage for water years 1961–66 is estimated on basis of hours of operation and design capacity of the pump. Pumpage in 1967 is based on hours of operation and measured discharge of pump.

from loss of well efficiency caused by corrosion and encrustation.

In addition to withdrawals by project wells, there was a large but mostly unmeasured amount of water pumped by other wells within SCARP–1. It is estimated that 400–500 Rasul wells within SCARP–1 pump about 250,000 acre-feet of water annually. Several hundred private tubewells are estimated to have pumped on the order of 50,000 acre-feet annually since 1961. Thus, it is estimated that the total pumpage from all wells in SCARP–1 since 1960 has ranged from slightly more than 3 million acre-feet in 1962 to slightly less than 2 million acre-feet in 1966. The gross pumpage between June 1960 and June 1968 has been about 16.6 million acre-feet, or an average of about 13 acre-feet per acre. Maximum pumping occurred in the Harse Sheikh Scheme where a total of more than 17 acre-feet per acre of water was discharged. Minimum pumpage of about 8 acre-feet per acre occurred in the Shāh Kot and Shūhar Kāna Schemes.

DECLINE OF THE WATER TABLE AND DEPLETION OF STORAGE

Many lines of observation wells were established more or less coincident with the beginning of irrigation in the Punjab, and since about 1900 the Irrigation Branch has obtained semiannual water-level measurements in a network of wells in and adjacent to SCARP–1. Beginning in 1961, the Water and Soils Investigation Division (WASID), WAPDA, started monthly measurements of water levels in 60 wells and piezometer tubes in and adjacent to SCARP–1. In addition to the monthly measurements, 13 wells were equipped with continuous water-stage recorders. The original observation-well network was expanded during the period July 1963 to June 1964 by the addition of 70 more piezometer tubes and 12 additional continuous water-stage recorders.

The prepumping records show that the water table fluctuated as much as several feet from season to season and from year to year. Because of these fluctuations, the average altitude of the water table prior to full-scale pumping and the areal extent and magnitude of the decline in water level caused by subsequent pumping can only be approximated. The altitude and shape of the water table used as a reference for determining the annual and long-term change in water level is based on the average water level in 150 wells measured in June 1960 and June 1961. Since that time, however, all but 31 of the wells included in the original observation-well network have been destroyed or partially plugged.

Continued attrition of wells in the original network has required periodic replacement or substitution of wells. A few additional wells, added to fill gaps in the data, have expanded the observation-well network to about 160 wells. The water-table map for June 1968 (pl. 1) is based on data from 159 observation wells in the study area. Wells included in the monitoring network are never pumped, and most are a half mile or more from any pumping well. Temporary fluctuations of the water table due to periodic pumping of project and other wells, therefore, are minimized. The water-table contour maps based on the water-level data in the observation wells, therefore, may be somewhat conservative; that is, they may reflect the minimum changes in altitude resulting from pumping. The recent acquisition of computer facilities by WAPDA will make possible map-plotting programs that include data on water-level altitude from all wells in the project area. Although refinement in the configuration of the water table will be achieved by the inclusion of all water-level data in preparation of future water-table maps, the values of the annual and long-term change in altitude of the water table, changes in ground-water storage, and related items, probably will not be materially different from the values determined by the methods presently employed.

Data currently available indicate that the cone of depression that has developed since pumping began locally extends a mile or two beyond the boundaries of the study area. Although the lack of a sufficient number of control points beyond the boundary of the study area prevents the precise areal delineation, a reasonable approximation of the total area affected by pumping can be made by superimposing the water-table contour map for successive years on the composite water-table map for 1960–61; a line drawn through successive points where contours of equal elevation on the two maps intersect or are coincident is used in determining the approximate boundary for the area of the cone of depression.

The altitude of the water table changes in response to recharge to and discharge from the ground-water reservoir. It is axiomatic that when ground-water discharge exceeds recharge, water in storage in the ground-water reservoir is depleted and the altitude of the water table is lowered. Under the hydrologic conditions that prevailed in SCARP–1 prior to the installation of wells, the ground-water regimen over a long period of time was in dynamic equilibrium. Discharge was equal to recharge, and after about 1955, there was no significant long-term change in ground-water storage; temporary seasonal increments of recharge can be attributed to appreciable amounts of precipitation or to increase in canal seepage that followed changes in the canal distribution system or adjustments in canal deliveries.

After the installation of wells and the beginning of pumping, the equilibrium or near-equilibrium conditions that had prevailed previously came to an end. During the initial phases of pumping, most of the pumpage is derived from storage, and, as a result, there is a rapid decline of the water table in the vicinity of the pumping wells. As pumping continues, the rate of lowering of the water level in the well and in the surrounding area diminishes, but the lowering will continue until the cone of depression intercepts sufficient recharge to satisfy the pumping demand. If the pumping demand exceeds the available ground-water recharge, depletion of ground-water storage will continue, and the water level in the well will continue to decline. On the other hand, if the cone of depression intercepts sufficient recharge to meet the pumping demand, equilibrium will be reestablished and the altitude of the water table will again stabilize.

Pumping began in SCARP–1 at irregular intervals, starting in 1954, in the four widely scattered schemes completed by the Irrigation Branch. With the exception of the Jarānwāla Scheme, the schemes are small and the lowering of the water table in response to pumping was highly localized. In June 1960 the water table was at a depth of 10 feet or less in an area of about 990,000 acres, or about 80 percent of the area. Plate 2 shows the approximate depth to the water table in June 1960. During 1961 and 1962, pumping increased progressively as new schemes were completed and resulted in sporadic changes in altitude of the water table. The first attempt to determine the areal extent and magnitude of the decline of the water table resulting from full-scale operation of SCARP–1 was made on the basis of water-level data for June 1963 (Mundorff and Lateef, 1963). Since that time, water-table maps of the project area have been prepared annually to show the depth and configuration of the water table and related information.

By June 1963, the cone of depression resulting from pumping the project wells included an area of about 1.35 million acres and resulted in the lowering of the water table in the area of influence an average of about 4 feet (table 5). Within the boundary of SCARP–1, lowering of the water table averaged about 5 feet. The reduction in ground-water storage resulting from lowering the

TABLE 5.—*Depletion of ground-water storage in SCARP–1*

Water year starting July 1 (1)	Area of cone of depression [1] (millions of acres) (2)	Average depth of cone of depression (4)÷(2) (feet) (3)	Volume of cone of depression (millions of acre-feet) (4)	Cumulative depletion of ground-water storage [2] (millions of acre-feet) (5)	Annual change in ground-water storage [3] (millions of acre-feet) (6)
1961	---	---	---	[4] 0.74	---
1962	1.35	4.0	5.40	1.35	[5] —0.61
1963	1.85	4.4	8.14	2.04	—0.69
1964	1.60	3.8	6.08	1.52	+0.52
1965	1.86	5.0	9.26	2.32	—0.80
1966	1.66	4.7	7.80	1.95	+0.37
1967	1.55	4.45	6.90	1.73	+0.22

[1] Area at end of each water year ending in June.
[2] Assumed specific yield of 25 percent.
[3] Product of annual change in volume of cone of depression and specific yield of 0.25.
[4] Calculated by difference.
[5] Based on average decline of water levels in observation well of 1.8, area of cone of depression, and 0.25 specific yield.

water table is the product of the volume of the cone of depression and the specific yield of the drained material. In recent pumping tests utilizing a neutron soil-moisture meter, specific-yield values of about 25 percent are indicated. Insofar as the test data are applicable to the whole of SCARP–1, the net depletion of ground-water storage by the end of June 1963 totaled about 1.35 million acre-feet, or about 30 percent of the cumulative pumpage to that date.

By the end of June 1964, the area of influence expanded to about 1.85 million acres and increased to an average depth of about 4.4 feet. Within the boundary of the project, the average net decline increased to about 6.4 feet. The increase in volume of the cone from 5.4 million acre-feet to about 8.14 million acre-feet, or about 2.74 million acre-feet, is equivalent to about 690,000 acre-feet of water depleted from storage. Uniform withdrawal of this amount of water over the area of influence would result in the average lowering of the water table of about 1.5 feet.

Reduced pumping and ground-water recharge from excessive precipitation in water year 1964 caused the water table beneath SCARP–1 to rise. By June 1965, the area of the cone of depression had contracted to about 1.6 million acres. The rise in water table of about a foot from June 1964 to June 1965 can be equated with an increment of recharge to the ground-water storage of about 520,000 acre-feet.

Slightly less than average precipitation and continued pumpage at a rate of somewhat more than 2.5 million acre-feet per year caused a resumption of the decline of the water table in water year 1965. By June 1966, the cone of depression had expanded to about

1.86 million acres. The cumulative depletion of ground-water storage by June 1966 was about 2.32 million acre-feet (table 5); the resultant decline of the water table in the area of influence averaged about 5 feet. Electrical power shortages caused temporary shutdown of pumps during 1966–68. Because of reduced withdrawals, there was a general rise of the water table and a corresponding increase in ground-water storage during those 2 years.

The expansion and contraction of the cone of depression suggested by the available data indicate that a condition of equilibrium, or near equilibrium, may have been reestablished. Development of private wells, ground-water reclamation projects in adjacent areas, or the operation of the project at or near the design capacity of the wells (4.08 million acre-feet per year) will cause a further lowering of the water table and increased depletion of ground water in storage.

The net decline of the water table resulting from all pumping through June 1968 is illustrated in figure 2. The net effect of the cumulative pumpage to that time has resulted in general lowering of the water table in the project area averaging about 4.5 feet and a depletion of ground-water storage of about 1.73 million acre-feet.

Ground-water withdrawals during the period July 1961 to July 1968 in the different schemes in SCARP–1 ranged from about 17.4 feet per acre in Harse Sheikh to about 8.0 feet per acre in Shāh Kot and Chūhar Kāna (table 4). As a result, lowering of the water table in different areas of the project has been uneven.

By June 1968, three distinct cones of depression had developed in which the maximum lowering of the water table had exceeded 10 feet (pl. 2). The three cones center in Zafarwāl, Khāngāh Dogrān, and Hāfizābād Schemes. Maximum decline is in the Zafarwāl Scheme where local lowering of the water table exceeds 12 feet. The cones of depression are separated by ground-water divides or ridges that are sustained by seepage from the Lower Chenāb Canal and Upper Gugera Branch.

Although annual and short-term changes in the altitude of the water table have been recorded in all parts of SCARP–1, there has been practically no long-term effect on the water-table altitude in Chīchoki (Chīchoki Malliān) and adjacent areas in Shādmān Scheme along the southeastern boundary of SCARP–1, and little or no effect along the southwestern edge of the project area, notably along the border of Harse Sheikh, Berānwāla, Shāh Kot, and Jarānwāla Schemes.

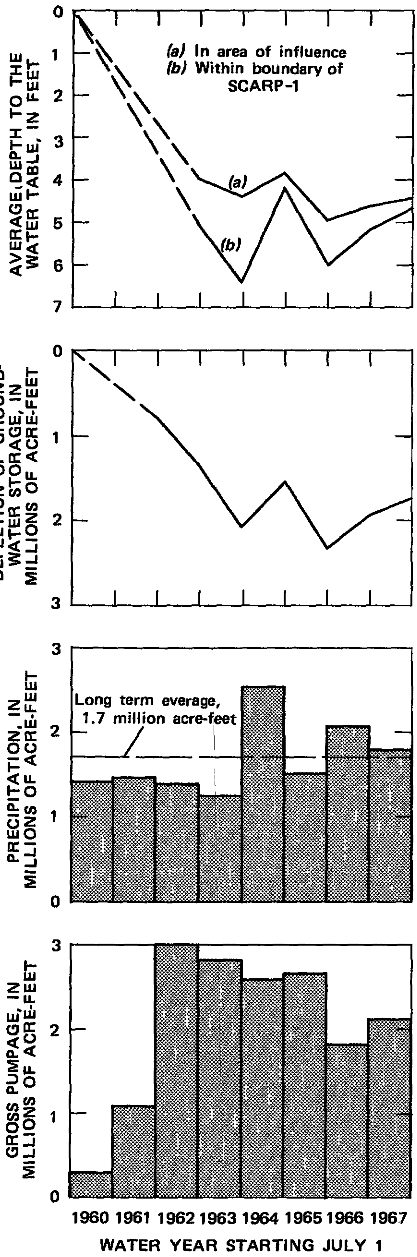


FIGURE 2.—Relation between pumpage, precipitation, water-level decline, and change in ground-water storage.

Ironically, there has been only an average of about 2 feet lowering of the water table in Harse Sheikh Scheme, despite the fact that the largest withdrawals of ground water occurred in that scheme (table 4). The probable reason for this anomalous situation is the high infiltration capacity of the sandy soils in the region and the correspondingly large losses in irrigation water by percolation.

In June 1968, the depth to the water table ranged from about 10 feet in Berānwāla Scheme to more than 20 feet in Zafarwāl (pl. 2). In no scheme was the average depth to the water table less than 10 feet below the land surface. The average decline of the water table in each of the schemes resulting from pumping through June 1968 is given below:

Scheme	*Average decline of the water table in 1960–61 to June 1968, in feet*
Harse Sheikh	2.3
Hāfizābād and Pindi Bhattiān	5.3
Khāngāh Dogrān	7.5
Berānwāla	3.0
Sāngla	5.4
Shāh Kot and Chūhar Kāna	5.4
Shādmān and Chīchoki (Chīchoki Malliān)	2.2
Zafarwāl	8.8
Jarānwāla	2.2
Average for SCARP–1	4.7

Hydrographs showing fluctuations of the water level in representative wells equipped with continuous water-stage recorders (figs. 3 and 4) illustrate the seasonal and long-term fluctuations of the water table at strategic points in the project area.

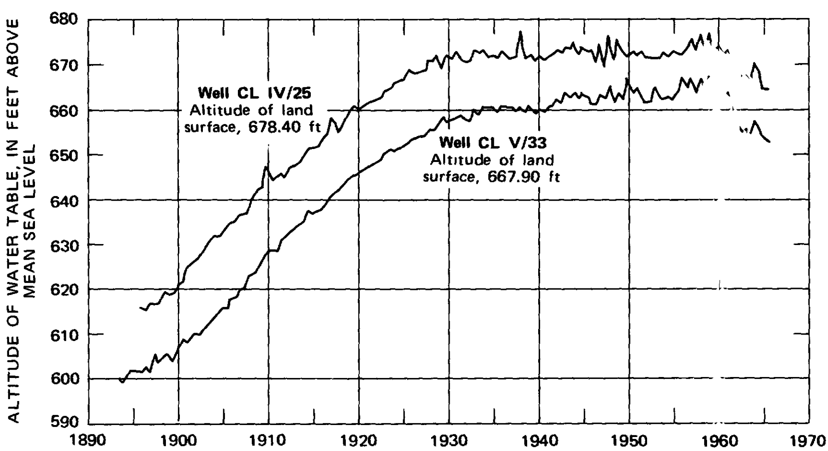


FIGURE 3.—Hydrographs of selected observation wells showing local history of water-level rise in SCARP–1.

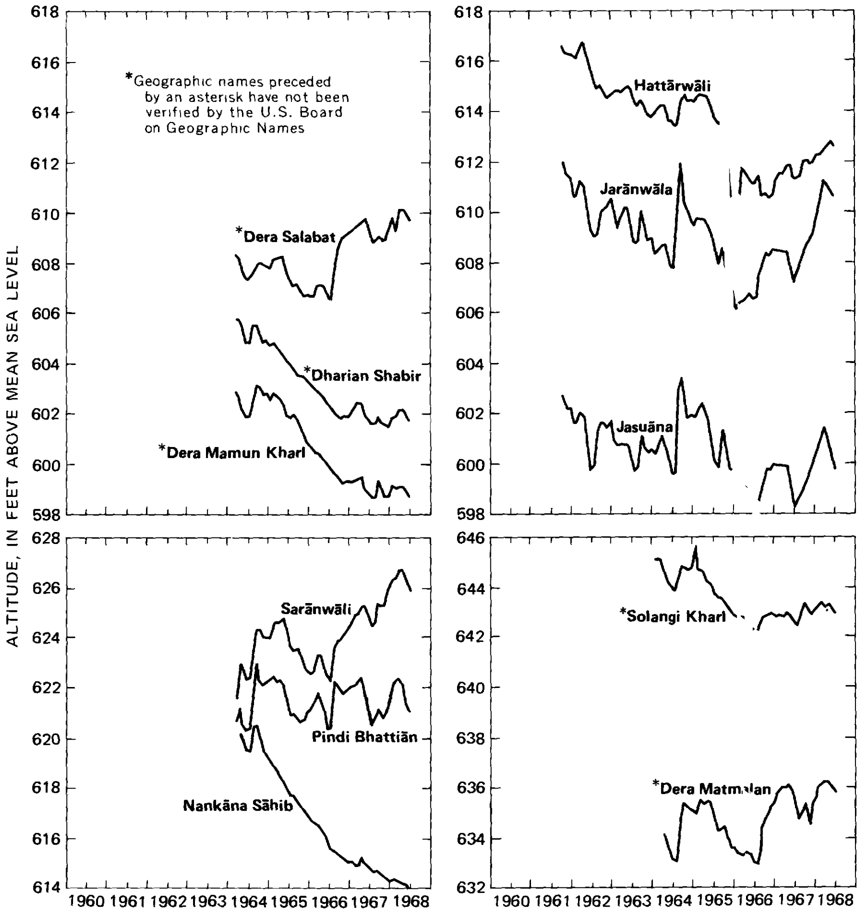


FIGURE 4.—Hydrographs of selected wells in SCARP–1 reflecting local changes in altitude of the water table since the beginning of project operation.

BUDGET ANALYSIS

Recharge to the ground-water reservoir from percolation of canal seepage, surplus irrigation water, and precipitatior cannot be measured directly but can be calculated indirectly from the equation of hydrologic equilibrium.

The equation of hydrologic equilibrium is based on the theory that a balance must exist between the quantity of water entering any given area and the amount stored within or leaving the same area for any period of time. Measurement of various components considered in the equation of hydrologic equilibrium permits a quantitative evaluation that is essential for the successful opera-

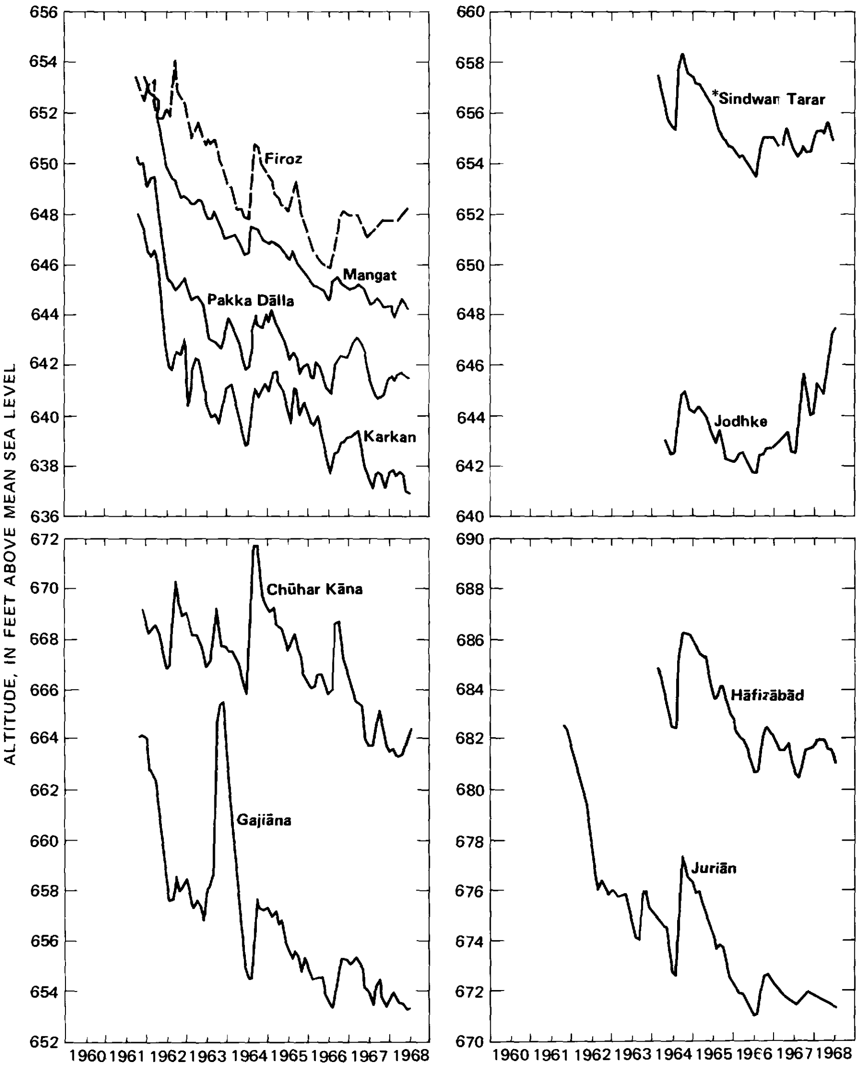


FIGURE 4.—Continued.

tion of any water-resources development program. In its simplest form, the equation is as follows:

$$I = O \pm \Delta S$$

where I is equal to inflow, O is equal to outflow, and ΔS is the net change in storage. If there is a net increase in storage it is added to the right side of the equation; if there is a net decrease, it is subtracted. The equation is suitable for the analysis of the total water budget, that is, for determining the source and disposition of all surface and ground water, or it may be used separately to analyze either a ground-water or surface-water budget.

The annual ground-water budget which follows is an attempt to estimate ground-water recharge in SCARP–1 by utilizing the components of ground-water inflow, outflow, and change in storage during the period of operation of the project.

In applying the equation to a ground-water budget analysis, *I* is equal to ground-water inflow plus direct infiltration of canal leakage, precipitation, and recycled irrigation water; *O* is equal to ground-water outflow, net pumpage, and ground-water discharge through drains; and ΔS is equal to the change in storage in the ground-water reservoir. The annual increments for each of these items and the calculated ground-water recharge are given in table 6.

The total annual recharge to the ground-water reservoir in SCARP–1 and the adjacent areas affected by pumping since full-scale pumping began in 1961 ranged from a maximum of about 3.17 million acre-feet in water year 1964, a year of above-average rainfall, to a minimum of about 1.87 million acre-feet in water year 1965. All the principal items of inflow, outflow, and change in storage can be approximated reasonably accurately from the annual ground-water inventories, except for the combined recharge from the direct infiltration of canal leakage, precipitation, and recycled irrigation water.

The amount of pumpage recycled to the ground-water reservoir, which is included in the estimates, is unknown, but it may be a significant percentage of the total recharge. Although no data are available on infiltration of irrigation water in the Indus Plain, studies in many other areas of the world indicate that from 25 to 40 percent of an irrigation supply diverted to fields returns to the ground-water reservoir by percolation. Inasmuch as irrigation in SCARP–1 is entirely by flood and ditch methods, it seems reasonable to assume that the net pumping draft on the ground-water reservoir may be about 70 percent of the gross pumpage from private and project wells. Pumpage from the Rasul wells is not a part of the recycled water, for it is discharged to canals. Any ground-water recharge from recirculation from the Rasul wells is included with canal losses. If the above assumptions are valid, annual net recharge to the ground-water reservoir in the area of influence would range from a maximum of about 2.48 million acre-feet to a minimum of about 1.16 million acre-feet during the period of record 1962–67 (table 6).

TABLE 6.—*Annual ground-water budget for SCARP–1*

Water year beginning July 1	Area of cone of depression (million acres) (from table 5)	Pumpage: Gross (from table 4) Million acre-feet	Pumpage: Gross (from table 4) Acre-feet per acre [1]	Pumpage: Net [2] Million acre-feet	Pumpage: Net [2] Acre-feet per acre [1]	Estimated ground-water discharge by drains (acre-feet) (from table 8)	Changes in ground-storage (acre-feet) (from table 5)	Ground-water inflow (acre-feet) (from table 2)	Ground-water outflow (acre-feet) (from table 3)	Gross recharge in area of influence: Million acre-feet	Gross recharge in area of influence: Feet	Net recharge in area of influence [2]: Million acre-feet	Net recharge in area of influence [2]: Feet
1960	----	0.37	0.29	0.33	0.26	115,000	−740,000 (1960–61)	35,000	57,000	0.96 (1960–61)	----	0.66 (1960–61)	----
1961	----	1.10	.87	.84	.67	80,000		42,000	48,000				
1962	1.35	3.06	2.45	2.22	1.77	66,000	−610,000	44,000	39,000	2.51	1.86	1.67	1.23
1963	1 85	2.88	2.30	2.10	1.68	46,000	−690,000	46,000	37,000	2.23	1.21	1.45	.79
1964	1.60	2.61	2.09	1.92	1.53	43,000	+520,000	37,000	36,000	3.17	1.98	2.48	1.55
1965	1.86	2.65	2.12	1.93	1.54	36,000	−800,000	45,000	34,000	1.87	1.00	1.16	.62
1966	1.66	1.85	1.48	1.37	1.10	14,000	+370,000	52,000	32,000	2.21	1.33	1.73	1.04
1967	1.55	2.13	1.70	1.56	1.25	15,000	+220,000	52,000	39,000	2.35	1.52	1.78	1.15
Total or average	1.55	16.64	13.30	12.27	9.80	415,000	—1,730,000	353,000	322,000	15.30	----	10.93	----

[1] Based on area of SCARP–1 of 1.25 million acres.
[2] Based on assumption that 30 percent of pumpage from project and private wells is recycled to the ground-water reservoir. Rasul wells discharge to canals.

Because of the arid climate and generally high temperatures, most precipitation evaporates soon after falling and probably never infiltrates more than a few inches of the soil. Significant recharge from deeper percolation of precipitation occurs only when storms of widespread areal extent and sufficient intensity provide enough water to exceed the field capacity of the soil. Thus, the intensity and duration of individual storms is more significant in terms of potential recharge to the ground-water reservoir than the annual precipitation, and recharge to the ground-water reservoir from percolation of precipitation can vary significantly from year to year. On the other hand, recharge from infiltration of canal water may remain fairly constant. If the canals were not in hydraulic continuity with the water table during the period of water-table decline since 1960–61, infiltration from canal leakage would have remained relatively constant. Differences in annual recharge to the ground-water reservoir, then, could be attributed largely to differences in infiltration of precipitation or to differences in the amount of recycled irrigation water recharging the ground-water reservoir. Inasmuch as farming methods and practices did not materially change during this time, it can be assumed that differences in annual recharge are due largely to differences in precipitation. Under these conditions, recharge from canal seepage and from infiltration of canal irrigation water would be equal to, or somewhat less than, the calculated minimum net annual recharge.

If 30 percent of the pumpage recycles to the ground-water reservoir as is speculated, the minimum recharge in the area of influence from canal seepage, irrigation losses, and precipitation during the period of full-scale pumping was about 1.16 million acre-feet in water year 1965. Because precipitation in 1965 was below the long-term average and because storms during the year were of low intensity and duration, it seems reasonable to assume that little or no recharge was derived from precipitation in 1965. Thus, most of the 1.16 million acre-feet of net recharge to the ground-water reservoir in 1965 must have been derived from infiltration of canal water. The net canal inflow in 1965 was about 2.13 million acre-feet, or about 16 percent above the 8 year average (1960–67). Therefore, canal seepage in 1965 probably was somewhat higher than average also.

If the canals were hydraulically connected with the water table during the period of operation, recharge from canal seepage would have increased progressively as the water table declined, until hydraulic continuity was broken. Thereafter, recharge from infiltration of canals would have remained relatively uniform. Since July 1966, the depth to water beneath SCARP–1 has remained relatively stable and, therefore, the annual infiltration from canals during 1966–67 should have remained about the same during these two years, irrespective of whether the canals were in hydraulic continuity with the water table or not. The assumption can be made, then, that recharge from percolation of canal water in water years 1966 and 1967 probably was on the order of 1 million acre-feet annually, also. During the period of the declining water table from 1960–61 to June 1965, the annual ground-water recharge from canal seepage probably would have been less than the 1.16 million acre-feet estimated for 1965 because of the lower hydraulic gradient between the canals and the water table during the initial period of pumping. Thus, the annual recharge to the ground-water reservoir from percolation of canal water probably has not substantially exceeded 1 million acre-feet per year in the area of influence since pumping began.

SURFACE WATER

The Upper Chenāb and Lower Chenāb Canals divert water from the Chenāb River at Marāla and Khānki Headworks southwestward to the project area and adjacent areas in Rechna Doāb. Within the boundary of SCARP–1, the distribution network includes about 253 miles of main canal and branches and about 875 miles of subordinate canals or distributaries (table 1). These canals provide a perennial supply of irrigation water to the central part of the doāb through an extensive distribution system of unlined canals. All these canals are elevated above the general land surface, and distribution is by gravity flow. Substantial seepage losses from the canals and from canal irrigation provide the largest source of recharge to the ground-water reservoir and are the principal contributing factor that led to waterlogging and salinization in the Punjab. There is no natural drainage to SCARP–1 from adjacent areas upgradient. All surface-water inflow to the area is through canals.

Part of the canal water diverted to SCARP–1 leaves the area through canals to adjacent areas southwest. In addition, some surface water is discharged through natural and artificial drains to the Chenāb River on the northeast and the Rāvi River on the southeast. The southwestern boundary of the project area is formed by a natural drainage channel known as Degh Nāla. Because of low relief and low gradient of the land surface throughout most of the Punjab region, however, natural drainage is poorly developed. The rise of the water table that followed the development of an extensive irrigation system emphasized the need for artificial drains for the disposal of storm runoff and excess irrigation water. To carry the excess water from the irrigated areas an extensive network of open-ditch drains totaling about 14,000 miles in length was constructed in Rechna Doāb. Several hundred miles of this drainage network cross SCARP–1. The areal distribution of the principal canals and drains and the discharge measuring sites are illustrated on plate 3.

INFLOW

Practically all surface-water inflow to the area is from the Upper and Lower Chenāb Canals and is evaluated largely on the basis of daily staff-gage readings and discharge rating curves developed during the early years of canal operation. All measuring sites are on canal structures that control bed depth and cross-sectional area, and, therefore, the gage-discharge relationship originally developed probably remains valid.

The principal stations where inflow from the Lower Chenāb Canal to SCARP–1 is estimated are the measuring sites at Sāngar Kalān (Sanghar Rest House) at the bifurcation of the Lower Chenāb Canal and Upper Gugera Branch and the one at the headgates of the Murādiān and Kot Nikka Distributaries. Based on daily staff-gage records and stage-discharge relations, the inflow past these stations during the period of this report has averaged about 6.3 million acre-feet annually, or about 98 percent of the total canal inflow to SCARP–1.

Inflow from the Upper Chenāb Canal is limited to the flow in the Chīchoki (Chīchoki Malliān) Distributary on the east side of the study area. Inflow from this canal during the period under consideration has averaged about 0.11 million acre-feet annually. The total annual canal inflow, which is summarized in table 7, averages about 6.4 million acre-feet annually, and ranged from a maximum of 6.7 million acre-feet in water year 1964 to a minimum of about 6 million acre-feet in water year 1961.

For all practical purposes, there is no natural surface-water inflow to SCARP–1, as stated previously, and, therefore, the total inflow of surface water to SCARP–1 for any particular year may be considered as the annual inflow through canals.

TABLE 7.—*Canal inflow to SCARP–1 (by water years starting July 1)*

Canal or distributary	Discharge, in thousands of acre-feet							
	1960	1961	1962	1963	1964	1965	1966	1967
Lower Chenāb Canal at Sāngar Kalān (Sanghar Rest House)	3,100	2,930	3,170	3,170	3,180	3,020	3,040	2,900
Upper Gugera Branch at Sāngar Kalān	2,980	2,780	2,950	3,020	3,290	3,190	3,350	3,340
Murādiān Distributary	5	14	5	5	1	0.3	1	4
Kot Nikka Distributary	130	120	93	95	98	89	120	100
Chichoki (Chīchoki Malliān) Distributary	110	110	110	110	120	110	110	[1] 110
Hāfizābād Distributary	24	21	19	20	14	11	16	[1] 15
Total (rounded)	6,350	5,980	6,350	6,420	6,700	6,420	6,640	6,470

[1] Estimated value.

OUTFLOW

Surface water is discharged from SCARP–1 by canals, drains, and "nālas" (natural drainage channels). Discharge through canals occurs principally along the southwestern margir of the area through the Jhang and Rakh Branches and a few small distributaries. The principal measuring site on the Jhang Branch is near RD 277,500 (RD is an abbreviation for reduced distance measured from point of diversion in thousands of feet) about 19 miles beyond the west boundary of SCARP–1. Diversions between the measuring site and the boundary of the study area are added to the calculated discharge in the main canal to obtain the total canal outflow through this canal network.

Outflow from the Rakh Branch is calculated from daily staff-gage readings at RD 114,000 at Sāngla (Sangla Hill), about 3 miles east of the boundary of SCARP–1. Diversions into the study area by Sāngla (Minor) and Arūri Distributary are subtracted from the total flow past Sāngla to obtain the total outflow. Discharge from the Lower Gugera Branch is calculated on the basis of daily staff-gage readings and a discharge rating curve at a site at RD 27,000 on the Lower Gugera Branch, about 5 miles east of the boundary of SCARP–1. Downstream from this main gaging site, three small distributaries including Butiwāla, Kheowāla, and Jasuāna divert water from the Lower Gugera Branch into SCARP–1. The annual discharge of each of these three distributaries, measured at the point of diversion, is subtracted from the annual flow past the Lower Gugera gaging station. Within a distance of 3 miles upstream from the Lower Gugera gaging station, two distributaries, the Āwāgat and the Pauliāni, divert water from the Lower Gugera Branch. Part of the flow in these two distributaries discharges into the adjacent area beyond SCARP–1. The flow past the project boundary in these distributaries is included in the total outflow from this canal system shown in table 8.

A summary of the canal discharge from SCARP–1 shown in the table indicates that the total outflow of surface water through canals during the period of this study ranged from a maximum of about 5 million acre-feet in water year 1963 to a minimum of about 4.3 million acre-feet in water year 1965. The average annual canal discharge to adjacent areas downgradient during the 7 years of project operation is about 4.6 million acre-feet.

Two escapes, the Hinduāna Escape on the Jhang Branch and the Buchiāna Escape on the Upper Gugera Branch, occasionally

TABLE 8.—*Discharge of canals, drains, and escapes in SCARP–1 (by water years starting July 1)*

CANALS

	Discharge in thousands of acre-feet							
	1960	1961	1962	1963	1964	1965	1966	1967
Jhang Branch	1,670	1,710	1,850	1,980	1,960	1,560	1,440	1,500
Rakh Branch	560	560	600	610	610	540	560	620
Lower Gugera Branch	1,130	1,100	1,240	1,340	1,150	1,200	1,240	1,250
Burāla Branch	1,070	1,080	1,030	1,120	1,150	990	1,080	1,170
Subtotal (1)	4,430	4,450	4,720	5,050	4,870	4,290	4,320	4,540

DRAINS

	Estimated total discharge, in thousands of acre-feet (top number); estimated base flow, in thousands of acre-feet (bottom number)							
	1960	1961	1962	1963	1964	1965	1966	1967
Jarānwāla Drain	50	50	45	40	100	50	13	17
	30	30	25	20	17	[2]17	0	0
Degh Nāla	75	50	35	20	75	25	29	22
	55	20	15	5	10	5	0	0
Chiniot (Drain)	35	35	35	30	75	25	17	23
	20	20	18	15	10	10	10	11
Ahmadpur Kot Nikka Drain	25	25	23	20	50	15	15	15
	10	10	8	6	6	4	4	4
Approximate total flow (2)	185	160	138	110	300	115	74	77
Approximate base flow (3)	115	80	66	46	43	36	14	15

ESCAPES

	Estimated discharge, in thousands of acre-feet							
	1960	1961	1962	1963	1964	1965	1966	1967
Hinduāna Escape	5	5	5	5	5	5	5	3
Buchiāna Escape	5	5	5	5	5	4	10	6
Subtotal (4)	10	10	10	10	10	9	15	9

TOTAL DISCHARGE

	1960	1961	1962	1963	1964	1965	1966	1967
Items (1) + (2) + (4) (rounded)	4,630	4,620	4,870	5,170	5,180	4,410	4,410	4,630

[1] Discharge through drains and escapes estimated largely on basis of incomplete data.
[2] Jarānwāla Drain went dry for first time on May 10, 1965.

divert canal flows from SCARP–1. The escapes are utilized to divert water from the main canals to the rivers to minimize damage from flooding in the event of a breach in the canal embankment. Occasionally, they are used for carrying off surplus canal supplies when the supply exceeds the demand. Under normal operating conditions, the escapes may be used only a few days each year. Outflow through the escapes, which is generally less than a few thousand acre-feet per year, constitutes an insignificant proportion of the total outflow of surface water. Annual discharge calculated on the basis of staff-gage readings and design cross-sectional area at the point of diversion are given in table 8 for the period covered by this report.

Precipitation runoff and effluent ground-water seepage are discharged through four principal drains and their tributary network along the west, southwest, south, and southeast sides of the project areas. These drains include the Ahmadpur Kot Nikka Drain, Chiniot (Drain) and Jarānwāla (Drain), and the Degh Nāla.

The Ahmadpur Kot Nikka Drain, originating in the Hāfizābād Scheme, flows southwestward draining most of the northern tier of schemes of SCARP–1. Surface-water runoff and effluent ground water carried by this drain is discharged into Chenāb River. The Chiniot (Drain) originates at the northeastern edge of SCARP–1 and drains part of Khāngāh Dogrān, Sāngla, Berānwāla, and Harse Sheikh Schemes. The Chiniot (Drain) leaves the project area near the village of the same name in the southwest corner of SCARP–1. The Jarānwāla Drain also originates at the northeastern edge of SCARP–1 and was designed to drain Chūhar Kāna, Shāh Kot, and Jarānwāla Schemes, and part of the Khāngāh Dogrān and Sāngla Schemes. The Jarānwāla (Drain) discharges in Degh Nāla and ultimately to the Rāvi River. Degh Nāla and several small tributary drainage ditches drain the southeastern tier of schemes including most of Chīchoki (Chīchoki Malliān), Shādmān, and Zafarwāl Schemes.

Records of drain discharge during the early years of project operation are incomplete, and, therefore, only rough approximations of the total flow during this period can be made. However, some data are available to construct hydrographs from which a rough estimate of the base flow in the principal drains can be made prior to the beginning of tubewell pumping. Hydrographs of the existing data for Degh Nāla during the period 1958–60 indicate that the base flow in the years before ground-water reclamation was on the order of 75 cfs, or about 55,000 acre-feet per year. The total flow in Degh Nāla during this period is unknown because of incomplete data and can only be roughly approximated on the basis of precipitation runoff in other years having approximately equivalent precipitation.

For example, flow in Degh Nāla in 1967–68, which was derived almost entirely from precipitation runoff, totaled about 20,000 acre-feet. Precipitation in 1960 was only slightly less than in 1968, and thus, it seems reasonable to assume that runoff from precipitation in 1960 may have been on the same order of magnitude as in 1968, or about 20,000 acre-feet. In this event the total flow in Degh Nāla in 1960 may have been on the order of 75,000 acre-feet.

In a similar manner, rough approximations of the flow in the other drains have been made on the basis of the existing data for the prepumping period. Estimates of the discharge by drains are given in table 8.

Gaging stations equipped with continuous water-stage recorders were installed on each of the four principal drains in November 1966, and since that time a continuous record of drain discharge from SCARP–1 has been maintained. Hydrographs of the discharge at the measuring sites indicate that Degh Nāla and the Jarānwāla (Main Drain) in the southeastern half of SCARP–1 are dry except for periods following rainstorms. By May 1965, the water table in most areas served by these drains had been depressed more than 10 feet below land surface and, in most places, was below the bed of the drain. Since that time, flow in these two drains has become intermittent, the drain carrying flow only during periods of heavy precipitation.

Perennial flow in the Chiniot (Drain) and the Ahmadpur Kot Nikka Drain in the northwestern part of SCARP–1 is in part sustained by effluent ground-water seepage. When the hydrographs of these two drains are separated into surface- and ground-water components, the base flow, or ground-water component, in these drains since November 1966 has averaged about 3,600 acre-feet per year and 11,000 acre-feet per year, respectively. The reduction in the combined base flow in these two drains (from about 30,000 acre-feet in water year 1960 to about 15,000 acre-feet in water year 1967), indicated by the estimates given in table 8, has resulted from a lowering of the water table in the areas serviced by these drains.

Estimates of the total annual surface-water discharge from

SCARP–1 by drains and rough approximations of the component part derived from ground-water seepage are shown in table 8. The estimates of drain discharge for the period before 1966 are only approximations, subject to considerable error. However, because discharge through the drains is only a small percentage of the total quantity of surface-water outflow from the project area, a large error in the estimated drain discharge will not significantly affect the solution of the hydrologic budget.

DEPLETION OF STORAGE

A large amount of surface water is in channel storage in canals that divert irrigation water to SCARP–1. However, on the average, the stage and flow of the canals is the same at the beginning and end of each water year. The pattern of operation of the canal network remains practically the same from one year to the next. Accordingly, for practical purposes, the net change in storage in the canals from the beginning to the end of one water year, or over the longer period of 7 years since full-scale pumping began, is zero.

Prior to the beginning of ground-water reclamation in 1960–61, the water table was above land surface in approximately 10,000 acres of SCARP–1 (West Pakistan Water and Power Development Authority, 1959). The inundated areas were largely in the northeastern part of the project in areas adjacent to the Upper Gugera Branch and Lower Chenāb Canals. Ponding occurred in about 1,800 acres in the Khāngāh Dogrān Scheme, 1,700 acres in Harse Sheikh, and 1,600 acres each in the Shāh Kot, Sāngla, and Zafarwāl Schemes. The depth of the water in these inundated areas usually was limited to a foot or less, and most places averaged only a few inches. The total quantity of water in these ponds probably never exceeded 5,000 acre-feet, and, in terms of volume and its affect on the hydrologic budget, are generally insignificant.

In addition, a small amount of water is stored in the drains. The amount of channel storage throughout the year varies widely, depending on the stage and the discharge. Before pumping began, the average stage and flow of the drains at the beginning and end of each year remained about the same. Therefore, for practical purposes, it can be assumed that there was no net change in channel storage from the beginning to the end of a year in the period preceding reclamation pumping. As pumping began to cause a decline of the water table, however, there was an annual decrease in the flow and a corresponding decrease in channel storage from one year to the next. By May 1965, the water table had been lowered in all areas served by the drains. In the southeastern half of the areas, the water table had been lowered below the bed of the Jarānwāla Drain and Degh Nāla. As a result, there was an annual decrease in channel storage during the 3-year period from 1961–62 to 1965. The change in storage resulting from decreased stage and flow in the drains during this period was about 5,000 acre-feet. The total depletion in storage resulting from the desiccation of the flooded areas and reduction of channel storage in the drains during the first 7 years of project operation has been on the order of 10,000 acre-feet. This depletion has been distributed over water years 1961–64 during initial phases of development when the decline of the water table was most rapid; however, since 1962, practically all surface-water storage has been confined to channel storage in the canals.

PRECIPITATION

The average annual precipitation in the area computed from the isohyetal map of Rechna Doāb for the period 1916–57 (Sheikh and Hussain, 1963, fig. 2) is about 17 inches or about 1.7 million acre-feet. Precipitation on the area is unevenly distributed, progressively increasing from a minimum of about 14 inches in the southwest to a maximum of about 24 inches in the northeast. Most of the annual precipitation normally occurs during a 3-month period from July through September. The least precipitation normally occurs in May, October, and November, and during these months rainfall averages less than half an inch per month. The average monthly precipitation at three stations in and adjacent to SCARP–1 is shown in figure 5. Precipitation during the summer occurs largely during the monsoon period beginning about the middle of July and extending to about the middle of September. However, because the area lies near the western extremity of the Indian Ocean monsoon belt, the amount of precipitation during the monsoon may vary considerably from year to year depending on the prevailing meteorological conditions. During the remainder of the year, precipitation is sporadic and commonly occurs as thunderstorms of short duration and limited areal extent. Consequently, the distribution and amount of precipitation may vary considerably within the area during any one year, or from one year to the next, and ground-water recharge and runoff will vary accordingly.

The average monthly precipitation in SCARP–1 is about an inch

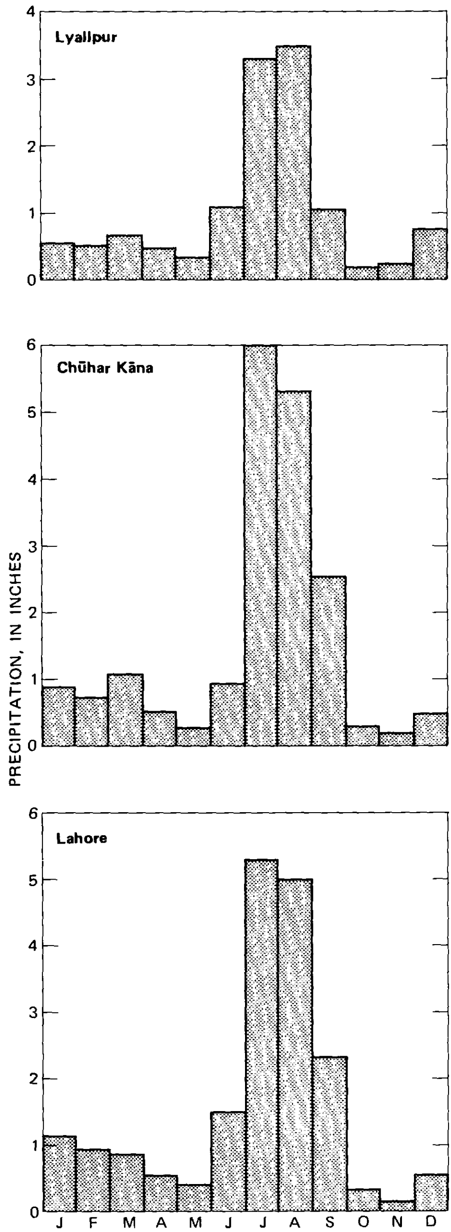


FIGURE 5.—Average monthly precipitation at three stations in and adjacent to SCARP-1.

or less, except during July, August, and September, when the average increases to 5 or 6 inches. Most recharge to the ground-water reservoir probably occurs during July, August, and September, following periods of high rainfall. During the rest of the year, precipitation is usually insufficient to contribute any significant recharge to the ground-water reservoir.

Estimated average annual precipitation, in inches, and the equivalent amount of water in acre-feet, given in the following table, are computed from isohyetal maps prepared from annual precipitation data from 14 stations in and adjacent to SCARP–1, for the period July 1960–June 1968:

Approximate precipitation in SCARP–1
(by water years starting July 1)

Year	*Inches*	*Millions of acre-feet*
1960	14.6	1.46
1961	14.8	1.48
1962	14.0	1.40
1963	12.8	1.28
1964	25.4	2.54
1965	15.5	1.55
1966	21.0	2.10
1967	18.4	1.84

During this 8-year period, the average annual precipitation ranged from a low of about 12.8 inches in water year 1963 to a high of about 25.4 inches in water year 1964. The average annual precipitation on SCARP–1 during this period was about 17 inches, an amount equal to the average precipitation during the long-term period of record. Thus, it would appear that precipitation during the period of project operation probably has had no long-term significance on the cumulative effects of lowering of the water table in SCARP–1 to July 1958.

The slope of the graph in figure 6 shows cumulative departure from average annual precipitation. A positive or upward slope to the right indicates above-average precipitation; a negative or downward slope indicates below-average precipitation. A cumulative excess of precipitation occurred at all stations in the area during water years 1958 and 1959, ranging from a minimum of about 10 inches at Lyallpur to about 24 inches at Chūhar Kāna. Except in 1964, when an unusually large amount of rainfall occurred, precipitation was generally below average in the period 1960–68. Had precipitation since 1965 been normal, the average net decline of the water table probably would have been somewhat less than the 4.7 feet observed in June 1968.

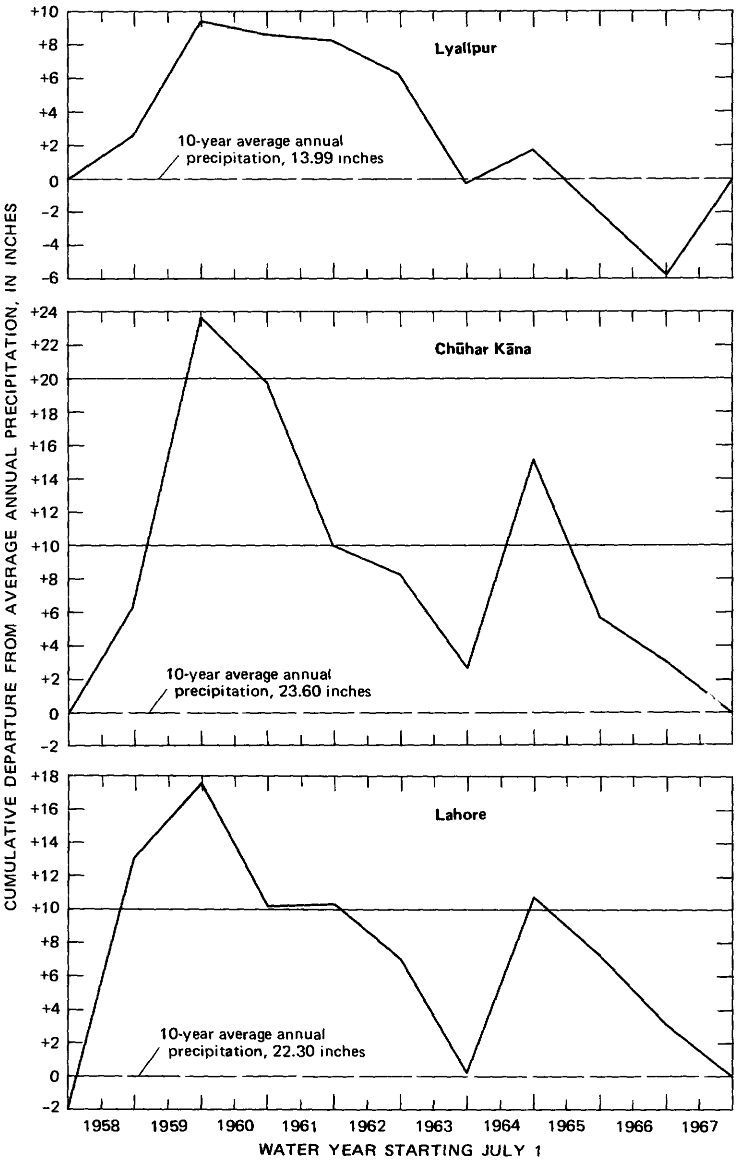


FIGURE 6.—Cumulative departure from average annual precipitation at three stations in and adjacent to SCARP-1.

HYDROLOGIC BUDGET ANALYSIS

Brief descriptions of the qualitative and quantitative relations between the major components of the hydrologic system were given in the preceding sections of the report. In this section a quantitative analysis, or a water-budget analysis, is made to show the relative magnitude of the various components of ground water and surface water, respectively, and to show their relation to the ground-water reservoir. Solution of the hydrologic equation, utilizing data available for SCARP–1, provides a quantitative figure for the evapotranspiration losses or the consumptive use of water in the area.

The following water-budget analyses are based on the theory of the hydrologic cycle and on the concept of long-term dynamic equilibrium defined by the equation of hydrologic equilibrium discussed in an earlier section. To obtain a total water budget for SCARP–1, the equation must be expanded to include all items of water supply, disposal, and changes in storage for both ground and surface water. In expanded form, I is equal to precipitation, ground-water inflow, and surface-water inflow; O is equal to evapotranspiration (or consumptive use), ground-water outflow, and surface-water outflow; and ΔS is equal to change in storage in the ground-water reservoir, surface-water reservoirs, and channel storage.

Each of the principal items except evapotranspiration have been obtained from the annual hydrologic inventory or have been calculated from basic data. Measurements of evapotranspiration generally are difficult to obtain directly, except for small plots, and evapotranspiration is almost always evaluated by empirical methods. For this budget, evapotranspiration is the only major item of the equation that has not been measured, and, therefore, it can be calculated in the solution of the equation by difference. However, because all errors in measurements of each of the separate components of the equation are incorporated into the computed value of evapotranspiration, the value must be considered as an approximation. By substituting the proper value for each respective parameter given in the previous tables into the hydrologic equation, the value for annual evapotranspiration is computed as follows:

Precipitation + ground-water inflow + surface-water inflow + decrease in ground-water and surface-water storage = evapotranspiration + ground-water outflow + surface-water outflow.

For example, for water year 1965, the equation expressed in quantitative terms of acre-feet becomes

$$1.55 \times 10^6 + 0.045 \times 10^6 + 6.42 \times 10^6 + 0.80 \times 10^6 = \text{ET} + 0.034 \times 10^6 + 4.41 \times 10^6$$

$$\text{ET} = 8.815 \times 10^6 - 4.44 \times 10^6$$

$$\text{ET} = 4.37 \times 10^6$$

Thus, during water year 1965, the total annual evapotranspiration from SCARP–1 computed by this method is on the order of 4.37 million acre-feet (table 9).

A comparative estimate for evapotranspiration, computed on the basis of consumptive use of water by crops and corresponding acreage during 1965, indicates that about 1.75 million acre-feet of water was transpired from 550,000 acres of cropped land during the Karif or wet summer season from April to September and about 0.95 million acre-feet was consumptively used by crops on 597,000 acres during the Rabi or dry season from October 1965 to March 1966. Uncropped area during these periods was about 700,000 and 652,000 acres, respectively. It can be reasonably assumed that practically all precipitation on the fallow or uncultivated land during the Rabi season evaporates within a short period, and perhaps as much as 75 percent of the rain that falls evaporates during Kharif period. Evaporative losses for 1965 are estimated to have been about 0.4 and 0.75 foot, respectively. The total evaporation of precipitation on the uncultivated land was about 785,000 acre-feet. In addition to evaporation of precipitation from these areas, there was an additional amount of about 150,000 acre-feet of evaporation directly from the water table, if it is assumed that the average depth of the water table is about 20 feet and that the average evaporation loss is about 0.2 centimeters per day, or 2.9 inches per year (Garner and Fireman, 1958).

The last item to be considered in determining the total evapotranspiration losses is evaporation from free-water surfaces, which, in 1965, was almost entirely from canals. Only a crude approximation of this item can be made at this time because of the limited data on the average evaporation from moving bodies of water. However, inasmuch as evaporation from the canals is a small percentage of the total evapotranspiration losses, a large percentage of error in this item will have little effect on the total value. Evaporation from 9,000 acres of free-water surface of the canals in SCARP–1 is estimated to be about 45,000 acre-feet per year assuming that the average annual lake evaporation of about 60 inches (Harza Engineering Co. Internat., written commun., 1965) is applicable to canals.

Summing all of the above items gives a total discharge by evapotranspiration from SCARP–1 in 1965 of about 3.7 million acre-feet. This value is within 13 percent of the evapotranspiration value computed by the solution of the hydrologic equation.

TABLE 9.—*Hydrologic budget for SCARP-1*

[All terms in acre-feet]

Water year starting July 1	Inflow			Outflow				Change in storage		Calculated evapotranspiration ($\times 10^6$)
	Precipitation ($\times 10^6$)	Ground water	Surface (canals) water ($\times 10^6$)	Ground water	Surface water			Ground water	Surface water	
					Canals ($\times 10^6$)	Drains [1]	Escapes			
1960	1.46	35,000	6.35	57,000	4.43	185,000	10,000	−740,000	0	6.83
1961	1.48	42,000	5.98	48,000	4.45	160,000	10,000		−4,000	
1962	1.40	44,000	6.35	39,000	4.72	138,000	10,000	−610,000	−3,000	3.50
1963	1.28	46,000	6.42	37,000	5.05	110,000	10,000	−690,000	−3,000	3.23
1964	2.54	37,000	6.70	36,000	4.87	300,000	10,000	+520,000	0	3.54
1965	1.55	45,000	6.42	34,000	4.29	115,000	9,000	−800,000	0	4.37
1966	2.10	52,000	6.64	32,000	4.32	74,000	15,000	+370,000	0	3.98
1967	1.84	52,000	6.47	39,000	4.54	77,000	9,000	+220,000	0	3.47

[1] Drain discharge includes both effluent ground-water seepage and precipitation runoff.

The difference of about 670,000 acre-feet between the two values is due to errors in the estimates. The most likely errors are in the larger items, principally canal inflow and outflow and precipitation in the budget analysis and the estimated evaporation of precipitation and consumptive use of crops in the more direct methods.

GEOCHEMISTRY OF THE HYDROLOGIC SYSTEM

The large accumulation of water-quality data gathered over the years from test and reclamation wells in the upper Indus Plain indicates a wide variety of water types and a complex areal and vertical distribution of ground water beneath SCARP–1. The data also indicate that much of the ground water is moderately to highly mineralized; therefore, unless proper irrigation-management practices are developed and exercised, soil and crop deterioration will result.

Because the success of SCARP–1 and future reclamation projects is dependent largely on ground water to supplement the existing irrigation supply from canals, it is essential that the agencies responsible for the operation of the project develop procedures that will insure the optimum use of the available ground-water supply. Inasmuch as management practices necessarily will vary from one area to another, depending on the chemical quality of the ground water, soil types, and other variable factors, selecting the most beneficial option will require knowledge of the distribution of fresh and saline ground water, the type and concentration of dissolved minerals, and the magnitude and rate of change in chemical quality of the ground water.

In this section of the report, a brief description is given of the areal distribution of ground water of different chemical composition in the upper 300–400 feet of the saturated sediments in SCARP–1 and of some of the changes that have occurred in the chemical character of the water during the first 7 years of reclamation pumping.

COLLECTION AND ANALYSIS OF DATA

The data on the chemical character of the ground water in SCARP–1 are obtained from the analysis of water samples from wells penetrating numerous water-bearing strata within the upper 300–400 feet of the ground-water reservoir. Variation in lithology imparts a wide range of hydraulic properties and different chemical characteristics to ground water, and, consequently, the project tubewells, screened opposite the most permeable sand lenses, may pump water of different chemical quality from different horizons. The ground-water discharge at each well is a mixture from the several water-bearing zones and represents the average water quality that has been imposed by local geological conditions, the rate of pumping, and the hydraulic characteristics of the wells. The mixed samples collected from many wells distributed areally over an aquifer do not necessarily indicate the upper or lower limits of dissolved-solids concentration, but, in a general way, they do show the distribution pattern of the water quality in the upper few hundred feet of the ground-water reservoir affected by pumping. Isogram maps for SCARP–1 in 1960–62 and in 1967, included in this report, are drawn on the basis of composite water samples from wells of different depth and construction, and they represent average water-quality conditions caused by mixing water from multiple water-bearing zones.

Water samples for analysis are collected after 4 hours of continuous pumping from a tubewell in an effort to obtain a composite sample of approximately uniform chemical composition. The unstable constituents or properties, including pH, alkalinity, and conductivity are analyzed at the collection site at some wells, as are the dissolved gases, such as oxygen and carbon dioxide. The concentration of the principal cations and anions in solution is determined in the Quality of Water Laboratory of WASID, WAPDA, along with a determination of specific conductance and the total dissolved-solids content. A small percentage of water samples collected for laboratory analysis are also analyzed for common minor chemical constituents, such as nitrate, fluoride, silica, iron, and boron. The sodium-adsorption-ratio (SAR) is computed for all water samples collected.

The plots in plate 5, which show the magnitude and areal distribution of the total dissolved solids (TDS) and the sodium-adsorption-ratio (SAR) in 1960–62 and 1967, are based on chemical analysis of water samples collected from about 1,300 tubewells in 1960–62 at about the time pumping started, and from about 1,800 tubewells sampled in 1967 after about 7 years of pumping. The maps graphically illustrate the geographic distribution and magnitude of these two water-quality characteristics during the two periods of observation, and they form the basis for determining changes in water quality and for the interpretations of how these changes will affect future utilization. Discussion is confined to these chemical characteristics because of their significance as an index to the suitability of water for irrigation.

DISTRIBUTION OF FRESH AND SALINE GROUND WATER

The areal and vertical distribution of fresh and saline ground water in SCARP–1 principally is the result of circulation in the reservoir. Flow of ground water from areas of recharge to areas of discharge is three-dimensional along curvilinear flow paths controlled by vertical differences in hydraulic head. Variations in lithologic facies, both horizontally and vertically, result in differences in the hydrologic properties of the reservoir that locally affect the hydraulic continuity of the ground-water reservoir, the hydraulic head, the direction and rate of ground-water flow, and the chemical quality of the ground water. The type and amount of chemical constituents dissolved by ground water moving through this environment is in part dependent on the composition of the material through which it moves, the residence time the water is in the aquifer, the length of the flow path, water temperature, the chemical composition of the recharge, and other factors. In addition, the distribution of fresh and saline ground water is further complicated by mixing of unlike waters and chemical reactions such as base exchange and adsorption of dissolved ions.

Prior to the construction of canals in the late 1800's and early 1900's, ground water moved downward and away from the Rāvi and Chenāb Rivers and from areas of high precipitation in the upper Rechna Doāb to areas of low precipitation and potentially high evaporation in the southwestern part of the doāb. Within Rechna Doāb dynamic equilibrium was maintained through a balance between ground-water recharge and evapotranspiration.

In areas of recharge where the principal component of movement of ground water is downward, active circulation is effective to a depth of 1,000 feet or more. In addition to the vertical component of flow away from the recharge areas created by the difference in hydraulic head between the area of recharge and the area of discharge.

As ground water moved toward the center of the doāb, depletion of flow through evaporation caused a flattening of the hydraulic gradient and a reduction of circulation. Accompanying the reduction in circulation, there was a corresponding increase in mineralization of the ground water resulting from progressive concentration through evaporation and from prolonged opportunity for contact with the soluble constituents of the rocks.

Compilation of water-quality data for the preirrigation period by Greeman, Swarzenski, and Bennett (1967, pl. 9) shows that highly mineralized ground water occurs along the longitudinal axis of Rechna Doāb, with transitions to fresher water toward the rivers.

Although there are numerous local anomalies in the chemical character of the water, both areally and at depth, the distribution of fresh water in Rechna Doāb prior to canal irrigation can be generalized as two wedges, 1,000 feet or more in thickness beneath the margins of the doāb, that thinned in the direction of flow towards the center of the doāb. Studies by Swarzenski (1968) pointed out that the boundaries between fresh and saline water are not sharp; rather, mineralization gradually increases with depth and distance from sources of recharge. Neither the fresh nor saline ground water can be defined as separate and distinct bodies of water in terms of stratigraphic position, sea level datum, or by any particular lithology. Chemical profiles showing the vertical distribution of different concentrations of dissolved solids in the ground-water reservoir prior to operation of the project are shown on plate 4.

The progressive deterioration in water quality with depth and distance from areas of recharge appears to be related principally to the direction of flow and rate of circulation in the ground-water reservoir. Below the depth of active circulation, mineralization of ground water is high.

After the construction of the perennial canals and importation of river water to the central parts of the doāb, recharge to the ground-water reservoir from canal leakage caused the water table to rise, and this rise eventually changed the pattern of circulation in the reservoir. Under natural conditions, the lateral movement of ground water was generally towards the center of the doāb. After about 1930, the water table in the center of the doāb had risen above the adjacent rivers, and the change in the hydraulic gradient changed the direction of ground-water flow.

Recharge from canal leakage and infiltration of irrigation water in the central part of the doābs has superficially modified the areal and vertical distribution of fresh and saline ground-water bodies that existed in the preirrigation period. Canal leakage locally diluted brackish ground water and increased circulation, creating lenses or ridges of fresh water beneath the canals in an otherwise saline environment. Inasmuch as leakage usually is a function of the size of canal, the largest and most extensive developments of fresh-water lenses are in the vicinity of the larger canals. In some areas, circulation of ground water beneath the canals has been effective in depressing or flushing the more mineralized indigenous ground water to a depth of 200–300 feet; however, in some areas canals have had little apparent effect on the chemical character of the underlying ground water.

Other modifications in the distribution pattern of fresh and saline water are due to the disproportionately large evaporation losses brought about by irrigation practices and waterlogging problems. In areas where the water table has risen to or near the land surface, evaporation has increased mineralization of the ground water at shallow depths, and in these areas it is not uncommon to find water of relatively poor quality overlying water of better quality.

With the completion of the ground-water reclamation project in SCARP–1 and with the beginning of large-scale withdrawals of ground water in 1961, additional changes in the flow net and the chemical composition of ground water have been occurring. Pumping has increased ground-water circulation within the upper few hundred feet of the ground-water reservoir and has locally induced inflow of brackish water from depth or from adjacent lenses of saline water toward pumping centers. The increased circulation, particularly in the vicinity of canals, has gradually decreased the mineralization of the ground water. On a project-wide basis, however, circulation caused by pumping has resulted in mixing and blending water of different chemical composition into a more homogeneous ground-water body. Although hydrologic equilibrium may have been reestablished between recharge, discharge, and ground water in storage, it is doubtful that chemical equilibrium of the ground water will ever be attained.

Inasmuch as each doāb functions to a large degree as a separate hydrologic unit with little or no external drainage, the consumptive use of water by continued irrigation will result in progressive mineralization and deterioration in the quality of ground water. On the basis that about 1.67 million acre-feet net canal diversions have an average total dissolved-solids content of about 150 mg/l (milligrams per litre) (table 10), the input of salt to SCARP–1 is calculated to be about 334,000 tons annually. The principal salt in solution in the canal water is calcium-magnesium bicarbonate. Although part of the ions may precipitate out of solution, some of the ions will remain in solution and will eventually be added to the ground-water reservoir by recirculation of

TABLE 10.—*Water quality of the Chenāb River at Alexandra Bridge (pl. 4 and other maps)*

Date sampled	Constituents, in equivalents per million (epm)							Total dissolved solids (mg/l)
	Ca	Mg	Na	CO_3	HCO_3	Cl	SO_4	
11–11–66	1.66	0.28	0.52	0	1.52	0.20	0.74	150
11–25–66	1.71	.60	.42	0	1.74	.20	.79	170
1– 7–67	1.40	.88	.25	0	1.82	.19	.52	150
2–12–67	1.88	.51	.01	0	2.08	.19	.73	190
3–17–67	1.45	.42	.53	0	1.57	.19	.66	150
4–11–67	1.83	.30	.43	0	1.95	.14	.47	160
5– 4–67	1.59	.37	.20	0	1.56	.19	.32	128
6–17–67	1.28	.38	.25	0	1.34	.10	.51	112
7–12–67	1.13	.34	.16	0	1.26	.10	.27	100
8–12–67	1.18	.39	.15	0	1.35	.10	.20	98
9–14–67	1.37	.53	.28	0	1.57	.09	.60	126
10– 7–67	2.00	.90	.32	0	2.50	.25	.50	172
Average	1.54	.49	.29	0	1.69	.15	.53	142

irrigation water. Additional mineralization will also result from the solution of minerals in the soil column above the water table and from increased use of soil amendments and fertilizer. Consequently, it is to be expected that changes in ground-water equality will continue to change both areally and at depth with the passage of time.

CHEMICAL CHARACTERISTICS OF GROUND WATER

TOTAL DISSOLVED SOLIDS AND SPECIFIC ELECTRICAL CONDUCTIVITY

The total concentration of minerals dissolved in a sample of water, or the total dissolved-solids content, may be determined approximately in the laboratory by weighing the residue remaining after evaporation of a known volume of water, or approximated in the field by measuring the specific electrical conductance of the water.

Specific electrical conductivity, or electrical conductance, is a measure of ease with which an electric current passes through water, it is directly related to the total concentration of dissolved minerals in solution and to temperature. Specific electrical conductance increases as the concentration of dissolved minerals and temperature increase, and, therefore, when the conductance is referred to a constant temperature, it is an approximate measure of the dissolved-solids content. Conductivity is the reciprocal of resistance; the units in which it is reported, mhos, are the reciprocal of ohms, and measurements usually are expressed in mhos or micromhos per centimeter at 25°C.

Because certain substances contained in water, such as silica, may not ionize, they do not contribute to the conductance of the solution; for this reason, the relationship between the total dissolved-solids content and electrical conductance is not exact. Figure 7 shows the relationship between specific electrical conductance and dissolved solids for ground water from about 100 wells randomly selected in SCARP–1 during 1966. The relationship does not deviate greatly from linearity throughout the range of concentration of dissolved solids encountered in ground water in SCARP–1. The slope of the curve in figure 14 indicates that the total dissolved-solids content in ground water in SCARP–1 can be approximated by multiplying the specific conductance measured in micromhos per centimeter at 25°C (Celsius) by a factor of 0.67.

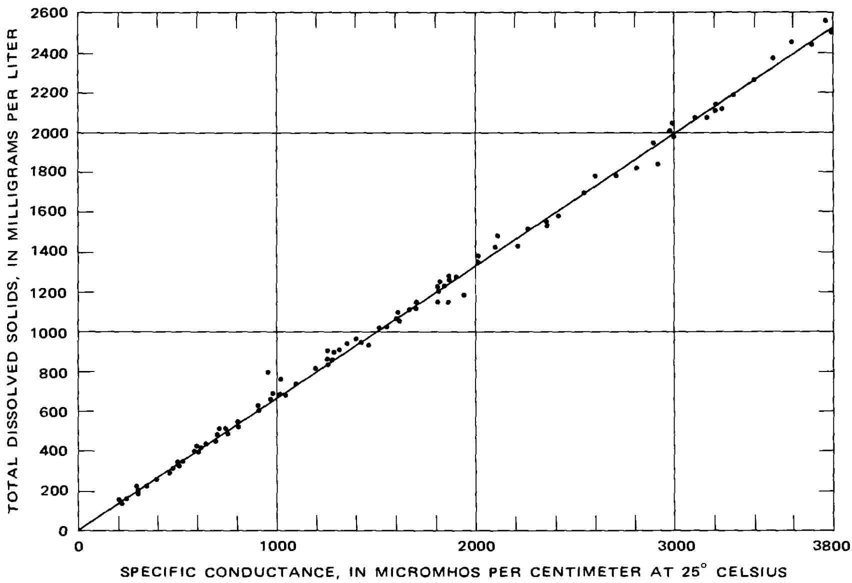


FIGURE 7.—Relation between total dissolved solids and specific electrical conductance of ground water in SCARP–1, 1966.

The principal chemical constituents in solution in ground water in the project area include silica, iron, calcium, magnesium, sodium and potassium, carbonate, bicarbonate, chloride, sulfate, and nitrate.

Plate 5 shows the concentration of dissolved solids in ground water in SCARP–1 in central Rechna Doāb in 1960–62 and 1967, respectively. The contours are based on laboratory determinations of the average total dissolved solids in ground water pumped from project wells and show the approximate areal distribution of dissolved solids contained in the upper part of the ground-water reservoir tapped by the wells.

The map for 1960–62 shows the areal distribution of dissolved solids in ground water in SCARP–1 prior to, or during, the initial phases of reclamation pumping. It is based on data obtained during tubewell development or during the first round of sampling following the beginning of pumping. Because pumping in the various schemes began at different times, the water-quality data used in the preparation of the map were collected over a span of about 26 months including most of 1960–61 and the first 2 months in 1962. Although the initial round of sampling spans a considerable period of time, the distribution of dissolved solids indicated by the data probably is an accurate representation of water quality in SCARP–1 prior to the development of ground water.

The areal and vertical distribution of the less mineralized water in the ground-water reservoir supports the theory that mineralization of the ground water is principally an expression of the regional pattern of circulation. Ground-water underflow from areas of recharge in the upper reaches of Rechna Doāb northeast of SCARP–1 moves generally southwestward toward areas of discharge in the lower part of the doāb. Although the complexity of the contours indicates numerous local anomalies, the general trend of increase in dissolved solids is toward the southwest. Ground water in the northeastern part of the project area and in the areas adjacent to the Chenāb and Rāvi Rivers generally contains less than 500 mg/l of dissolved solids, whereas along the southwestern margin of SCARP–1, the dissolved-solids content generally is 2,000 mg/l or more.

Superimposed on the regional pattern of circulation in the ground-water reservoir are local anomalies in the flow pattern resulting from percolation of canal seepage. Seepage moving downward and away from the canal dilutes or replaces the indigenous ground water in the vicinity of canals and creates narrow zones of water, a mile or more in width and several hundred feet deep, whose total dissolved-solid content is less than that of the native ground water. Narrow zones of relatively good-quality water having low total dissolved solids occur along the Lower Chenāb Canal and the Jhang, Rakh, Upper Gugera, and Burāla

Branches. At increasing distances from the canals, the total dissolved solids increase.

Unusually high concentrations of dissolved solids occur locally in the southeastern part of the area, principally in Jarānwāla, Shāh Kot, and Zafarwāl Schemes, where areas of a few square miles in extent are underlain by ground water containing dissolved solids in excess of 2,500 mg/l. Although the reasons for these relatively high concentrations are unknown, it seems highly probable that their existence is due to the impedance of ground-water circulation by the underlying bedrock of the Shāhpur-Delhi buried ridge that extends eastward from Chiniot to Sāngla and then southeast to Shāh Kot and Māngtānwāla.

The areal distribution of the total dissolved solids shown on plate 5 and tabulated in tables 11 and 12 indicates that during the period of reclamation pumping from 1960–62 to 1967, numerous areas have been affected by a change in the dissolved solids in ground water.

In 1960–62 wells were pumping water having a total dissolved-solids content of less than 1,500 mg/l in an area covering about 1,071,300 acres, or about 86 percent of the area. In the remaining area of about 171,000 acres the total dissolved solids in ground water pumped from project wells exceeded 1,500 mg/l.

By 1967, the area producing ground water with a dissolved-solids content of less than 1,500 mg/l increased slightly to about 1,089,500 acres, or about 18,200 acres. There was a corresponding decrease in the area from which ground water containing more than 1,500 mg/l total dissolved solids was pumped. Changes in each scheme can be determined by comparing tables 11 and 12.

SODIUM-ADSORPTION-RATIO

It has been recognized for many years that when a soil containing exchangeable calcium and magnesium ions is irrigated with water in which sodium ions exceed other cations, the calcium and magnesium of the soil will tend to be replaced with sodium. This process of exchange of cations in solution for others in solid form is known as base exchange. Long continued adsorption of sodium by soil often results in the formation of a hard crust on the soil and a change in soil texture that lowers the natural permeability. The base-exchange process is a reversible one and, therefore, the adverse effects can be corrected by the use of soil amendments such as gypsum or lime, or by reducing the soil pH, enough to allow the calcium carbonate in the soil to go into solution.

TABLE 11.—*Distribution of dissolved solids in ground water in SCARP–1, 1960–62*

Scheme	Gross area (acres)	Total dissolved solids (mg/l)						
		0–500	500–1,000	1,000–1,500	1,500–2,000	2,000–2,500	2,500–3,000	>3,000
Harse Sheikh	24,500	7,800	15,900	800	-----	-----	-----	-----
Berānwāla	104,600	6,400	34,900	38,400	24,900	-----	-----	-----
Hāfizābād	171,900	62,900	104,800	4,200	-----	-----	-----	-----
Khāngāh Dogrān	115,300	90,900	24,400	-----	-----	-----	-----	-----
Sāngla	138,000	9,000	75,300	45,200	3,800	4,700	-----	-----
Shāh Kot	254,900	4,200	79,700	80,200	44,100	35,000	10,200	1,500
Chūhar Kāna	10,800	3,100	7,700	-----	-----	-----	-----	-----
Shādmān	78,500	53,200	25,300	-----	-----	-----	-----	-----
Chīchoki (Chīchoki Malliān)	7,000	6,100	900	-----	-----	-----	-----	-----
Zafarwāl	243,600	37,100	138,600	40,000	19,300	7,400	1,200	-----
Jarānwāla	93,100	3,300	31,400	39,600	7,800	8,100	2,900	-----
Total [1]	1,242,200	284,000	538,900	248,400	99,900	55,200	14,300	1,500

[1] Exclusive of Pindi Bhattiān, which was not included in the water-quality sampling program in 1960–62.

TABLE 12.—*Distribution of dissolved solids in ground water in SCARP–1, 1967*

Scheme	Gross area (acres)	Total dissolved solids (mg/l)						
		0–500	500–1,000	1,000–1,500	1,500–2,000	2,000–2,500	2,500–3,000	>3,000
Harse Sheikh	24,500	10,700	11,300	2,500	-----	-----	-----	-----
Berānwāla	104,600	8,500	28,000	66,900	1,200	-----	-----	-----
Hāfizābād	171,900	52,000	108,600	11,300	-----	-----	-----	-----
Khāngāh Dogrān	115,300	78,000	37,300	-----	-----	-----	-----	-----
Sāngla	138,000	13,200	77,700	33,800	9,400	3,300	600	-----
Shāh Kot	254,900	6,500	97,100	74,900	25,100	42,300	6,600	2,400
Chūhar Kāna	10,800	2,900	7,900	-----	-----	-----	-----	-----
Shādmān	78,500	40,100	38,400	-----	-----	-----	-----	-----
Chīchoki (Chīchoki Malliān)	7,000	7,000	-----	-----	-----	-----	-----	-----
Zafarwāl	243,60	24,100	125,700	56,400	27,800	6,600	2,000	1,000
Jarānwāla	93,100	7,400	33,400	27,900	15,100	7,900	1,400	-----
Total [1]	1,242,200	250,400	565,400	273,700	78,600	60,100	10,600	3,400

[1] Exclusive of Pindi Bhattiān, which was not included in the water-quality sampling program in 1960–62.

The potential effects in soil of the base-exchange process is indicated by the sodium-adsorption-ratio (SAR) which, when expressed in equivalents per million (epm), is calculated as follows:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

The potential sodium hazard (SAR) of irrigation water in a particular area is based largely upon soil texture, total dissolved solids of the water used, and the availability of exchangeable calcium or other cations on soil particles. Irrigation water may be classified into four principal SAR classes (U.S. Salinity Laboratory Staff, 1954, p. 81). Plate 5 shows the areal distribution of ground water in SCARP–1 with respect to the sodium-adsorption-ratio using the values 0–5; 5–10; 10–18; 18–26; and greater than 26. In areas where the SAR value generally is shown as less than 5 the sodium hazard is low enough so that the water can be used for irrigation with little likelihood of an increase in the alkali content of the soil (Fireman and Haque, 1966).

Plate 5 shows that ground water in the northeastern two-thirds of SCARP–1 generally has an SAR value of less than 10, whereas along the southwestern side of SCARP–1, notably in Ferānwāla, Sāngla, Shāh Kot, and Jarānwāla, large areas are underlain by ground water having SAR values greater than 10. Ground water in several relatively small areas in Shāh Kot, Zafarwāl, and Sāngla (Sangla Hill) Schemes has an SAR value of more than 18 and, therefore, presents a serious sodium hazard to nearly all soils regardless of the conductivity of the water.

During the initial period of reclamation pumping from 1960–62 to 1967, the sodium-adsorption-ratio of ground water changed in many areas. Comparison of tables 13 and 14 indicates the magnitude of the change in each scheme for each of the different classes of sodium water during the period of pumping. The data indicate that in 1960–62, ground water derived from tubewells in an area of 900,000 acres, or about 72 percent of the project area, had SAR values of less than 10. During the same period, ground water having SAR values ranging from 10 to 18 was pumped from wells in an area of about 285,000 acres, or 23 percent of the total area. In the remaining area of about 57,000 acres, tubewells produced water having SAR values greater than 18.

By 1967, ground-water withdrawals had locally induced infiltration of canal water or the migration of brackish water, causing

TABLE 13.—*Sodium-adsorption-ratio of ground water in SCARP–1, 1960–62*

Scheme	Gross area (acres)	Sodium-adsorption-ratio (meq/1)				
		0–5	5–10	10–18	18–26	<26
Harse Sheikh	24,500	12,800	11,700	------	------	------
Berānwāla	104,600	9,600	35,500	54,500	5,000	------
Hāfizābād	171,900	116,000	44,800	11,100	------	------
Khāngāh Dogrān	115,300	105,100	10,200	------	------	------
Sāngla	138,000	34,400	57,200	44,900	1,500	------
Shāh Kot	254,900	18,000	88,900	104,400	36,100	7,000
Chūhar Kāna	10,800	4,100	5,100	1,600	------	------
Shādmān	78,500	41,700	36,800	------	------	------
Chīchoki (Chīchoki Malliān)	7,000	6,800	200	------	------	------
Zafarwāl	243,600	63,200	122,700	49,800	7,900	------
Jarānwāla	93,100	11,600	63,200	18,300	------	------
Total [1]	1,242,200	423,700	476,300	284,600	50,500	7,100

[1] Exclusive of Pindi Bhattiān, which was not included in the water-quality sampling program in 1960–62.

TABLE 14.—*Sodium-adsorption-ratio of ground water in SCARP–1, 1967*

Scheme	Gross area (acres)	Sodium-adsorption-ratio (meq/1)				
		0–5	5–10	10–18	18–26	<26
Harse Sheikh	24,500	17,600	6,300	600	------	------
Berānwāla	104,600	5,100	37,600	61,900	------	------
Hāfizābād	171,900	106,200	55,200	10,500	------	------
Khāngāh Dogrān	115,300	93,300	22,000	------	------	------
Sāngla	138,000	24,700	60,000	50,700	2,600	------
Shāh Kot	254, 00	6,500	60,500	124,400	58,800	4,700
Chūhar Kāna	10,800	5,100	5,700	------	------	------
Shādmān	78,500	68,800	9,700	------	------	------
Chīchoki (Chīchoki Malliān)	7,000	7,000	------	------	------	------
Zafarwāl	243,600	91,600	113,300	38,200	500	------
Jarānwāla	93,100	20,500	50,200	20,700	1,700	------
Total [1]	1,242,200	446,400	420,500	307,000	63,600	4,700

[1] Exclusive of Pindi Bhattiān, which was not included in the water-quality sampling program in 1960–62.

changes in the chemical composition and the potential sodium hazard.

In 1967 the area in which wells were producing ground water having SAR values of less than 10 was reduced to about 867,000 acres, or about 70 percent of the area. There was a corresponding increase in the size of the area from which ground water having SAR values greater than 10 was being pumped. During this same period of time the area in which wells were discharging water having SAR values of 18 or greater had increased to about 68,000 acres.

Although the above values suggest little change in gross area from which the different classes of ground water were pumped in the project area as a whole, significant changes occurred in several schemes. For example, the gross area included in the 0–10 range of SAR values remained unchanged in Khāngāh Dogrān, Shādmān, and Chīchoki (Chīchoki Malliān); increased in Chūhar Kāna and Zafarwāl; and decreased in all other schemes during the period of pumping. In the Shāh Kot Scheme, the area in which the ground water had SAR values ranging up to 10 was reduced from about 107,300 acres to about 67,000 acres, or about 38 percent during the period of project operation. Decrease in the size of the areas producing a similar type of water in the other schemes generally was less than 7 percent during the same period.

CHANGE IN CHEMICAL CHARACTER OF GROUND WATER

Changes in quality of the ground water in SCARP–1 have resulted from a variety of causes, most of which are directly or indirectly brought about by pumping. Disruption of hydraulic equilibrium and alteration of the natural flow regimen by pumping has caused changes in the quality of water pumped from wells over a period of time owing to the migration and mixing of waters of different chemical character.

Pumpage of about 2 million acre-feet or more of ground water annually since 1961 has provided sufficient supplemental water for increasing the irrigated area and cropping intensity and for the reclamation of agricultural land affected by the accumulation of salt in the root zone of plants. Most of the leach water and excess irrigation water drains vertically downward to the water table. Downward percolation of the residual irrigation water to the water table transports surface salts in the soil profile to the main ground-water body. In SCARP–1, where there is little direct return flow to the rivers and only a small amount of ground-water underflow to adjacent areas, pumping from tubewells will eventually create a closed circulation system in the ground-water reservoir that will result in a gradual increase in concentration of the dissolved solids. The deterioration in water quality will eventually require the export of saline water from the project area.

The reuse of water through successive cycles of irrigation causes the accumulation and concentration of salts in the soil through the process of repeated evapotranspiration. During each successive irrigation the more soluble chloride and sulfate salts are redissolved and returned to the ground-water reservoir, leaving behind some of the salts of lower solubility such as calcium and magnesium carbonate and bicarbonate. Continued recycling of irrigation water will eventually result in the accumulation of the highly soluble salts in the ground water. An increase in the relative concentration of chloride and sulfate over a period of time may be an indication that percolation of irrigation water has moved vertically to the depth of the well screen.

Changes in concentration of dissolved minerals in ground water also result from the migration of highly mineralized water into areas of low mineralized water and vice versa. Locally, in wells penetrating zones of highly mineralized water or in wells screened in the proximity of a highly mineralized ground-water body, water quality changes rapidly during pumping. Pumping of wells in the vicinity of canals induces leakage from the canals into the ground-water reservoir; and inasmuch as the dissolved solids in canal water are less than the dissolved solids in ground water, seepage dilutes or replaces the underlying ground water.

Swarzenski (1968) has shown that for ground water in Rechna Doāb having less than 300 mg/l total dissolved solids, the dominant ions in solution are calcium, magnesium, and bicarbonate. In samples having a dissolved-solids content ranging from 500 to 1,000 mg/l the dominant ions in solution are sodium and bicarbonate or a mixture of bicarbonate, chloride, and sulfate in about equal proportions, whereas in samples having a dissolved-solids content ranging from 3,000 to 10,000 mg/l, the principal ions in solution are sodium and chloride. An increase in the dissolved-solids content resulting from the migration of more highly mineralized waters into fresh-water zones will be accompanied usually by a change in the relative ionic concentration; checking ionic balances periodically will provide a clue to the cause of the change in quality.

In an effort to determine whether the cause of local deterioration in ground-water quality was due principally to recirculation of excess irrigation waters or to migration of poor quality water induced by pumpage, trilinear plots were made showing the chemical character of ground water from several wells in each scheme area. Water-quality data for successive years were plotted for each of the selected wells in an effort to determine the rate and change in the chemical composition of the ground water. The large volume of data available on the chemical quality of ground water in SCARP–1 and the absence of computer facilities at the time of this report prevented the analysis of all wells on trilinear diagrams. Wells selected for analysis in this study were chosen largely on the basis of geographic distribution and without regard to well construction or rate of pumping.

Interpretation of the trilinear plots suggests that in most instances the deterioration in water quality resulted from complex mixtures of two, or more, different types of water. In many of the wells selected for analysis, the increase in total dissolved solids was accompanied by an increase in the relative ionic concentration of sodium and bicarbonate, or a mixture of bicarbonate, sulfate, and chloride. An increase in the relative proportion of these constituents suggests that the deterioration in water quality may be the result of induced inflow of water containing from 500 to 1,000 mg/l total dissolved solids that Swarzenski (1968) found common to Rechna Doāb. The trilinear plots also indicate that in some wells increased mineralization was accompanied by an exchange of calcium and magnesium for sodium. Of the wells analyzed, none showed a progressive increase in relative concentration of the highly soluble chloride and sulfate salts that would be expected if recharge was derived from recycling. Preliminary analysis of the data suggests that deterioration in the quality of ground water through 1967 resulted from inflow of indigenous ground water of different chemical character and not to recycling of irrigation water. Although the conclusions are based on data from a limited number of wells, the data that were analyzed are believed to be representative of the wide variety of conditions in SCARP–1.

SUMMARY AND CONCLUSIONS

A review of hydrologic data gathered in SCARP–1 during the first 7 years of operation of the project indicates that several preliminary conclusions can be drawn with respect to the annual and long-term pumping effect on the hydrologic regimen and on the chemical character of the ground water.

Pumpage through June 1968, totaling more than 17 million acre-feet and averaging about 2.3 million acre-feet per year, has resulted in the average lowering of the water table of about 5 feet beneath the project. The gross pumpage has been withdrawn unevenly over the area, with a maximum of 17.4 feet pumped in the Harse Sheikh Scheme and a minimum of 8.0 feet in the Shāh Kot and Chūhar Kāna Schemes. As a result of the uneven distribution of the ground-water withdrawal, the water table has been lowered from an average minimum of about 2 feet in the Jarānwāla, Shādmān, Chīchoki Malliān and Harse Sheikh Schemes to nearly 9 feet in the Zafarwāl Scheme. By June 1968, three distinct cones of depression, separated by ground-water divides, had developed in Zafarwāl, Khāngāh Dogrān, and the Hāfizābād Schemes. Maximum lowering has been in the center of the Zafarwāl Scheme where the water table has been depressed more than 12 feet.

Locally, effects of pumping extend beyond the boundary of SCARP–1, up to a distance of a mile or more. The areal extent and magnitude of the cone of depression in the water table caused by pumping has fluctuated in response to changes in recharge and discharge. The maximum area affected by pumping occurred in water year 1965 when the area of the cone of depression expanded to about 1.86 million acres. As a result of significant reduction in pumpage in water years 1966 and 1967, the water table rose somewhat more than a foot and the area of the cone of influence decreased to about 1.55 million acres.

The annual ground-water inflow has increased from about 35,000 acre-feet in water year 1960 to about 52,000 acre-feet in 1968. During this same interval of time, ground-water flow to adjacent areas downgradient decreased from a maximum of about 57,000 acre-feet in 1960 to about 32,000 acre-feet in 1966. Ground-water flow increased to about 39,000 acre feet in 1968 as a result of the rise in water table and increase in hydraulic gradient in that year.

The net effect of pumping to July 1968 has been a depletion in the ground-water reservoir of about 1.7 million acre-feet of water. In every scheme in SCARP–1, the average depth of the water table has been lowered to a depth of 10 feet or more. In the Zafarwāl Scheme, where maximum lowering of the water table has occurred, the depth of the water table locally exceeds 20 feet. As a result, open-ditch drains have ceased or nearly ceased to function as ground-water drains, and waterlogging has been eliminated.

Owing to a reduction in pumpage in water years 1966 and 1967, the water table appears to have stabilized at about the June 1967–June 1968 level, suggesting that, under the operating conditions existing at that time, equilibrium conditions had been reestablished between recharge, discharge, and ground-water in storage. Accordingly, all pumpage during those 2 years was derived from local sources of recharge, including canal seepage and percolation of irrigation water.

During the period of full-scale operation since 1962, gross recharge to the ground-water reservoir has averaged about 2.4 million acre-feet per year. Distributed over the area of influence, this amount of recharge would be equivalent to about 1.5 acre-feet per acre per year. Assuming 30 percent of the pumpage from project and private wells is recycled, net recharge since 1961 has totaled about 10.27 million acre-feet, or about 1 acre-foot per acre per year. Most of this recharge undoubtedly was derived from deep percolation of canal water.

Canal inflow to SCARP–1 during the period 1960–67 averaged about 6.4 million acre-feet annually. Canal outflow to adjacent areas downgradient, plus the amount spilled through escapes during this same period, averaged about 4.6 million acre-feet per year. Accordingly, the net canal inflow to SCARP–1 averaged about 1.8 million acre-feet per year and was sufficient only for 47 percent of the irrigation requirement in the project area.

There is additional discharge from the project area through surface-water drains. The drains convey effluent ground-water seepage as well as precipitation runoff to the Chenāb and Rāvi Rivers. By May 1965, the water had been lowered below the bed of most of the Jarānwāla and Degh Nāla drainage network in the southeastern half of the project area, and since that time the flow in the drains has been largely derived from precipitation runoff. Most of the estimated 85,000 acre-feet of ground-water seepage discharged annually by these two drains in the period before pumping began has been diverted to wells.

The water table in the northwestern half of the project served by the Chiniot (Drain) and the Ahmadpur Kot Nikka Drain has not been lowered sufficiently to stop effluent ground-water seepage. Of the total flow of about 38,000 acre-feet in these two drains in water year 1967, approximately 15,000 acre-feet was derived from ground-water seepage. It is estimated that by June 1967 about two-thirds of the ground-water seepage to these drains had been salvaged through wells.

Changes in the quality of ground water in SCARP–1 since reclamation pumping began indicate that changes in the areal distribution and concentration of dissolved solids and the sodium-adsorption-ratio have been relatively insignificant. Inasmuch as the rate of movement in the ground-water reservoir probably does not exceed 50 feet a year, the movement of bodies of mineralized water, and thus changes in chemical quality of the well discharge, has been slow. It should be emphasized that the changes that have been observed represent only a transient condition in time and space, and, as pumping continues, changes will continue to occur in the chemical character of the water.

Analysis of data on the quality of ground water suggests that the distribution and concentration of dissolved minerals in ground water in SCARP–1 is principally the result of circulation of water in the ground-water reservoir. The increased concentration of dissolved solids toward the center of the doāb supports other hydrologic data indicating that under natural conditions circulation in the aquifer was from areas of high precipitation in the upper reaches of the doāb, and from the adjacent rivers toward areas of natural discharge in the center of the doāb.

After the construction of canals around the turn of the century and after the importation of river water to the central part of the doāb, leakage from canals materially changed the source and amount of ground-water recharge. As a result of the increased recharge, low hydraulic gradient, and generally poor subsurface drainage, the water table eventually rose to the land surface, or within a few feet of land surface, causing widespread waterlogging and salinization. Recharge from canal seepage contains relatively low dissolved minerals and, therefore, as it moved downward and away from the canals, it diluted or displaced the more highly mineralized indigenous ground water in the vicinity of the canals. Canal seepage forms narrow bands of water of low mineralization usually less than a mile in width and a hundred or more feet deep. The superimposition of this movement on the regional ground-water flow pattern has created a complex pattern of lateral and vertical movement of ground water of different chemical character.

With the beginning of ground-water reclamation and full-scale pumping, the flow pattern in the upper few hundred feet of the ground-water reservoir underwent additional change.

During the period of project operation (1961–67), the area in which wells were pumping ground water containing less than 1,500 mg/l of dissolved solids increased from about 1.07 million acres to about 1.09 million acres. During the same period the area in which tubewells were producing ground water containing more than 3,000 mg/l total dissolved solids increased from about 1,500 acres to about 3,400 acres. On a project-wide basis, there was a relatively small reduction from 900,000 acres to 867,000 acres, or about 30,000 acres in which the SAR value of the pumpage was less than 10. In the different schemes however, the SAR value of the pumped ground water changed over a significant area. For example, in the Shāh Kot Scheme the area served by wells producing water with an SAR value of less than 10 was reduced by 38 percent.

The general increase in the sodium content of ground water with respect to calcium and magnesium suggests that, if the increasing trend continues, remedial measures in irrigation practices, in the use of soil amendments, or in mixing well water with canal water, will have to be taken to prevent undesirable changes in the permeability of the soil.

Most areas that have shown a general improvement in quality of the ground water are near canals where pumping has induced inflow to the wells of relatively good-quality water commonly present beneath canals. Water is inferior in quality in many wells remote from the influence of canals and in wells where recharge from canal seepage is impeded by stratification and anisotropic conditions of the aquifer. In these instances, deterioration has resulted largely from the migration of mineralized bodies of water to the well. There is little evidence to indicate deterioration in water quality up to 1967 resulted from recycling of irrigation water.

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[Italic page numbers indicate major references]

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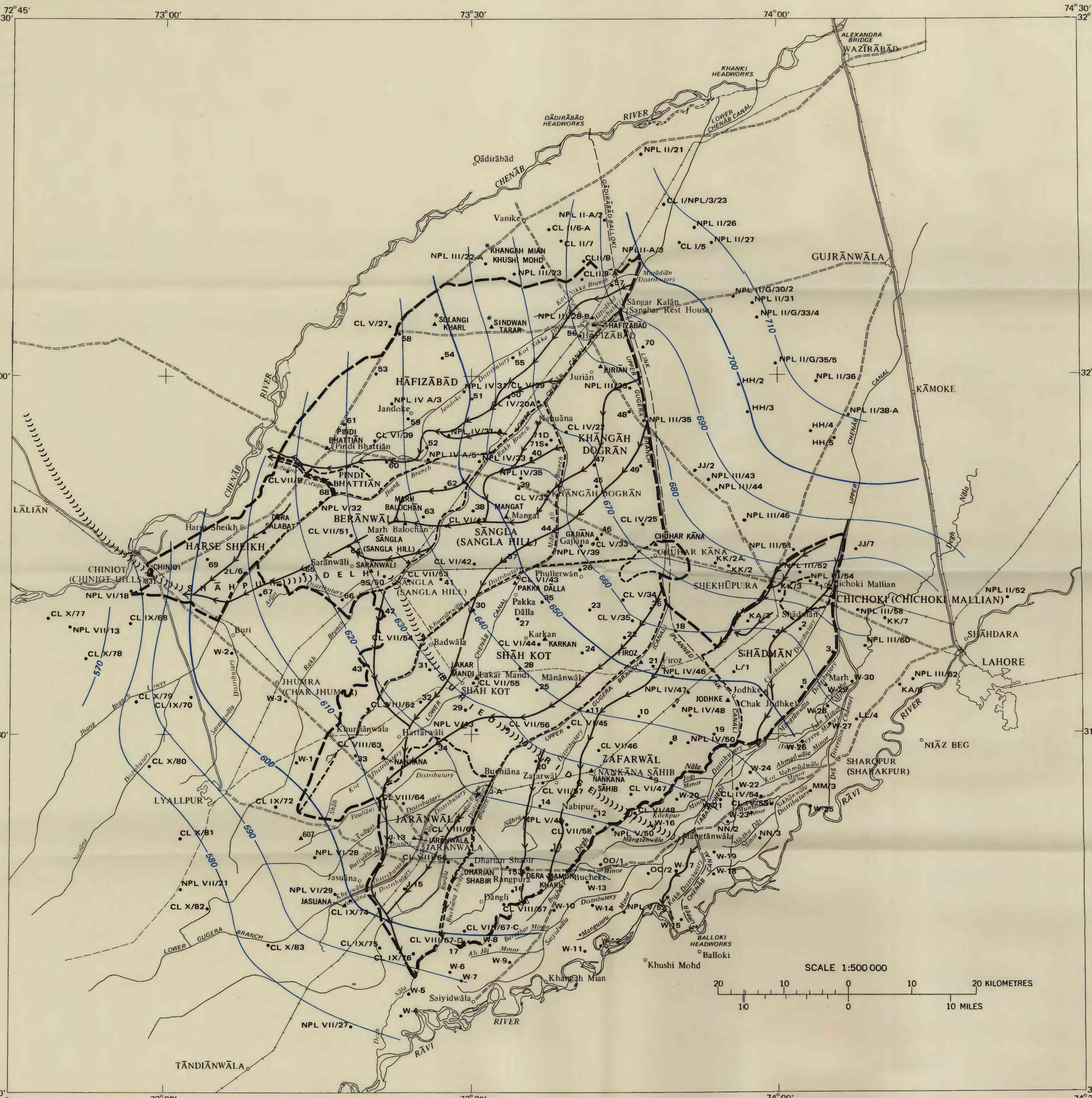
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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-O
PLATE 1



Geographic names preceded by an asterisk have not been verified by the U.S. Board on Geographic Names

A.—1960–61

EXPLANATION

HH/2 — GROUND-WATER OBSERVATION WELL AND IDENTIFICATION NUMBER

CHINIOT — OBSERVATION WELL – Equipped with continuous water-stage recorder and identifying location name or number

Note: Well-numbering system varies with country agency in charge of well drilling or reclamation project

650 — WATER-TABLE CONTOUR – Shows altitude of water table. Dashed where approximately located. Contour interval 10 feet. Datum is mean sea level

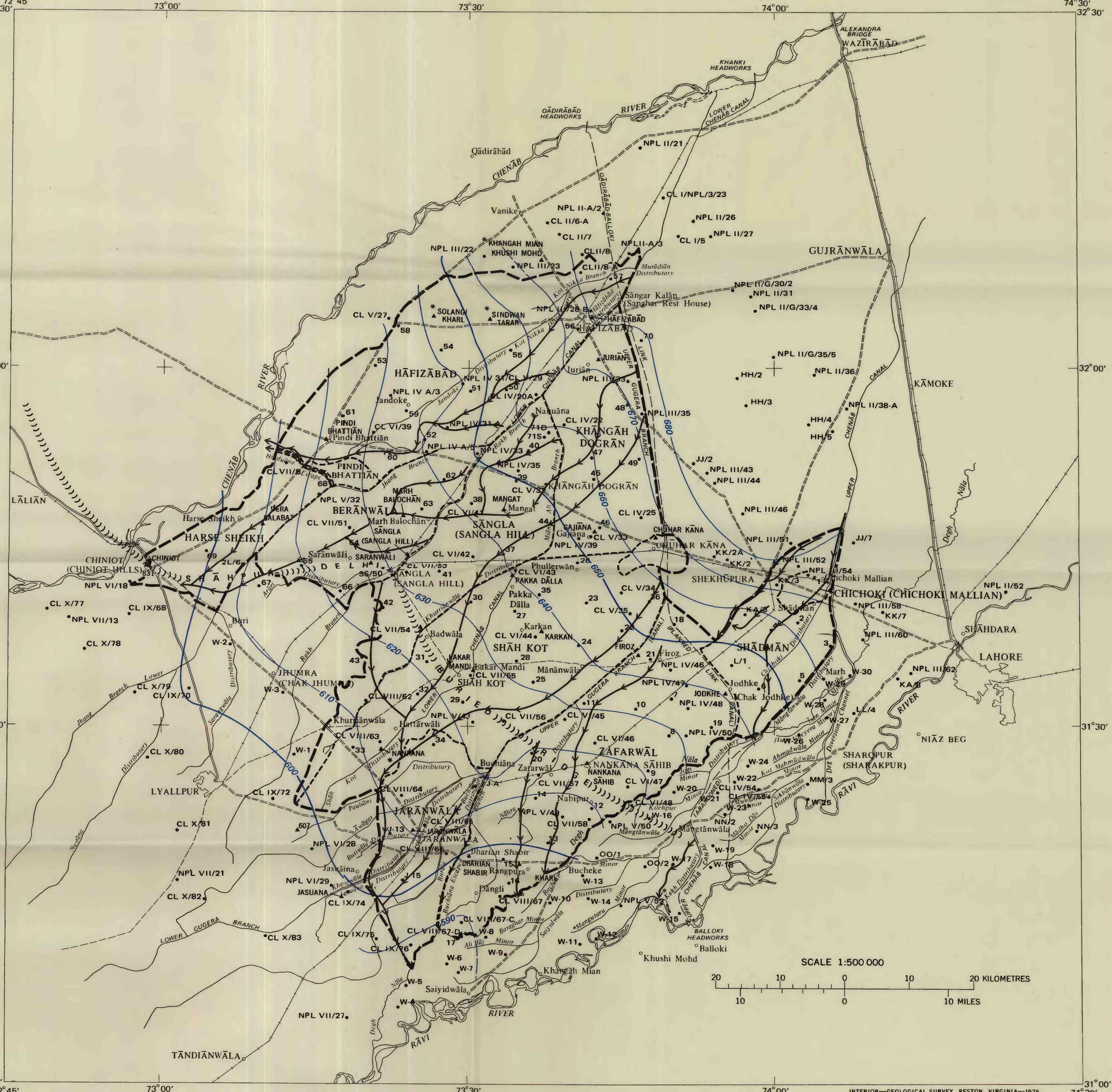
BOUNDARY OF SCARP–1

BOUNDARY OF SCHEME

CANAL

DRAIN

ESCAPE



INTERIOR—GEOLOGICAL SURVEY, RESTON, VIRGINIA—1975

B.—1968

MAPS SHOWING ALTITUDE OF WATER TABLE IN SCARP–1, RECHNA DOĀB, PUNJAB REGION, PAKISTAN

UNITED STATES DEPARTMENT OF THE INTERIOR
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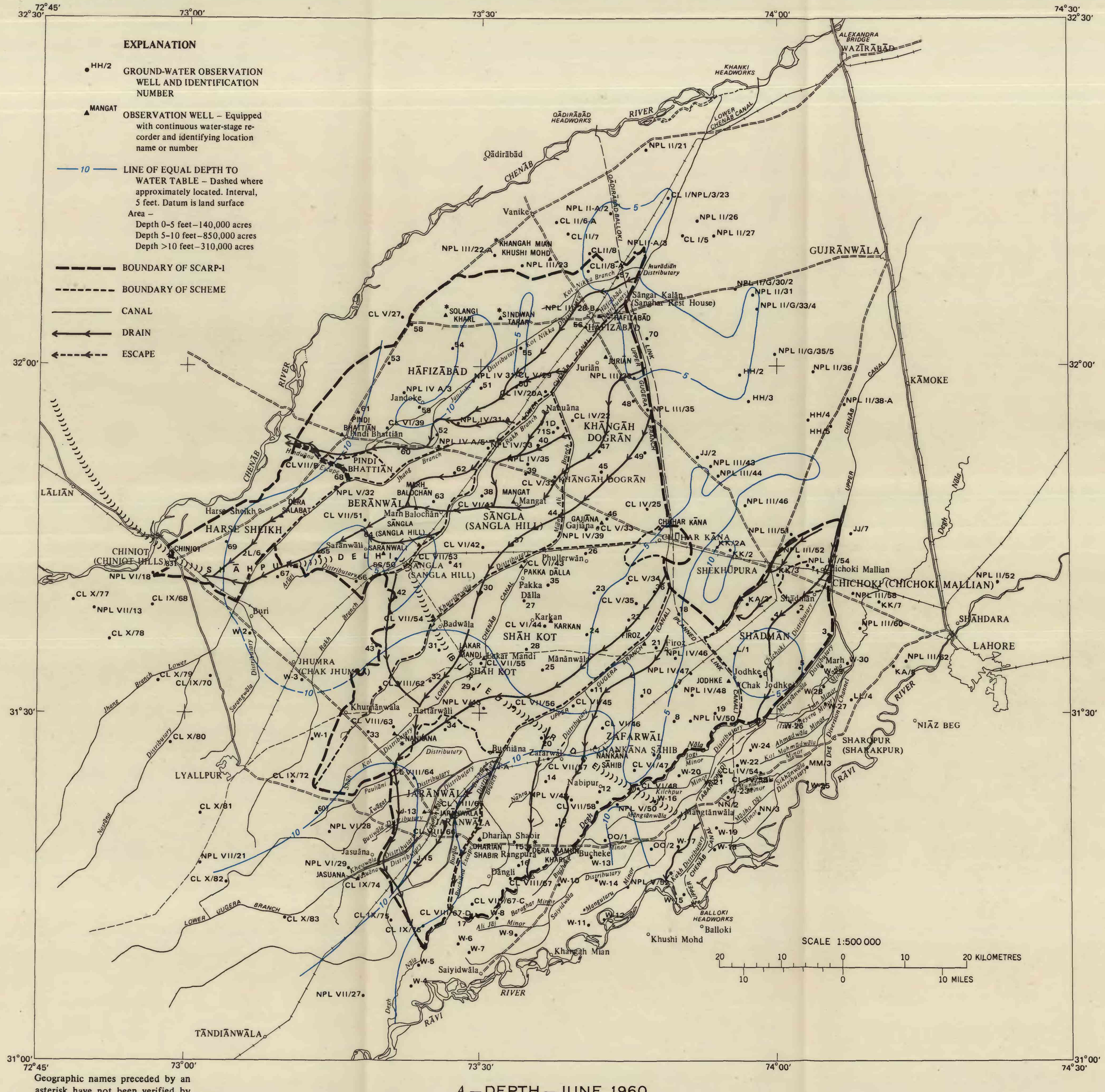
WATER-SUPPLY PAPER 1608-O
PLATE 2



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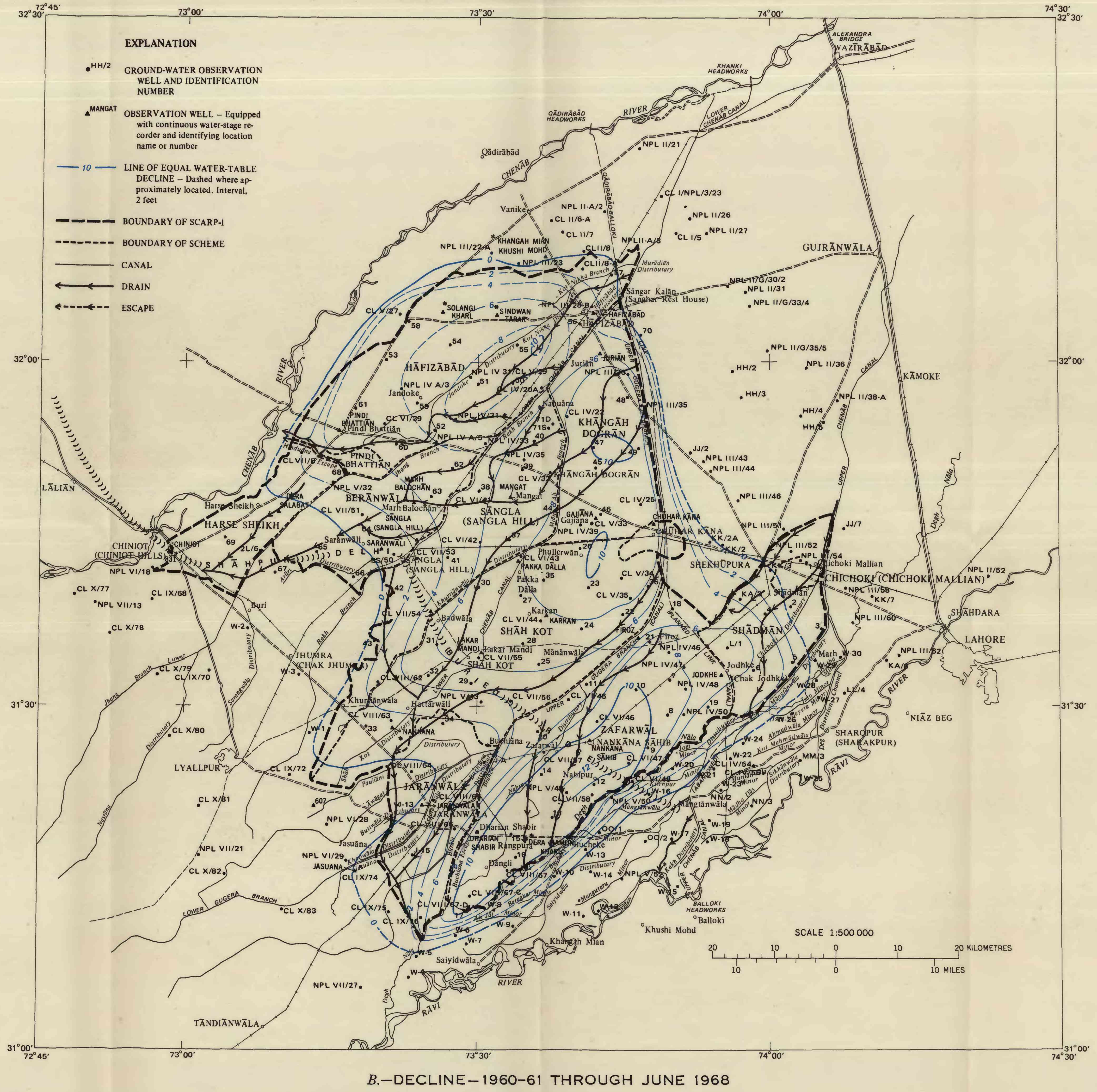
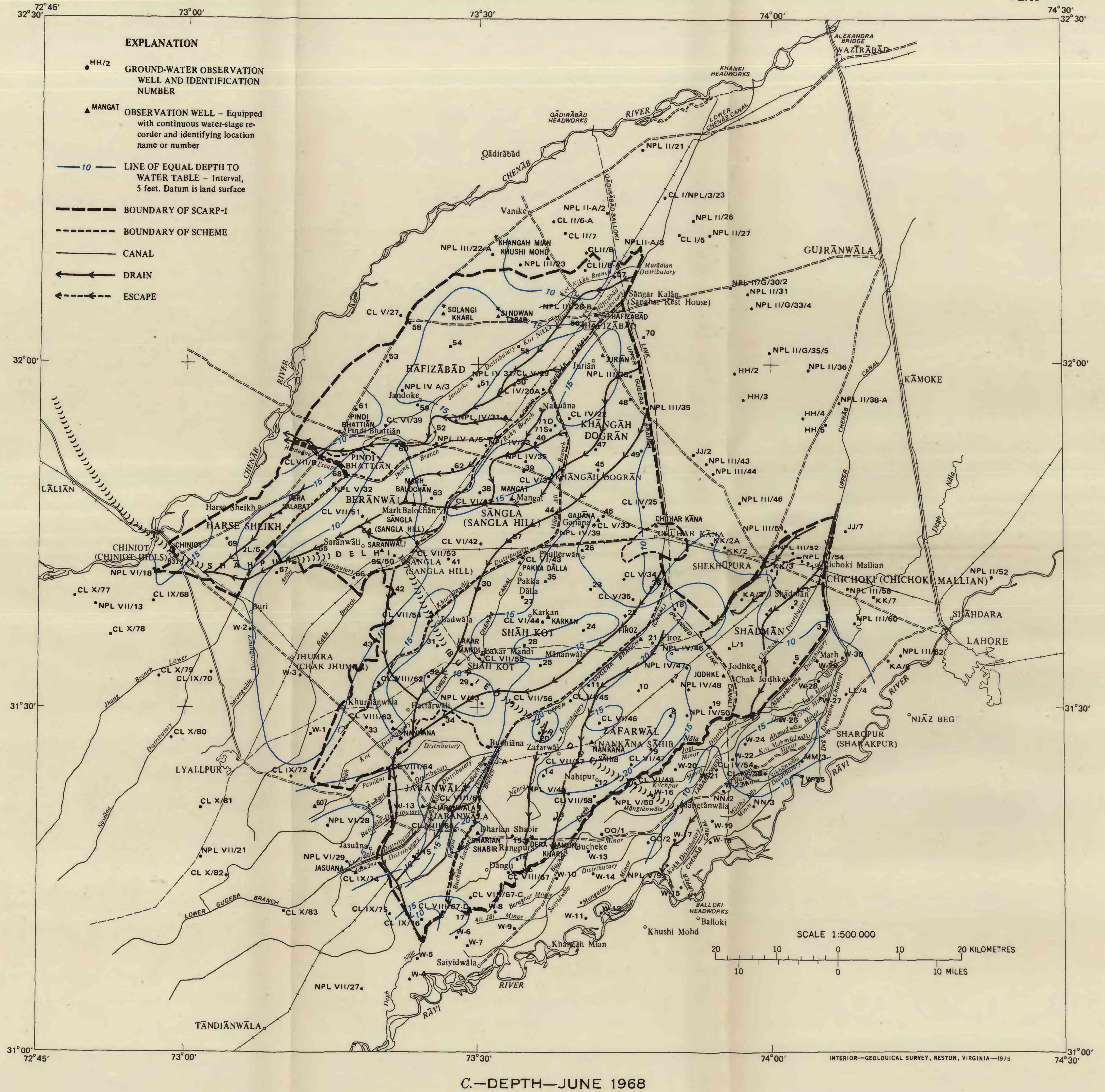
A.—DEPTH—JUNE 1960



B.—DECLINE—1960–61 THROUGH JUNE 1968



C.—DEPTH—JUNE 1968

MAPS SHOWING APPROXIMATE DEPTH TO AND DECLINE OF WATER TABLE IN SCARP–1, RECHNA DOĀB, PUNJAB REGION, PAKISTAN

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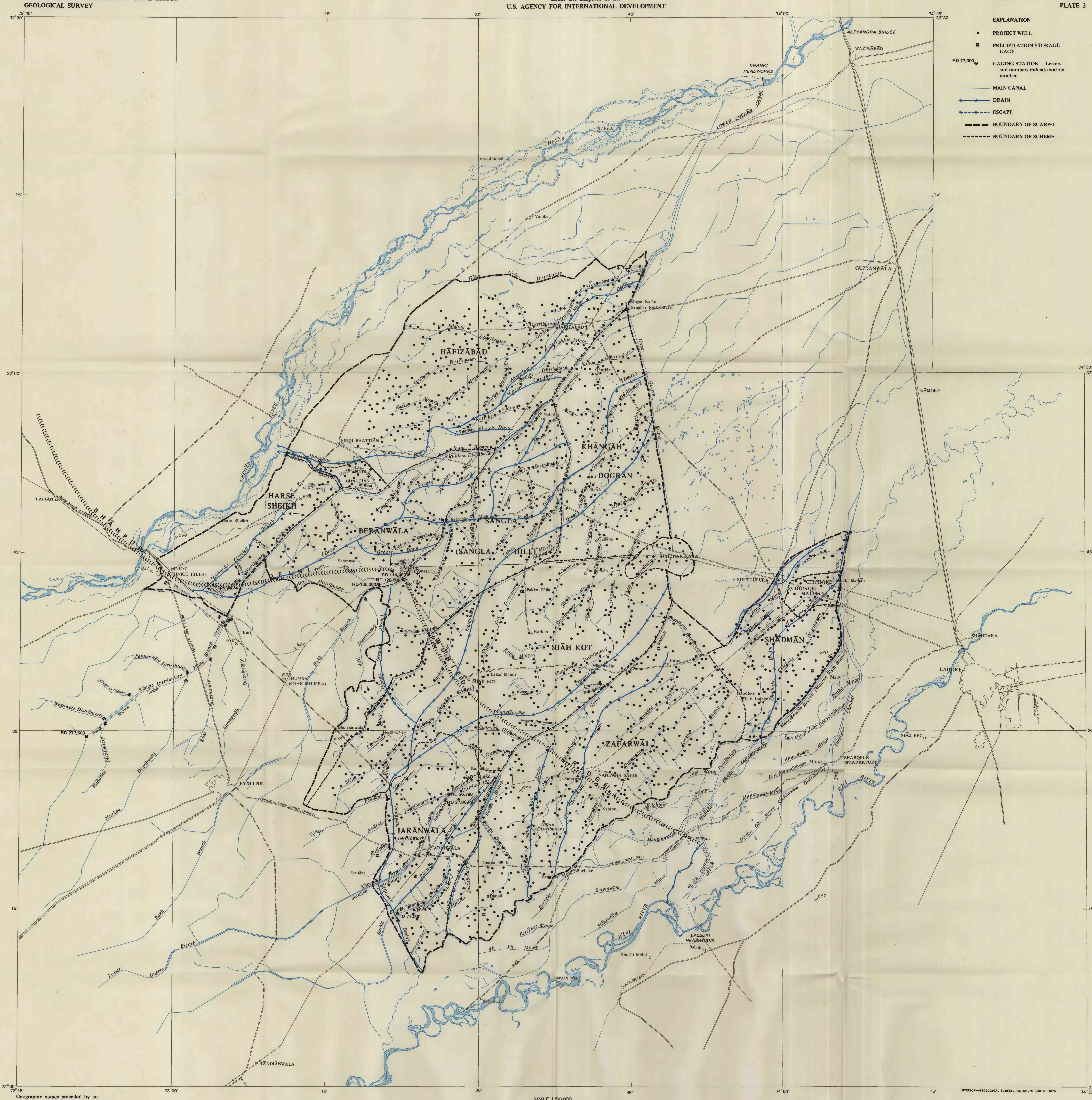
WATER-SUPPLY PAPER 1608-O
PLATE 3



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MAP SHOWING PRINCIPAL CANALS, DRAINS, AND WELLS, IN SCARP-1, RECHNA DOĀB, PUNJAB REGION, PAKISTAN

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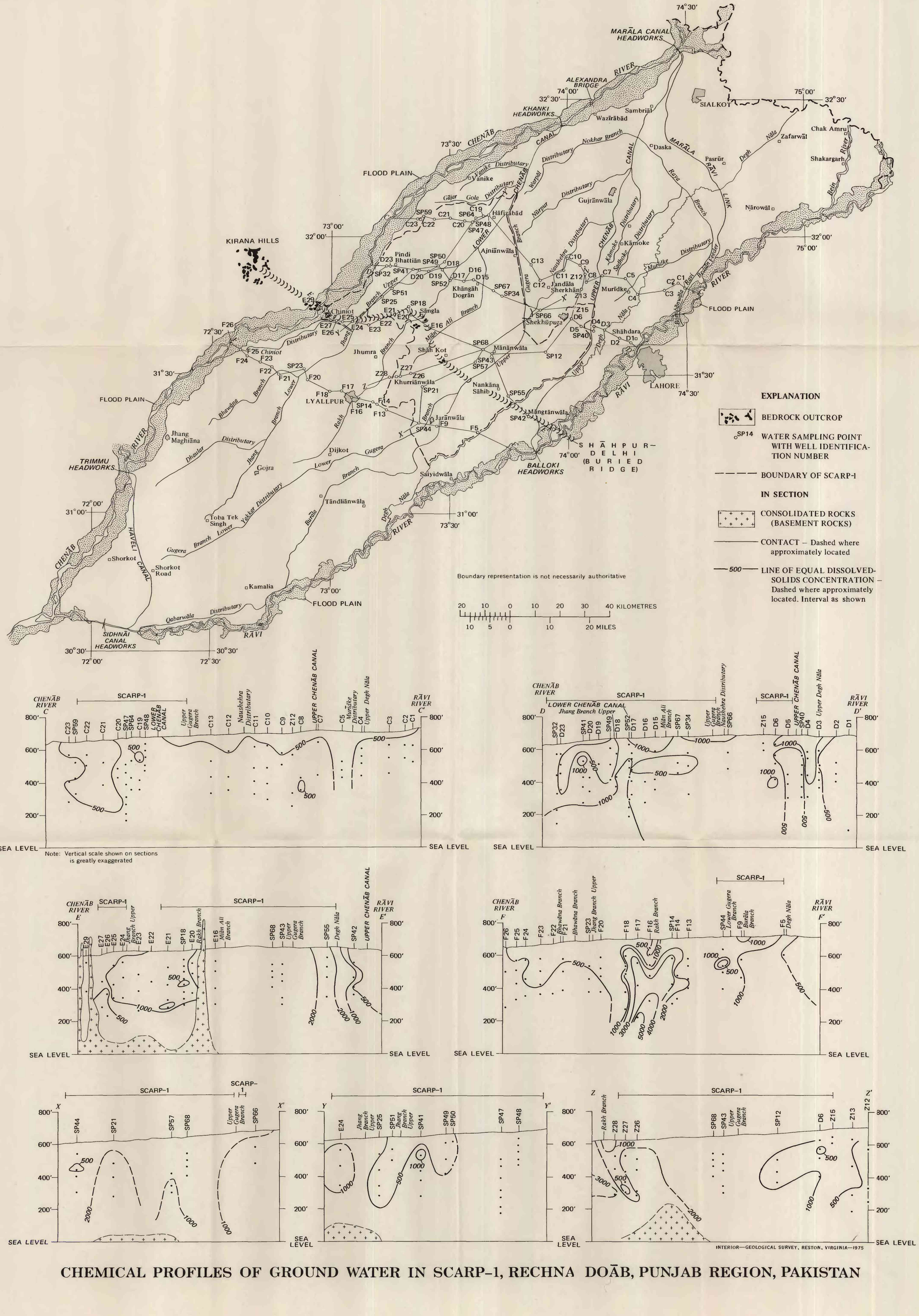
WATER-SUPPLY PAPER 1608-O
PLATE 4



CHEMICAL PROFILES OF GROUND WATER IN SCARP-1, RECHNA DOĀB, PUNJAB REGION, PAKISTAN

UNITED STATES DEPARTMENT OF THE INTERIOR
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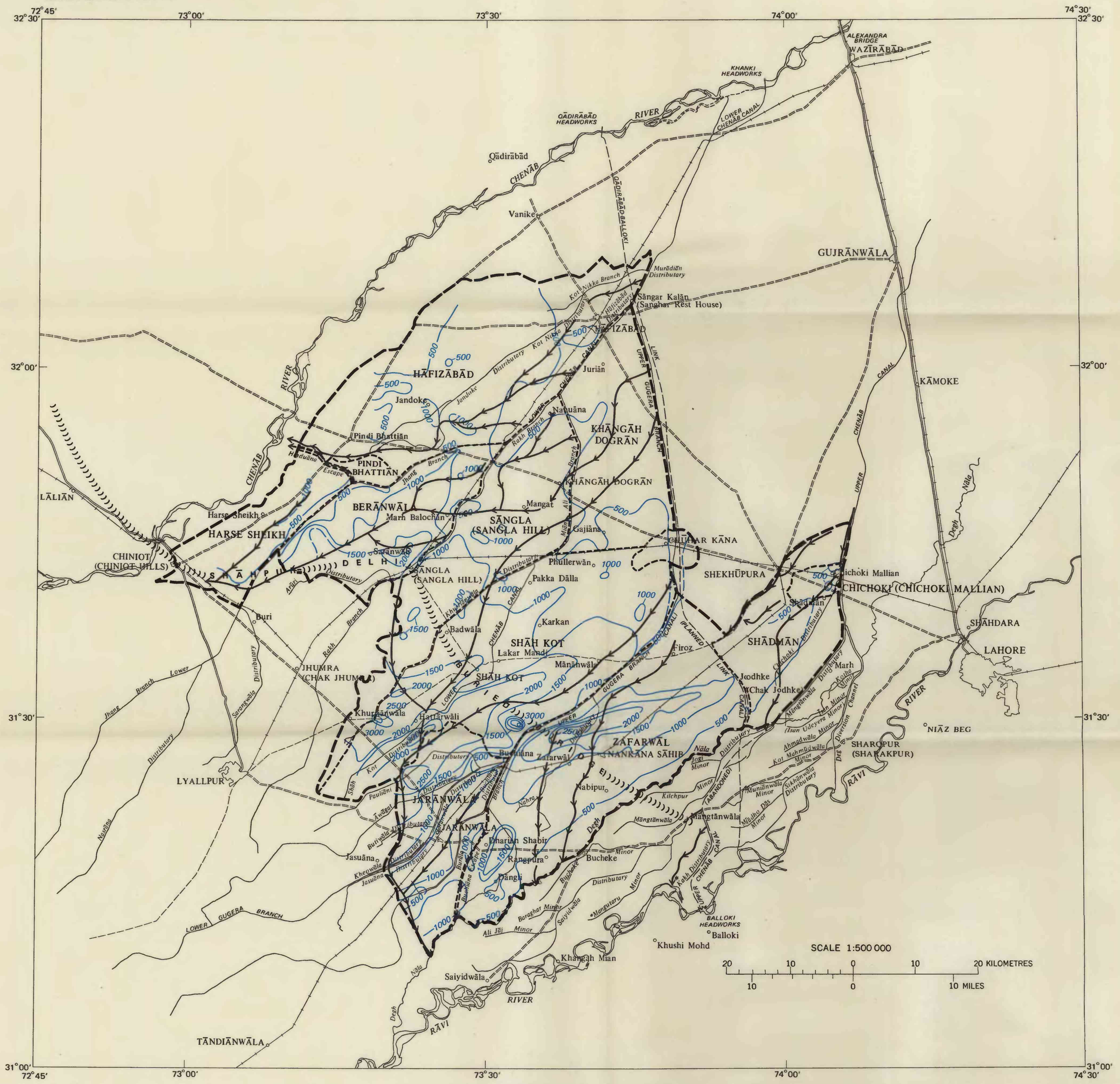
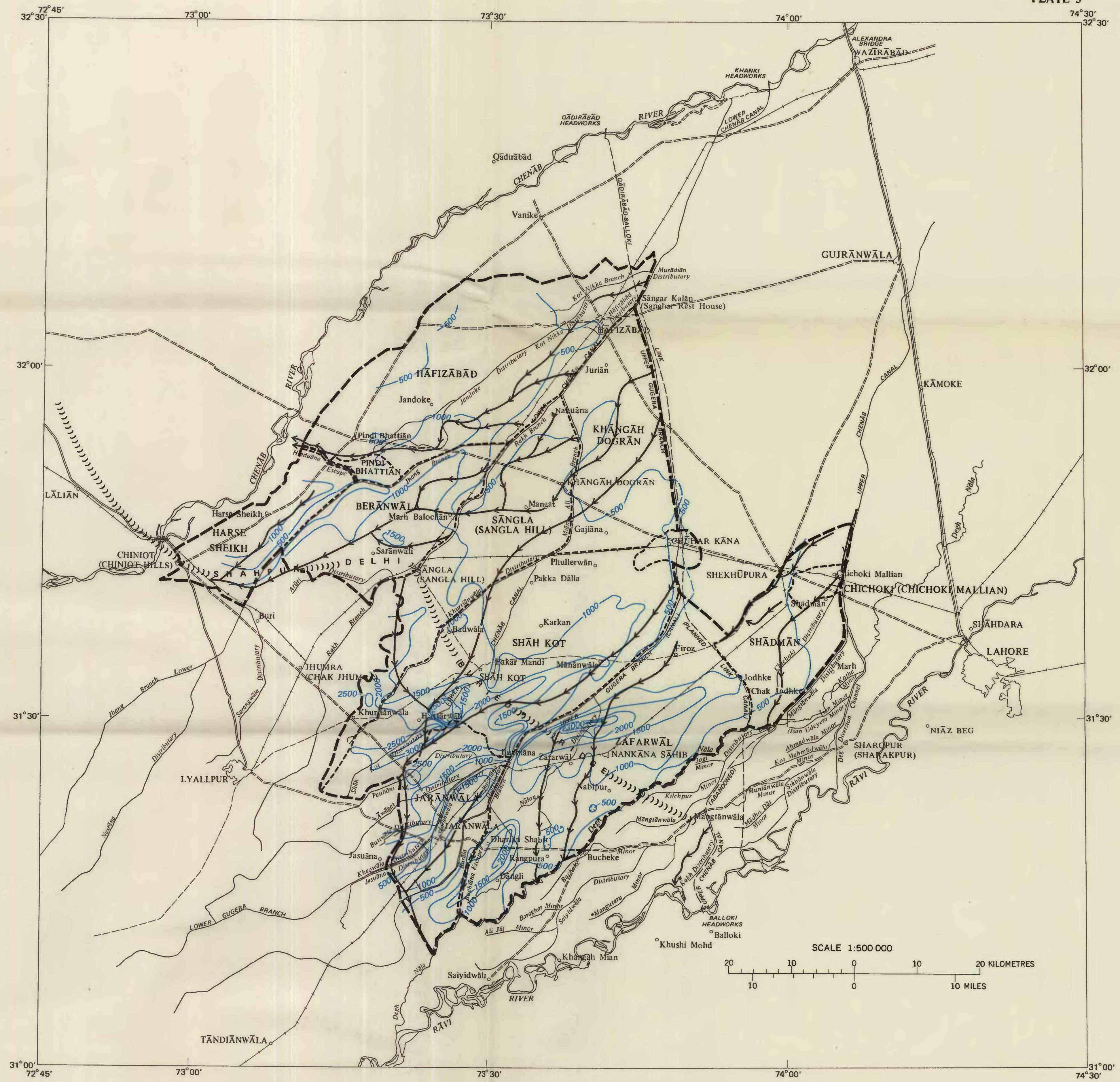
WATER-SUPPLY PAPER 1608-O
PLATE 5



A.—DISSOLVED SOLIDS—1960–62



B.—DISSOLVED SOLIDS—1967

EXPLANATION

500 — LINE OF EQUAL DISSOLVED-SOLIDS CONCENTRATION — Dashed where approximately located. Interval, 500 milligrams per litre

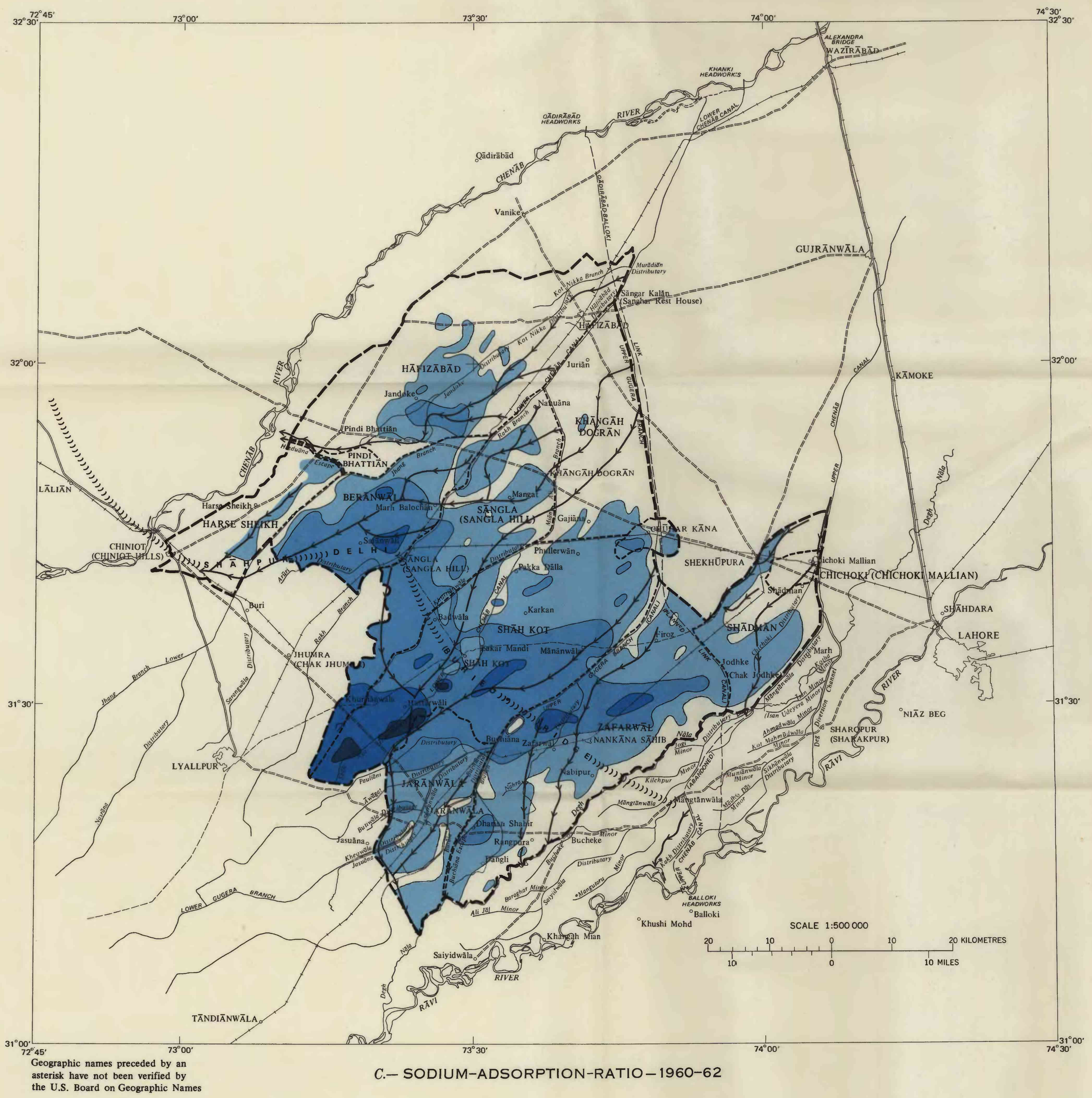
BOUNDARY OF SCARP-1

BOUNDARY OF SCHEME

CANAL

DRAIN

ESCAPE



Geographic names preceded by an asterisk have not been verified by the U.S. Board on Geographic Names

C.—SODIUM-ADSORPTION-RATIO—1960–62

EXPLANATION

SODIUM-ADSORPTION-RATIO (SAR)— The ratio is determined by the relation

$$\frac{Na}{\sqrt{\frac{Ca+Mg}{2}}}$$

when ion concentrations are expressed in milliequivalents per litre

0 to 5

5 to 10

10 to 18

18 to 26

Greater than 26

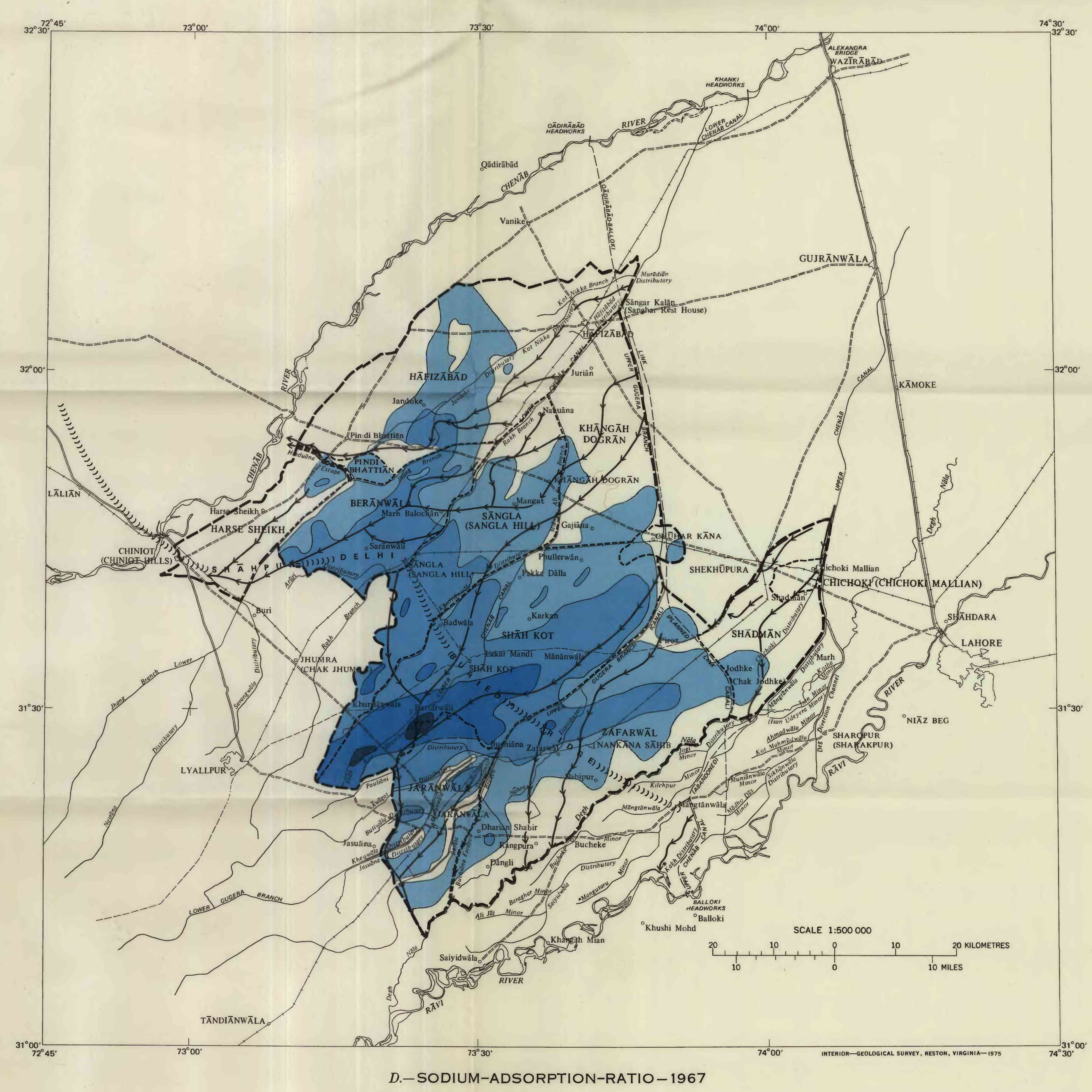
BOUNDARY OF SCARP-1

BOUNDARY OF SCHEME

CANAL

DRAIN

ESCAPE



D.—SODIUM-ADSORPTION-RATIO—1967

MAPS SHOWING DISSOLVED-SOLIDS CONCENTRATION AND SODIUM-ADSORPTION-RATIO OF GROUND WATER IN SCARP-1, RECHNA DOĀB, PUNJAB REGION, PAKISTAN