Hydrologic Evaluation of Salinity Control and Reclamation Projects in the Indus Plain, Pakistan—A Summary

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1608-Q

Prepared in cooperation with the West Pakistan Water and Power Development Authority under the auspices of the United States Agency for International Development

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By M. J. MUNDORFF, P. H. CARRIGAN, JR., T. D. STEELE, *and* A. D. RANDALL

CONTRIBUTIONS TO THE HYDROLOGY OF ASIA AND OCEANIA

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METRIC-ENGLISH EQUIVALENTS

Metric unit		English equivalent	
Length			
millimetre (mm)	=	0.03937	inch (in)
metre (m)	=	3.28	feet (ft)
kilometre (km)	=	.62	mile (mi)
Area			
square metre (m^2)	=	10.76	square feet (ft^2)
square kilometre (km^2)	=	.386	square mile (mi^2)
hectare (ha)	=	2.47	acres
Volume			
cubic centimetre (cm^3)	=	0.061	cubic inch (in^3)
litre (l)	=	61.03	cubic inches
cubic metre (m^3)	=	35.31	cubic feet (ft^3)
cubic metre	=	.00081	acre-foot (acre-ft)
cubic hectometre (hm^3)	=	810.7	acre-feet
litre	=	2.113	pints (pt)
litre	=	1.06	quarts (qt)
litre	=	.26	gallon (gal)
cubic metre	=	.00026	million gallons (Mgal or 10^6 gal)
cubic metre	=	6.290	barrels (bbl) (1 bbl=42 gal)
Weight			
gram (g)	=	0.035	ounce, avoirdupois (oz avdp)
gram	=	.0022	pound, avoirdupois (lb avdp)
tonne (t)	=	1.1	tons, short (2,000 lb)
tonne	=	.98	ton, long (2,240 lb)
Specific combinations			
kilogram per square centimetre (kg/cm^2)	=	0.96	atmosphere (atm)
kilogram per square centimetre	=	.98	bar (0.9869 atm)
cubic metre per second (m^3/s)	=	35.3	cubic feet per second (ft^3/s)

Metric unit		English equivalent	
Specific combinations—Continued			
litre per second (l/s)	=	.0353	cubic foot per second
cubic metre per second per square kilometre [$(m^3/s)/km^2$]	=	91.47	cubic feet per second per square mile [$(ft^3/s)/mi^2$]
metre per day (m/d)	=	3.28	feet per day (hydraulic conductivity) (ft/d)
metre per kilometre (m/km)	=	5.28	feet per mile (ft/mi)
kilometre per hour (km/h)	=	.9113	foot per second (ft/s)
metre per second (m/s)	=	3.28	feet per second
metre squared per day (m^2/d)	=	10.764	feet squared per day (ft^2/d) (transmissivity)
cubic metre per second (m^3/s)	=	22.826	million gallons per day (Mgal/d)
cubic metre per minute (m^3/min)	=	264.2	gallons per minute (gal/min)
litre per second (l/s)	=	15.85	gallons per minute
litre per second per metre [(l/s)/m]	=	4.83	gallons per minute per foot [(gal/min)/ft]
kilometre per hour (km/h)	=	.62	mile per hour (mi/h)
metre per second (m/s)	=	2.237	miles per hour
gram per cubic centimetre (g/cm^3)	=	62.43	pounds per cubic foot (lb/ft^3)
gram per square centimetre (g/cm^2)	=	2.048	pounds per square foot (lb/ft^2)
gram per square centimetre	=	.0142	pound per square inch (lb/in^2)
Temperature			
degree Celsius (°C)	=	1.8	degrees Fahrenheit (°F)
degrees Celsius (temperature)	=	[(1.8×°C)+32]	degrees Fahrenheit

CONTRIBUTIONS TO
THE HYDROLOGY OF ASIA AND OCEANIA

HYDROLOGIC EVALUATION OF SALINITY CONTROL AND RECLAMATION PROJECTS IN THE INDUS PLAIN, PAKISTAN—A SUMMARY

By M. J. MUNDORFF, P. H. CARRIGAN, JR., T. D. STEELE, and A. D. RANDALL

ABSTRACT

This report summarizes the observations and findings of a team of four specialists from the U.S. Geological Survey assigned to Pakistan under the auspices of the U.S. Agency for International Development during May to August 1972 for a hydrologic evaluation of Salinity Control and Reclamation Projects in the *Indus Plain.[1] Individual members of the team undertook comprehensive studies related to climatology, surface-water hydrology, and the canal system; streamflow and sediment yields of the rivers; computer applications to hydrologic data; aquifer characteristics; hydrologic evaluation of Salinity Control and Reclamation Projects (SCARPs); tubewell performance; hydrology of shallow versus deep tubewells; well and well-screen design in the Indus Plain; evaluation of observed and anticipated trends in both private and public tubewell development; evaluation of water-quality programs, data analysis, and records, and computer coding of special water-quality data; and evaluation of water-level data, well discharge and specific-capacity tests and aquifer tests.

The reclamation program, by pumping from tubewells, has been notably successful in lowering the water table, in providing supplemental water for irrigation and for leaching of salinized soils, and in improving crop production. Some changes in water quality have been observed in SCARP–I and the Mona Scheme of SCARP–II, but these have not as yet (1972) significantly

[1] Geographic names in this report have been verified by the Board on Geographic Names (BGN) of the Geographic Names Division, U.S. Army Topographic Command, Washington, D.C. Other verification of names, compilation of names, and editing for cartographic and report use were done in the Office of International Activities, National Center, Reston, Va. Names in this report are in three categories: verified and standard names of BGN, not verified names from BGN, "Scheme" names in Salinity Control and Reclamation Projects edited to the nearest geographic feature name. Names not verified are shown on the illustrations preceded by an asterisk (*). A note explaining this usage follows the explanation on plates 1 and 2.

affected the utility of the water for irrigation. Problems associated with reclamation include control of deterioration in performance of tubewells and their rehabilitation, local brackish or saline-water encroachment, and maintenance of a favorable salt balance in the ground-water system.

Rapid and as yet (1972) unregulated growth of shallow private tubewell development in the past decade has introduced complicating factors to the reclamation planning of the early 1960's which had emphasized public tubewell development through the SCARP program. In comparing shallow (0–200 feet) with deep (200–400 feet) tubewell development, it is concluded that long-term response of the water table is the same, whether many shallow wells of small capacity or fewer deeper wells of large capacity pump the same total volume of water in the same area. Moreover, it is concluded that there is no definite advantage for either type of pumping regime with respect to water quality.

Utilization of the Punjab aquifer could be greatly enhanced by recharge of high-quality water diverted from the Chenāb and Jhelum Rivers to the Rāvi and Sutlej Rivers by way of the link and irrigation canals during periods of surplus flow. Recharge to the aquifer could also be improved by diversion of high-quality water from the Chenāb and the Jhelum to natural nalas and other surface drainageways during periods of surplus flow. Such recharge would be of much better quality than water leaching downward from irrigated fields.

Continued monitoring of the hydrologic system and research on problems engenderd by reclamation are essential to the viability of the SCARP program and related water-resources development in the Indus River Basin.

INTRODUCTION

GENERAL SETTING

The *Indus Plain [1] was formed from alluviation by the Indus River and its tributaries, the Jhelum, Chenāb, Rāvi, Beās, and Sutlej in an extensive tectonic depression lying between the Himalayas and other mountain ranges. This vast plain is bounded on the east by the Himalayan foothills, on the north by the Salt Range and the Potwar Plateau, on the southeast by the Thar Desert, and on the west by the Sulaiman and Kīrthar Ranges. From the Himalayan foothills the plain extends 750 miles southwestward to the Arabian Sea (pl. 2).

On this plain lies the world's largest contiguous block of irrigated land. In 1959 the total canal-irrigated area was more than

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21 million acres, of which about 15 million acres were in the Punjab region and Bahawalpur (Plain) of the Upper *Indus Plain and 6 million acres were in the Sind region of the Lower *Indus Plain (White House-Department of the Interior Panel Report, 1964). The majority of the people gain their living by cultivating the land, and most of the rest are dependent on industries based on agriculture. Thus, the availability of water for irrigation is fundamental to the economy and the livelihood of the people.

Prior to the beginning in 1859 of development of major irrigation systems, waterlogging and salination were not problems in the *Indus Plain. Leakage from the unlined irrigation canals began to raise the water table. As development of the irrigation system continued through the last part of the 19th century and the first few decades of the 20th, the water-table rise accelerated until major parts of the agricultural lands were waterlogged or salinated. Steady-state conditions in the position of the water table were reached in the 1940's in some areas, because evaporation from the water table at or near the land surface balanced recharge from canal leakage.

Since gaining independence in 1947, Pakistan has been increasingly concerned with the problems of waterlogging and salination of soils in the *Indus Plain. According to the White House-Department of the Interior Panel Report (1964, p. 62), "a total of 6.5 million acres of actually or potentially culturable lands in the Indus Plain is seriously affected by waterlogging and/or high soil salinity," and "the area of damaged canal-irrigated and cultivated land is roughly 5 million acres, or about 18 percent of the gross area in the *Indus Plain, and 22 percent of the canal-irrigated sown area." The report also concluded that the area of severe waterlogging and salinity damage in the cultivated lands of the Indus Plain was increasing in the late 1950's at a rate of 50,000 to 100,000 acres per year.

HISTORY OF HYDROLOGIC INVESTIGATIONS, MONITORING, AND RESEARCH

A comprehensive project of water and soils investigations was begun in 1954 under a cooperative agreement between the Government of Pakistan and the United States. According to the agreement, the Provincial Government of West Pakistan provided personnel and office and field facilities for carrying out the investigations. The U.S. International Cooperation Administration and its successor agency the U.S. Agency for International Development (US AID) provided technical advisors, largely on loan from the U.S. Geological Survey (USGS), vehicles, field and laboratory equipment, drilling and construction equipment, and other commodities. The Ground Water Development Organization and its successor, the Water and Soils Investigation Division (WASID) of the West Pakistan Water and Power Development Authority (WAPDA), provided the counterpart personnel and organization for carrying out the investigative program.

The broad objectives of the investigative project were to inventory the water and soils resources of the Punjab region; to determine aquifer characteristics; to delineate fresh and saline water zones; and to identify and describe the interrelations of various components of the hydrologic system, including canal seepage, irrigation, waterlogging, and salinity. The analysis and evaluation of the information obtained from this project have provided the scientific and technical base for planning reclamation and development programs.

As the investigative project of WASID neared completion in the Punjab region in the mid-1960's, WASID's role increasingly emphasized monitoring the results of the reclamation projects and research on the problems related to ground-water development and reclamation. Also, it was considered at the time that the investigative and training objectives of the original U.S.-Pakistan project agreement had essentially been completed. Accordingly, that project was terminated at the end of 1967, and a new project emphasizing hydrologic monitoring and research was begun. This project was essentially terminated in December 1971.

The first reclamation projects based on the findings of WASID's investigations became operational in 1960–61. To date (August 1972) four Salinity Control and Reclamation Projects (SCARPs) in the Upper *Indus Plain (Punjab region), and one in the Lower *Indus Plain (Sind region) have become partly or entirely operational; about 7,950 publicly-owned tubewells and other works had been completed in the SCARP areas aggregating 6.1 million acres.

SCOPE AND OBJECTIVES OF PRESENT STUDY

As the first reclamation project (SCARP–I) had been in operation for more than 10 years, it was decided in early 1972 that a team of hydrologic specialists would undertake a review of monitoring procedures and of the results of antecedent investigations, and evaluate the effects of the SCARPs and related projects on the hydrologic regimen of the region. This decision was based on plans worked out during 1971 by P. R. Seaber and A. R. Leonard, USGS advisors, in cooperation with WASID colleagues and in consultation with the U.S. Agency for International Development Mission in Pakistan. The team for the present evaluation consisted of the authors who are hydrologic specialists of the U.S. Geological Survey on loan to the U.S. Agency for International Development. They devoted about 15 man-months in Pakistan to the hydrologic analyses and related work tasks summarized in this report during May to August 1972.

Primary objectives of the USGS team were to describe the hydrologic regimen of the Indus River Basin, to summarize significant findings from a multitude of past studies, and to orient ongoing studies with respect to providing the necessary hydrologic inputs for a proposed future economic evaluation of the SCARPs. Consideration was given by the USGS team where possible (1) to describing changes in the hydrologic regimen due to past stresses, particularly with respect to canal development, the SCARPs and other tubewell developments, and (2) to predicting future responses to a range of possible hydrologic stresses and management decisions.

Secondary objectives included guidance for (1) assembly, summarization, and computerization of several types of hydrologic data to insure their preservation, and (2) compilation of significant maps and bibliographhc and data sources. In addition, the adequacy of the monitoring and research program of Central Monitoring Organization (CMO) and WASID was review and evaluated.

This report presents only a summary of more comprehensive studies made by members of the USGS team during May to August 1972 of special problems, including suggestions on program changes and recommendations for future or different program needs. Mr. Mundorff was concerned chiefly with studies relating to aquifer characteristics, hydrologic evaluation of Salinity Control and Reclamation Projects, tubewell performance, hydrology of shallow versus deep tubewell wells, and well-screen design in the *Indus Plain. Messrs. Mundorff and Steele together evaluated observed and anticipated trends in both private and public tubewell development. Mr. Carrigan directed his studies chiefly to climatology, surface-water hydrology, and the canal system; to streamflow and sediment yields of the Indus River Basin; and to computer coding of streamflow and sediment data. Mr. Steele undertook evaluations of water-quality programs, data analysis, and records and computer coding of special water-quality data. He also collaborated with Messrs. Carrigan and Randall on studies of computer applications to hydrologic data in the Indus River Basin. Mr. Randall concerned himself chiefly with evaluations of water-level data, well discharge and specific capacity tests, and aquifer test data in the *Indus Plain.

Although this summary report includes some discussion of hydrologic data for the Lower Indus Plain, including the Khairpur SCARP, most of the emphasis is on the Upper *Indus Plain or Punjab region included between the Indus River and its five tributaries, the Jhelum, Chenāb, Rāvi, Beās and Sutlej; their interfluves comprising Thal, Chaj, Rechna and Bāri Doābs; and the adjacent *Bahāwalpur plain area.

ACKNOWLEDGMENTS

The analyses and evaluation of data presented in separate studies and in this summary report would not have been possible without the willing cooperation and assistance of many governmental officers of Pakistan.

Special thanks are due to the following officers of WASID: Chaudari Mohammad Umar, M. A. Lateef, R. A. Shamsi, M. A. Moghul, A. Rehman Khan, Z. U. Kidwai, Mohammad Hussain, Amjad Hussain Shah, Muhammad Abdullah, Abdul Gaffar Chaudhry, Sabir Ali Bhatti, I. A. Sheikh, Haji Mohammad, Maqsood Ali Shah, Mohammad Farooq, A. H. Naqui, Haider Ali Shah, Rizwan Jaffri, Ghulam Hussain, Mohammad Bashir, Hamid Ullah Khan, Hassan Mian and Mahmood Khan; officers of the Reclamation Division, WAPDA: Badr-ud-Din, Sheikh Mohammad Afzal, A. Gaffar Khan; WAPDA Computer Center: Jalid U. Ahmed, I. U. Haq, Abdul Rashid, M. A. Hayat.

Assistance of other agencies is also gratefully acknowledged; these include the Regional Meteorological Center, Soil Survey of Pakistan, Punjab Irrigation and Water Department, and the Water Management Cell of WAPDA.

Thanks are also due the US AID Mission and the staff who helped so greatly in support functions. Special thanks are due to Waheed Khalid of the US AID staff, who handled so many details for the USGS team during their stay in Pakistan.

UPPER INDUS HYDROLOGIC REGIMEN

The hydrologic regimen of the Upper Indus River Basin has been described in many reports. A brief summary, however, is presented here to serve as a background for better understanding of the more detailed discussion, which follows, of changes in the regimen caused by the developmental stresses of recent years. An excellent reference for a more detailed account is a report by Greenman, Swarzenski, and Bennett (1967).

CLIMATOLOGY

The climate of most of Pakistan, and particularly of the *Indus Plain, is classified as arid to semiarid (less than 8 and 20 inches of annual precipitation, respectively). The submontane zone of the Himalayan foothills is the only part of the Indus River Basin with more than moderate precipitation, exceeding 80 inches in places. Along the northern rim of the Upper *Indus Plain the annual precipitation ranges from 30 to 40 inches, normally. A marked decrease in annual precipitation occurs southward of the rim, being about 19 inches at Lahore and 8 inches at Multān. In the Lower *Indus Plain the precipitation in the vicinity of Gudu and Lloyd Barrage (Sukkur Barrage) may be 4 inches or less annually. An area of extremely low precipitation lies in the western part of the country near the Iranian border, where annual rainfall is less than 2 inches. Also moist air raises annual precipitation along the coast of the Arabian Sea somewhat above that found immediately inland. Summer maximum temperatures are high, commonly exceeding 100°F and at times exceeding 115°F. Winter minimum temperatures seldom fall below freezing in the *Indus Plain but may fall below freezing in bordering mountain valleys. The mean annual temperature at Lahore is 75.1°F, but it increases to about 85°F in the southwest part of the Punjab region. Humidity is generally low except in coastal areas and during the monsoon season (July to September).

The bulk of the precipitation on the plain occurs during the southwest monsoon season (June to September). As much as 70 to 80 percent of the annual total is received in this season. The moisture laden air for these rains is drawn mostly from the Bay of Bengal, and occasionally from the Arabian Sea, into the seasonal low-pressure trough created in the northern part of the *Indus Plain by high summer temperatures. There does not seem to be a secular trend in long-term precipitation.

Precipitation, both rain and snow, during winter is derived from westerly air masses moving across the Indus River Basin, and the bulk of the annual precipitation in the northwestern part of the basin occurs during this season.

Snowfall has been measured at higher elevations (above 10,000 feet) in the Kāgān Valley (Kaghan Valley [Kunhar River]) by WASID and is measured at mountain valley stations (generally lower than 5,000 feet) by the Pakistan Meteorological Department.

Three agencies collect climatological data in the Indus River Basin: the Pakistan Meteorological Department, WASID, and the Punjab Irrigation and Power Department, which collects precipitation only. The types of data and periods of record, for which these data are available, are quite variable between stations. Evaporation data are being collected presently (1972) only by WASID. Collection of evaporation data began at a few stations in the Indus Plain during the 1950's.

SURFACE-WATER HYDROLOGY AND CANAL SYSTEM

The Indus River and its tributaries form the principal drainage system in Pakistan. The Indus River system drains an area of about 372,000 sq mi (square miles) (fig. 1) and is one of the major river systems of the world. The mainstem and larger tributaries of the Indus River rise in the Himalayas, some in China, and others in India and Pakistan. One major western tributary, the Kābul River, rises in the Hindu Kush of Afghanistan. Major eastern tributaries, the Jhelum Chenāb, Rāvi, and Sutlej Rivers all rise outside of Pakistan, in Kashmīr or in India proper.

Other small drainage basins lie in the southwestern part of Pakistan, streams draining into the plains near Karāchi, and streams discharging into the Arabian Sea. The plains near Karāchi are nominally in the Indus River drainage basin, but little surface runoff from this area ever reaches the Indus River.

The bulk of the runoff in the Indus River and its major tributaries (table 1) is generated in the montane and submontane zones of their headwaters, being derived both from melting snow and ice and from the rains of the southwest monsoon. The high-water season, beginning in April to May and ending in September, is the result of the tandem effect of snowmelt and monsoon rains. An example of the monthly distribution of flow is shown in figure 2.

In their montane and submontane reaches, the streams of the Indus River system flow on steep gradients through deep gorges or narrow winding valleys, but when the streams reach the *Indus Plain, they flow on low gradients in meandering and braided channels over deep alluvium. Their downstream gradients across the plain are in the order of only 1 to 1½ ft/mi (feet per mile).

The surface waters in the Upper Indus River system commonly range in dissolved-solids content (table 2) from about 56 to 416 mg/l (milligrams per litre). The dissolved-solids content of the waters of most rivers of the system varies seasonally and inversely with volume of discharge, being lowest during the period of high flow (April to September) and highest during the period of low

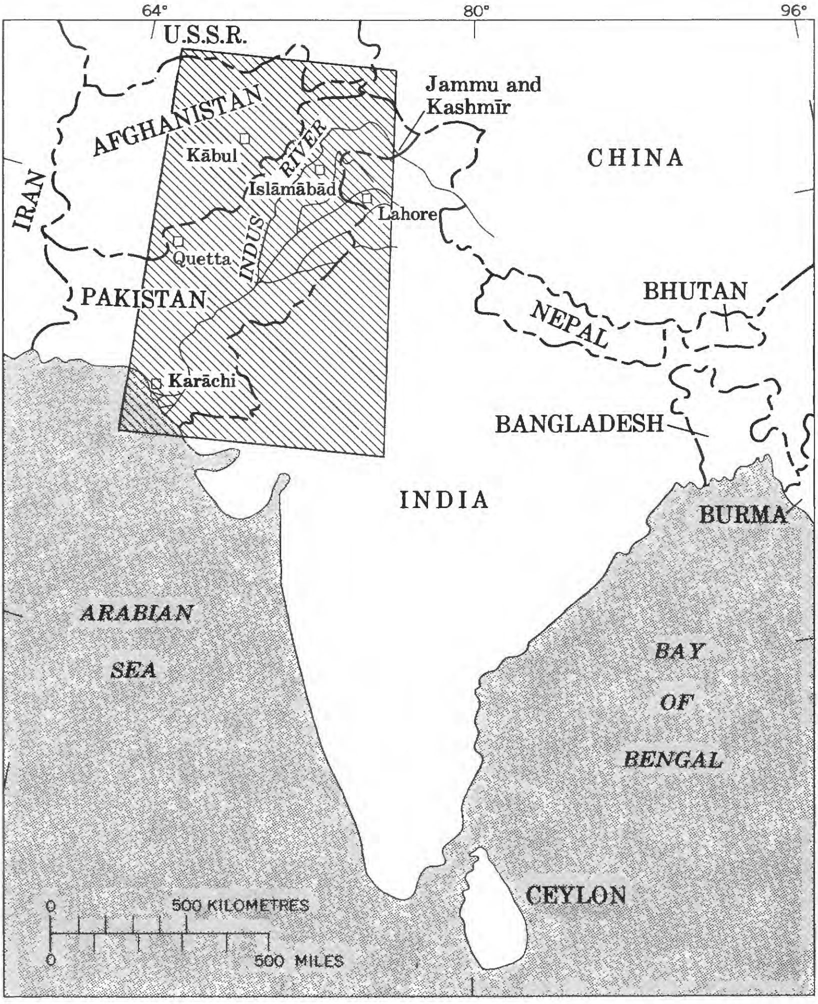

FIGURE 1.—Index map showing location of study area (shaded).

flow (October to March). The average solute concentration of the waters of the rivers of the Upper Indus system is in order of 150 to 180 mg/l.

As attested by the vast accumulation of stream deposits in their alluvial plain, the Indus River and its tributaries carry huge sediment loads derived from erosion of the Himalayas, the Hindu Kush, and contiguous mountain ranges. These loads vary seasonally and are greatest in the high-water period or during floods and least in the low-flow period. The annual magnitude of these loads in indicated in table 3.

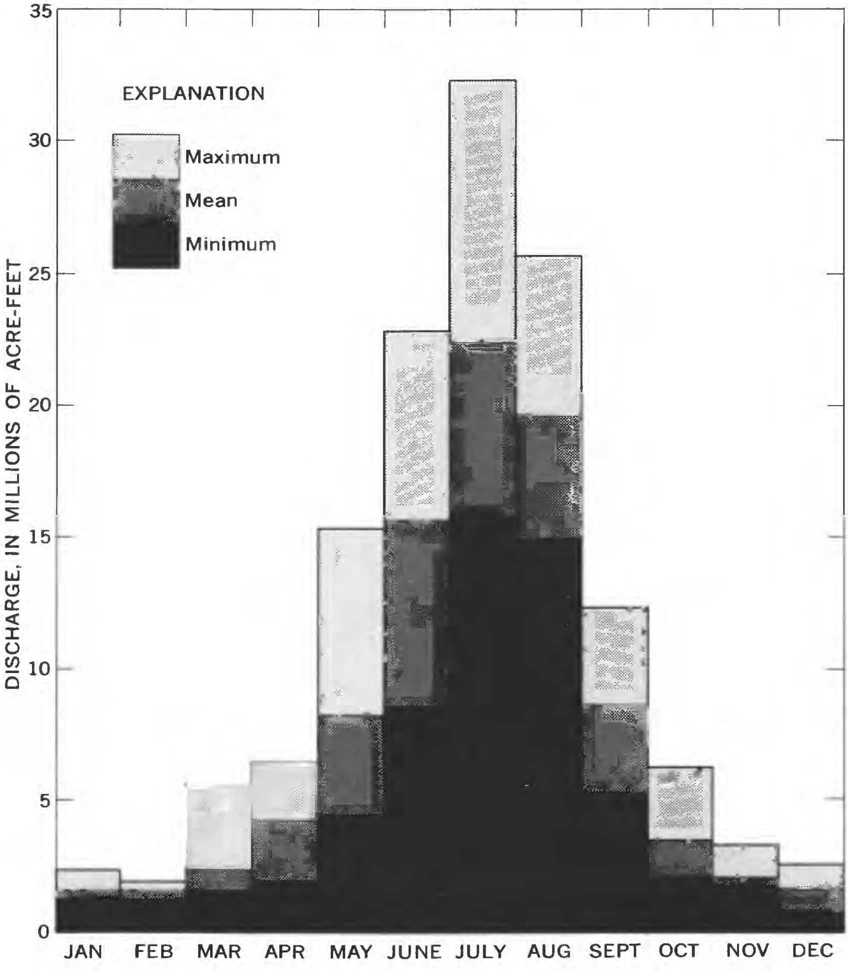

FIGURE 2.—Maximum, mean, and minimum discharge of the Indus River at Attock.

The mean annual flows for a base period 1962–68 were 123,500 ft^3/s (cubic feet per second) or 89.4 million acre-feet per year for the Indus River at Attock (Mandori), 30,600 ft^3/s for the Jhelum River above Mangla Dam, and 33,700 ft^3/s for the Chenāb River above Marāla Canal Headworks (Marāla Barrage). These flows are for stations near the northern rim of the *Indus Plain where diversions occur to canals of the irrigation system of the plain. Mean surface outflow from the Upper *Indus Plain in Indus River above Gudu Barrage was 86,000 ft^3/s and flow downstream from Ghulām Muhammed Barrage was 76,000 ft^3/s for the same base period.

TABLE 1.—*Mean annual discharge for selected streamflow stations in Indus River Basin for period 1962–68*

River and station	Millions of acre feet per year
Indus River near Darband	60.3
Kābul River at Warsak	18.2
Swāt River at Chakdara	4.52
Kābul River at Nowshera	25.0
Indus River at—	
Mandori	89.4
Above Jinnah Barrage (Kalabagh Barrage)	88.75
Below Jinnah Barrage (Kalabagh Barrage)	84.30
Above Taunsa Barrage	82.12
Below Taunsa Barrage	77.49
Chenāb River—	
Above Marāla Canal Headworks (Marāla Barrage)	24.38
Below Marāla Canal Headworks	13.98
At Alexandra Bridge	15.0
Above *Khanki Barrage	19.44
Below *Khanki Barrage	10.84
Above Trimmu Headworks	26.14
Below Trimmu Headworks	20.78
Kunhār River near Garhi Habībullāh Khān	2.79
Rāri River—	
Above *Balloki Barrage	11.11
Below *Balloki Barrage	2.83
Above Sidhnāi Canal Headworks (Sidhnai Barrage)	6.26
Below Sidhnāi Canal Headworks (Sidhnai Barrage)	2.01
Sutlej River—	
Above Sulaimānke Barrage	15.94
Below Sulaimānke Barrage	7.89
Above Islam Headworks (Islam Barrage)	6.88
Below Islam Headworks (Islam Barrage)	5.40
Panjnad River	
Above Panjnad Barrage	25.64
Below Panjnad Barrage	21.33
Indus River—	
Above Gudu Barrage	106.12
Below Gudu Barrage	97.21
Above Lloyd Barrage (Sukkur Barrage)	93.53
Below Lloyd Barrage (Sukkur Barrage)	69.82
Above Ghulām Muhammed Barrage	62.48
Below Ghulām Muhammed Barrage	55.03

TABLE 2.—*Dissolved-solids content of surface waters of Upper Indus River system, in milligrams per litre*[1]

River and station	Maximum (mg/1)	Minimum (mg/1)	Year of observation
Indus near Darband	217	94	1965–68
Swāt at Chakdara	150	56	1965–68
Kābul at Nowshera	416	112	1965–68
Jhelum at Mangla	250	88	1965–68
Chenāb at Alexandra Bridge	300	84	1965–68
Kunhār near Garhi Habībullāh Khān	230	84	1965–68
Sutlej at Sulaimānke Headworks	340	100	1960–63

[1] Based on A. G. Chaudhry, (1972) Chemical quality of water of West Pakistan rivers: West Pakistan Water and Power Devel. Authority, Water and Soils Inv. Div. Publ. 121.

TABLE 3.—*Mean annual suspended sediment yield for selected streamflow stations in Indus River Basin for the period 1962–68* [1]

River and station	Thousands of acre feet per year
Indus River near Darband	199
Kābul River at Warsak	15
Swāt River at Chakdara	1.08
Kābul River at Nowshera	29.2
Indus River at Mandori	226
Chenāb River at Alexandra Bridge	31.5
Kunhār River near Garhi Habībullāh Khān	4.00

[1] Based on West Pakistan Water and Power Development Authority, 1970, Sediment appraisal of West Pakistan Rivers, 1960–68, Surface Water Hydrology Project: West Pakistan Water and Power Development Authority, Water and Soils Investigation Division, Lahore.

Prediction of runoff during the high-flow season at the rim stations is critical to the operation of the irrigation canal system. Pilot field studies in a small drainage basin show that it is feasible to use snow surveys for prediction of snowmelt runoff in Pakistan. Areas of the snowpack critical to these determinations, however, lie in Indian territory.

Development of the modern irrigation system in the Upper *Indus Plain began in 1859 with the opening of the Upper Bāri Doāb Canal, which diverts water from the Rāvi River. Continuing development added major canals in 1882 and 1887, in the 1890's and early 1900's, and in the 1920's and 1930's (table 4). Shortly after the subcontinent was partitioned in 1947 (Michel, 1967), India began to divert water from the three eastern rivers (Rāvi, Sutlej and Beās) upstream, endangering irrigated agriculture in Pakistan. Pakistan's immediate protest led to negotiations chaired by the International Bank for Reconstruction and Development (World Bank). These negotiations, begun in 1952 and ended in 1960, led to a solution satisfactory to both sides, with the signing of the Indus Waters Treaty, which sanctioned India's diversion of the waters of the three eastern rivers for its own use. In return, Pakistan received substantial foreign aid for building two large storage dams on the western rivers (Jhelum, Chenāb, Indus) to conserve the flood waters of the rainy season for irrigation when the rivers ran low. The treaty provided for a sophisticated series of new interriver link canals, which were constructed in the 1950's and 1960's, to feed water more effectively to the irrigation canal system developed by the British in the 19th century. The treaty also authorized six barrages to divert river water to the canals, and it provided for remodeling of some existing structures. Major irrigation works in the Lower Indus Plain were begun in 1932 with the opening of Lloyd Barrage (Sukkur Barrage) and its canals. Later Ghulām Muhammed (1955) and Gudu (1962) Barrages were added.

TABLE 4.—*Chronology of canals and associated headworks in operation in Indus River Basin as of June 30, 1972* [1]

River	Headworks or barrage	Canal	Year commissioned	Canal capacity (cubic feet per second)
Swāt	*Amandarra	Upper Swāt	1915	1,800
	Munda	Lower Swāt	1890	800
Kābul	Warsak Dam	Left bank	1962	45
		Right Bank	1962	455
		Kābul River [2]	1890	450
Jhelum	Mangla [3]	Upper Jhelum	1915	1,900
	Rasūl [4]	Lower Jhelum	1901	5,300
		Rasūl-Qādirābād Link (R.-Q. Link).	1968	19,000
Chenāb	Marāla [4]	Marāla-Rāvi Link [4] (M.-R. Link).	1956	2,000
		Upper Chenāb	1912	4,100
	(Upper Chenāb Canal).	*Bambānwāla-Rāvi-Bediān-Dīpālpur Link (B.-R.-B.-D. Link).	1958	22,000
	Khānki	Lower Chenāb	1862	11,500
	Qādirābād	Qādirābād-Balloki Link (Q.-B. Link).	1967	18,600
		Lower Chenāb Canal (Feeder) (L.-C.-C.-F.).	1967	4,100
	Trimmu	Rangpur	1939	2,700
		Haveli [5]	1939	11,000
		Trimmu-Sidhnāi Link (T.-S. Link).	1965	11,000
Rāvi	Mādhopur [6]	Central Bāri Doāb [7]	1859	2,600
	Balloki	Lower Bāri Doāb	1913	7,000
		Balloki-Sulaimānke Link I (B.-S. Link I).	1954	18,500
		Balloki-Sulaimānke Link II (B.-S. Link II).	1968	6,500
		Montgomery-Pākpattan Link (M.-P. Link).	1939	700
	Sidhnāi [8]	Sidhnāi	1887	4,500
		Sidhnāi-Mailsi Link (S.-M. Link).	1965	10,100
Sutlej	Ferozepore [6]	Dīpālpur	1928	6,100
		Bīkaner [6]	1928	--
		Eastern [6]	1928	--
	Sulaimānke	Pākpattan	1927	6,600
		Ford Wāh Branch	1927	3,400
		Eastern Sādiqia	1926	4,900
	Islam	Mailsi	1928	4,900
		Qāimpur	1927	600
		Bahāwal	1927	5,400
	Mailsi Syphon	Mailsi-Bahāwal Link (M.-B. Link).	1966	4,000
Panjnad	Panjnad	Panjnad	1929	9,000
		Abbāsia Feeder	1929	1,100

See footnotes at end of table.

TABLE 4.—*Chronology of canals and associated headworks in operation in Indus River Basin as of June 30, 1972* [1]—Continued

River	Headworks or barrage	Canal	Year commissioned	Canal capacity (cubic feet per second)
Indus	Jinnah [9]	Thal	1947	10,000
	*Chasma	Pahārpur [10]	1909	500
		Chasma-Jhelum Link (C.-J. Link).	1970	21,700
	Taunsa	Dera Ghazi Khān	1958	8,800
		Muzaffargarh	1958	7,300
		Taunsa-Panjnad Link (T.-P. Link).	1970	12,000
	Gudu	Pat Feeder	1962	8,300
		Frontier Rāj Wāh (Desert Canal).	1962	12,900
		Begāri-Sind	1962	15,500
		Ghotki	1962	8,500
	Lloyd Barrage (Sukkur Barrage).	Northwestern	1932	5,100
		Rice	1932	10,200
		Dādu	1932	3,200
		Khairpur West	1932	1,900
		Rohri	1932	11,200
		Khairpur East	1932	2,700
		Eastern Nāra	1932	13,400
	Ghulām Muhammed (Kotri).	Pīnyari	1955	14,400
		Fuleli	1955	13,800
		Lined Channel (Lined Canal).	1955	4,100
		Kalri-Baghar Feeder	1955	9,000

1 Based on Harza Engineering Co. International (1964), Michel (1967, p. 279, 282, 283), Tipton and Kalmbach (1967, v. 6), and other more recent data.
2 Predates Warsak Dam.
3 Mangla Dam replaced Mangla Barrage in 1967.
4 Remodelling completed in 1968.
5 Remodelling completed in 1967.
6 In India since 1947.
7 Called Upper Bāri Doāb Canal before allocation of waters to India.
8 Remodelling completed in 1966.
9 Also called Kalabagh.
10 Canal predates *Chasma Barrage (1970).

A principal source of recharge to the alluvial aquifer underlying the Punjab region and adjacent areas has been seepage losses from the rivers of the Indus River system and from irrigation canals. It is an oversimplification, however, that is too often stated that only losses occur in canals and rivers. Some reaches of these appear to gain flow during most of the year, other reaches appear to gain flow in parts of the year and lose in other parts and still others lose flow throughout most of the year. Some studies have been undertaken to define these gains and losses. A review of information derived from these studies, however, indicates that a fresh approach needs to be made to define the gains and losses more accurately. There are indications that changes in the hydrologic regimen during recent years have produced corresponding changes in the rates of gain and loss in the rivers of the Punjab region.

Gains and losses to flow in canals can occur depending on whether the level of the contiguous water table is higher or lower than the water level in the canal. The phenomenon of gain to canal flow has been generally neglected in past investigations. Most approaches to determining canal seepage losses have utilized oversimplified assumptions with respect to hydraulic conditions. These oversimplifications may lead to misunderstanding in the functioning of the irrigation system as it relates to operational allocation of the canal waters.

GROUND-WATER GEOLOGY

The *Indus Plain is underlain by a thick alluvial complex deposited by the ancestral Indus River and its tributaries in a subsiding tectonic depression lying between the Himalayas and contiguous mountain ranges and plateaus. The bulk of the alluvium consists chiefly of fine to medium sand, silt, and clay. Coarse sand and gravel, however, are not uncommon, particularly near the mountainous borders of the plain. Pebbles of siltstone and mudstone commonly are found in the silt and clay deposits. Irregularly shaped concretionary nodules (kankar) occur in certain zones of the fine sand and silt beds, formed by cementation of the alluvial particles with secondary calcium carbonate. The alluvial complex contains a vast regional aquifer which extends to a depth of several hundred feet or more throughout virtually all the *Indus plain.

The alluvial deposits occur chiefly in irregularly shaped tabular bodies of sand, interspersed with lenticular layers of silt and clay. The configuration of these beds is well illustrated in cross sections given in reports by Kidwai (1962) and Greenman, Swarzenski, and Bennett (1967). Generally, it is found that lenses of silt, clay, and silty sand compose about 25 to 35 percent of the entire bulk of the alluvial complex. These fine-grained deposits, of low permeability, generally are discontinuous so that beds of sand constituting the remaining 65 to 75 percent of the alluvium serve as a unified highly transmissive aquifer.

The maximum thickness of the alluvial complex is not known. Logs of test wells show that the alluvium is 600 feet or more thick nearly everywhere. Nevertheless, a suballuvial ridge (pl. 1) of ancient crystalline rocks trends southeastward across the Chaj and Rechna Doābs, starting near Sargodha and extending beneath *Kirana, Chiniot Sāngla (Sangla Hill), Shāh Kot, and Māngtānwāla. A number of isolated peaks on this ridge rise above the surface of the plain at *Kirana, Chiniot, Sāngla, and Shāh Kot.

The bedrock surface declines sharply to the northeast of the ridge as indicated by a test hole near Shekhūpura (Sheikhupura) which failed to reach bedrock at 1,498 feet. Southwestward the surface of the ridge slopes more gradually, as shown on plate 1. Near the southwest ends of Chaj and Rechna Doābs, test holes from 900 to 1,500 feet deep failed to reach bedrock. Cross sections of the ridge are shown in a report by Kidwai (1962).

This bedrock ridge extending across the doābs locally has some effect on movement on ground water, even at the relatively moderate depth reached by tubewells. This effect, however, is not considered to be regionally significant (Greenman and others, 1967, p. 20–21). The presence of high salinity ground-water zones also is, in part, related to the suballuvial ridge.

AQUIFER CHARACTERISTICS

Between 1954 and 1963, 164 aquifer tests were completed in the alluvial complex of the Punjab region by WASID and its predecessor organization (Bennett and others, 1967). A number of constraints prevented accurate evaluation of aquifer coefficients in a few tests, but most of the tests yielded useful data on lateral (or radial) hydraulic conductivity and specific yield, and a few tests gave values for vertical hydraulic conductivity.

Specific-yield (approximately the same as storage coefficient in unconfined aquifers) determinations ranged from 1 to 42 percent and averaged 14 percent. Reevaluation and later work suggest that because of slow drainage the average long-term specific yield for these test sites may have been closer to 16 percent. Specific-yield determinations in these tests were for the material unwatered at the water table, generally 10 to 25 feet below land surface. A report by Zahir-ud-Din and Sheikh (1969) shows that there is a considerably higher percentage of fine-grained material in the upper 25 feet, in comparison with the strata below a depth of 25 feet. Using average specific yield values for different grain size materials given by Johnson (1967) and multiplying by weighted average content of the different sizes in the upper 25 feet of material, gives an average specific yield of 17 percent. It is recommended that 17 percent be used in computing withdrawal of ground water from storage in SCARP water budgets.

The lateral hydraulic conductivity (K_r) in 141 tests reported by Bennett, Rehman, Sheikh, and Ali (1967) ranged from about 0.001 to 0.01 ft/s (foot per second). About 70 percent of the results were in the range 0.0012 to 0.0039. The average was 0.0032 ft/s. There was some variation between doābs, and average values for doābs were given as follows: Rechna 0.0038, Chaj, 0.0028, Thal 0.0033, and Bāri 0.0026. Coefficients of lateral permeability (lateral hydraulic conductivity) at each test site are shown in Bennett, Rehman, Sheikh, and Ali (1967, pl. 1). These determinations were based on analysis by steady-state equations, using observation wells within about 400 feet of the pumped well. These values are the averages for the entire screened section of the well.

As noted by Bennett, Rehman, Sheikh, and Ali (1967, p. 25, 55), the assumption that the flow between the well and 400 feet was horizontal and confined to the thickness of aquifer screened may have been in error and resulted in a calculated value higher than the true value. Later work with analog models (Mundorff and others, 1972) suggests that values presented in Bennett, Rehman, Sheikh, and Ali (1967) may have been 20 to 25 percent too high. For the aquifer sand of the Punjab region, an average value of 0.0025 is recommended for the lateral hydraulic conductivity. This value applies only to aquifer sand. Studies by Zahir-ud-Din and Sheikh (1969) showed that the strata between 25 feet and the bottom of the wells used in their analysis (ranging from 200 to 1,000 feet deep) included nearly 22 percent silt and clay and 5 percent very fine sand. The average K_r for the entire section of alluvium would then be about 0.0019 ft/s.

The transmissivity (T) is obtained by multiplying K_r by the thickness of strata involved in the flow. Where information is not available on the relative percentages of sand and silt or clay, then the entire thickness would be multiplied by the K_r value of 0.0019 ft/s. However, where sand percentages are known, $T = K_r \times$ sand thickness, using 0.0025 for K_r. In the immediate vicinity of a pumped well, the flow thickness is equal to screen length. For general movement of water, the entire aquifer thickness is involved. The lower limit of active circulation of fresh ground water, however, is commonly marked by a zone of diffusion between fresh and saline water rather than by the contact of the alluvial deposits with underlying bedrock.

Vertical hydraulic conductivities (K_z) were determined by Bennett, Rehman, Sheikh, and Ali (1967) at 14 sites. The values ranged from 0.00001 to 0.00042. A few other values for K_z were determined by Bhatti (1972), at an aquifer test site near Chūhar-Kāna. The average K_z for that site was about 0.000048. Anisotropy ratios (K_r:K_z) at all 15 sites ranged from 3.3:1 to 195:1. Eliminating the 3 highest and 2 lowest values, the remaining 70 percent ranged from 15:1 to 90:1 and averaged about 55:1.

Hunting Technical Services and Sir Murdock MacDonald and Partners (1965) determined K_z in a number of tests in the Lower *Indus Plain. Values for K_z generally ranged from about 0.000001 to about 0.0001 and averaged about 0.00003–0.00004. Anisotropy ratios (K_r:K_z) for different areas ranged from 30:1 to 40:1.

CHEMICAL QUALITY OF WATER

The chemical quality of the surface waters of the Indus River system has been described in considerable detail in Chaudhry (1972). In his report he points out that the waters of the main-stem Indus and its major tributaries rising in the Hindu Kush and the Himalayas and draining through the *Indus Plain are dominantly of calcium magnesium bicarbonate type. These streams carry solute loads averaging about 150 to 180 mg/l of dissolved solids and range seasonally from about 56 to 416 mg/1 (table 2). Waters of minor tributaries rising in the Sulaimān and Kīrthar Ranges to the west of the Indus Plain are dominantly of sodium and magnesium sulphate type with dissolved-solids concentrations ranging seasonally from 150 to 2,500 mg/l.

Greenman, Swarzenski, and Bennett (1967, p. H29–38) have described in detail the chemical quality of the native ground water of the Punjab region (pl. 1). Swarzenski (1968) delineates the fresh and saline ground-water zones of the region, both areally and at depth, from a base of about 2,600 complete chemical analyses of water samples taken from about 800 test holes drilled between 1955 and 1962. As pointed out by Swarzenski, fresh ground water containing generally less than 500 mg/l dissolved solids is found in wide belts paralleling the major rivers and in other areas of ground-water recharge. The fresh ground-water zone of Upper (northeastern) Rechna Doāb, where annual precipitation in places exceeds 30 inches, is the most extensive of the Punjab region and attains a depth of 1,700 feet or more below land surface near Gujrānwāla. Fresh ground water adjacent to the Indus River extends locally to depths of about 1,500 feet.

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

The ground waters from more than 800 sampling sites in the Punjab region were classified into 8 geochemical types, according to dominant cations and anions. These types were further subdivided into groups containing different amounts of dissolved solids. The ground waters of the region are characterized by a gradation from the calcium magnesium bicarbonate type in the freshest water (less than 500 mg/l dissolved solids), near the sources of recharge, to waters containing a dominant proportion of sodium. Water containing from 500 to 1,000 mg/l dissolved solids is commonly of the sodium bicarbonate type, or it may be of the mixed type, having about equal proportions of the common anions (bicarbonate, chloride, and sulfate). With increasing mineralization from about 1,000 to 3,000 mg/1, the relative proportion of chloride and sulfate increases, and these waters are generally of the sodium chloride or sodium sulfate type. The highly mineralized ground waters (4,000 to 20,000 mg/l dissolved solids) of the Punjab region are generally of the sodium chloride type, but in areas west of the *Indus Plain, sodium sulfate waters predominate.

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

HYDROLOGIC REGIMEN BEFORE CANAL IRRIGATION

Prior to the advent of perennial canal irrigation, the hydrologic regimen of the Punjab region was in a state of dynamic equilibrium, as shown in Greenman, Swarzenski, and Bennett (1967, pl. 8). Each of the doābs (Thal, Chaj, Rechna, and Bāri) functioned essentially as an independent hydrologic unit. Rechna Doāb, moreover, is a reasonably typical example of the behavior of the others and in the following discussion is referred to in that context.

In the northeastern part of Rechna Doāb the water-level contours in preirrigation time extended nearly straight across the doāb from the Chenāb to the Rāvi. These contours indicate that recharge was derived from direct percolation of rainfall and torrential runoff from the foothills. There may even have been a small ground-water discharge to the rivers in this reach. The chief movement of ground water, however, was down-doāb with a gradient of about 2 ft/mi.

Farther down gradient in Rechna Doāb, in the vicinity of Gujrānwāla, the water-table contours began to show a slight down-doāb concavity; this concavity became quite prominent at Shāh Kot and Sāngla and very pronounced southeast of Lyallpur. Throughout this reach, from Gujrānwāla to the lower end of the doāb, the Chenāb and Rāvi served as line sources of recharge to the aquifer. Ground water flowing essentially at right angles to the contours moved on a curve towards to the center of the doāb. Down-doāb, the gradient became increasingly flatter, until near Shorkot Road (Shorkot), the gradient was less than 0.75 ft/mi. Concurrently, there was a thinning of the vertical thickness of flow along the flow path together with an upward trend of the salt-water fresh-water interface or zones of diffusion at the top of deeper static brine. With aquifer test data showing that the hydraulic conductivity and transmissivity do not increase in a down-doāb direction, simple flow net analysis demonstrates that most of the water recharged from the river was discharged before reaching the center of the doāb. The amount of ground water discharging from the lower end of Rechna Doāb into the bounding rivers above their confluence was apparently insignificant. In fact, Greenman, Swarzenski, and Bennett (1967, p. 24) suggest that there may have been a reverse gradient near the lower end of Rechna Doāb; that is, the water table reached its lowest elevation some miles upstream from the confluence of the bounding rivers. Thus, there would have been no down-doāb escape of ground water in preirrigation time.

Depth-to-water contours for preirrigation time (Greenman and others, 1967, pl. 8) indicate increasing depth-to-water toward the center of Rechna Doāb, reaching 100 feet between Shāh Kot and Lyallpur. It is obvious, then, that the only mechanism for discharge of ground water within the doāb was evapotranspiration. Rough calculations suggest that evapotranspiration losses may have ranged from 2 or 3 feet of water per year in the flood plains adjacent to the rivers, to less than 0.1 foot per year near the center of the doāb where the water table was originally 80 to 100 feet below the land surface. Ground water was discharged progressively as it moved towards the center and down the axis of the doāb, until along the central line of flow there was virtually no water left to move down-doāb. A ground-water flow system of this nature would result in the residual water becoming progressively more saline towards the center of and down the axis of Rechna Doāb, as is demonstrated to be the case in Greenman, Swarzenski, and Bennett (1967, pl. 9). Although this map depicts the position of the saline zones as found by test drilling in the late 1950's and early 1960's, consideration of the hydrologic factors involved leads to the conclusion that the position of these saline zones has been virtually unchanged since preirrigation time, except for an upward migration in some areas of as much as 80 or 90 feet.

CHANGES IN HYDROLOGIC REGIMEN INDUCED BY CANAL IRRIGATION

In the last half of the 19th century the natural balance between recharge, ground-water movement, and discharge, which had resulted in the stable hydrologic regimen in the Punjab region previously described, was upset by construction of barrages and diversion works on the rivers and of perennial canals crossing the doābs. The barrages created pools holding the water at higher levels than formerly, and seepage from the unlined canals greatly increased recharge, especially in the interior parts of the doābs, where the depth to water had been greatest. This resulted in a progressive rise in the water table which was recorded in numerous observation wells. The qualitative and quantitative changes are well documented in various reports by WASID and are summarized by Greenman, Swarzenski, and Bennett (1967).

Recharge to ground water continued to exceed discharge until the 1940's or 1950's. As the water table approached the land surface, increased evapotranspiration began to bring the hydrologic regimen into equilibrium again. The rise of the water table, ultimately to only a few feet below land surface or even above land surface in numerous water-table ponds, induced waterlogging and increased soil salination that seriously reduced agricultural productivity in the Punjab region. By the 1950's it was estimated that nearly 3 million acres of cultivated land in the Punjab region had been damaged by waterlogging and salination, equivalent to about 12.5 percent of the cultivated land (White House-Department of the Interior Panel Report, 1964, tables 1–12). According to this report, severe waterlogging and salinity damage to cultivated land of the *Indus Plain was then increasing at a rate of 50,000 to 100,000 acres per year.

SALINITY CONTROL AND RECLAMATION PROJECTS

RÉSUMÉ OF RECLAMATION PROGRAM

Basing their recommendations on the results of the investigations by WASID, West Pakistan Water and Power Development Authority (1959) proposed a project for reclamation of 1.2 million acres in Rechna Doāb to be known as Salinity Control and Reclamation Project I (SCARP–I). Two years later a broader program of SCARPs for the *Indus Plain was proposed (West Pakistan Water and Power Development Authority, 1961).

Briefly, the program proposed construction of moderate to large capacity tubewells (2 to 5 ft^3/s) that would furnish about 1 ft^3/s for each 150 acres. The ground water, together with the previously allocated canal supply, would provide sufficient water for intensified irrigation and leaching of salts from the soil. Moreover, large-scale pumping would lower the water table so that leaching would be effective. Somewhat later the White House-Department of the Interior Panel on Waterlogging and Salinity in West Pakistan (1964) recommended that each SCARP should be on the order of 1 million acres in size for optimum effectiveness. The Panel also recommended additional inputs such as improved seeds, greatly increased use of fertilizer, better pest and disease control, improved cultivation and land management practices, and improved marketing facilities.

Actual construction on SCARP–I began in 1961, although four antecedent operating schemes, Chūharkāna, 1954; Jarānwāla, 1957; Pindi Bhattiān, 1958; and Chīchoki Malliān, 1960 were subsequently incorporated in the SCARP. The general features of SCARP–I and subsequent SCARPs are summarized in table 5. Tubewells put down by public agencies in the SCARPs generally range from 200 to 400 feet deep, although a few have been drilled to depths of 500 feet. The boreholes generally are 22 inches in diameter with casing and screen chiefly of mild steel or fiberglass but also some of brass or stainless steel. Gravel is generally placed around an 8- or 10-inch slotted pipe (screen). The common design calls for 100 feet of screen for a 2 ft^3/s well, and about 40 feet of screen per cubic foot per second for larger discharges. Average discharge ranges from about 2.6 ft^3/s in the Khairpur SCARP to about 4 ft^3/s in SCARP-III (Lower Thal Doāb). Specific capacities on acceptance generally range between 80 and 120 (gal/min)/ft (gallons per minute per foot) of drawdown.

SCARP–I lies in central Rechna Doāb between the Chenāb and Rāvi Rivers. The gross area is about 1.2 million acres and the culturable area is about 1 million acres. As of June 30, 1972, 2,068 public tubewells had been installed in the SCARP. Nearly 1,600 tubewells were constructed with mild-steel screens and about 400 with brass screens. Several schemes included in SCARP–I were operational in 1961, and all 12 schemes in the SCARP were in operation by July 1962.

TABLE 5.—*Salinity Control and Reclamation Projects in operation as of June 30, 1972*

Project	Year Commissioned	Area		Authorized canal supply (ft^3/s)	No. of public tubewells constructed [1]	Pumping capacity installed (ft^3/s)
		Gross (acres)	Culturable (acres)			
SCARP–I	1961	1,215,000	1,060,000	2,400	2,068	6,352
SCARP–II [2]	1963	1,896,000			2,207	
SCARP–III [3]	1965	1,280,000	1,050,000		1,635	
SCARP–IV [4]	1969	526,000			935	3,714
Khairpur SCARP	1967	410,000	365,000		540	1,417
Rohri North Scheme [5]	1971	790,000			566	
Total		6,117,000			7,951	

[1] Total number of public tubewells installed as of June 30, 1972.
[2] Does not include Shāhpur Scheme which has not been constructed. Includes Shāh Jiwana and Ara Schemes which have been constructed but not electrified.
[3] Pumping began in the Alīpur Scheme in 1967, but only about 40 percent of the Kot Addu and 15 percent of the Rangpur Schemes were electrified as of June 30, 1972.
[4] Māngtānwāla and Murīdke Schemes.
[5] Not electrified as of June 30, 1972.

SCARP–II is in Upper Chaj Doāb between the Chenāb and Jhelum Rivers. The gross area is about 2.0 million acres (including about 100,000 acres in the Shāhpur Scheme where construction has not yet begun). Construction of SCARP–II began in 1963 and all but 1 of the 11 schemes were completed as of June 30, 1972. More than 600 wells, however, were unused as of that date, because of lack of electrification. Of the 2,207 public tubewells drilled in this SCARP, 487 have mild-steel screens, one has a wooden screen, and the remainder have fiberglass screens. Operations began in various schemes in SCARP–II, as follows: Lāliān, 1963; Mona, 1964; Khādir, 1967; Upper Jhelum subproject or SCARP–IIA (Phālia, Sohāwa, Busāl and Lower Hujjan Schemes), 1968; and Kot Muman, 1970. The Shāh Jiwana and Ara Schemes do not yet (1972) have electricity and are not operational.

SCARP–III includes three schemes in Lower Thal Doāb between the Indus and Panjnad-Chenāb Rivers. The gross area is about 1.28 million acres and culturable area is about 1.05 million acres. Construction began in December 1965 and was completed in 1969. All 1,635 public tubewells were completed with fiberglass screens. Delay in electrification prevented start of pumping until February 1969, when pumping began in some wells in the Alīpur Scheme. As of June 30, 1972, all 542 wells in the Alīpur Scheme, 201 wells in the Kot Addu Scheme, and 75 wells in the Rangpur Scheme had been electrified and were in operation.

SCARP–IV originally planned to include most of Upper Rechna Doāb, was reduced to two schemes in part because of a large antecedent increase in private tubewell development in the area. The Māngtānwāla and Murīdke Schemes lie along the northwest bank of the Rāvi River between the river and SCARP–I and close to the Marāla-Rāvi Link Canal. The gross area of the schemes is 526,000 acres, and 935 public wells with a design capacity of 3,714 ft^3/s have been constructed, all with fiberglass screens. All 311 wells in the Māngtānwāla Scheme were in operation as of July 1969, but as of June 30, 1972, only 245 of the 624 wells in the Murīdke Scheme had been electrified.

Khairpur SCARP extends downstream from the Lloyd Barrage (Sukkur Barrage) along the east bank of the Indus River, and this is the first and only SCARP thus far commissioned in the Lower *Indus Plain. The gross area is 410,000 acres, of which 365,000 acres is culturable commanded area. Of the 540 public wells installed, 175 are in the fresh-water zone, and 365 are in the salt-water zones. The 540 tubewells include 122 with stainless-steel screens and 418 with fiberglass screens. Tubewells in the Khairpur SCARP were put in operation progressively between June 1967 and January 1970.

EFFECTS OF RECLAMATION

It was anticipated that after the SCARPs became operational a number of changes would occur in the hydrologic regimen as well as in the agroeconomic realm. It was hoped that most of these changes would be beneficial. These included: provision of water for intensification of irrigated agriculture, reduction of evapotranspiration losses by lowering of the water table and elimination of waterlogging, leaching and improvement of salinized soils, better land utilization, and, ultimately, increased production of crops. Some of these changes, particularly as related to hydrology and soils, are examined in the following sections. The changes include not only those that were planned, but also some that occurred as incidental effects.

WATER SUPPLY

One of the chief objectives of the SCARP program was to provide additional water for intensification of irrigated agriculture and a sufficient surplus so that water would be available for leaching salinized soils. For the most part, this objective has been met. From the discussion of SCARPs I and II, which follows, it is apparent, however, that the available ground-water supply has not always been used to best advantage, and that not as much water has been used for leaching as has been available nor as has been needed.

SCARP–I.—The operating agencies in the SCARP program have considered 22 hours per day, 365 days per year to constitute 100 percent utilization of a tubewell. On this basis, annual utilization of tubewells in SCARP–I generally has ranged from 60 to 70 percent. Monthly or daily ranges, of course, have been much greater. Reasons for nonutilization include power outages, mechanical failures, no demand, and lack of distribution system. An example of tubewell utilization in SCARP–I is given below for the period October 1, 1963, to September 30, 1964:

	Percentage of total time	
	October 1, 1963– March 31, 1964	April 1, 1964– September 30, 1964
Power outages	2.8	4.9
Mechanical failures	3.9	4.9
No demand	25.0	8.3
Lack of distribution system	8.4	7.2
Total unused capacity	40.1	25.3
Total used capacity	59.9	74.7

The total installed capacity of SCARP–I tubewells was about 4.5 maf/y (million acre-feet per year) at time of commissioning in 1961. Because of well-yield deterioration, this capacity had decreased to about 2.9 maf/y by 1971, in spite of an intensive program of well rehabilitation and replacement of about 108 tubewells. Pumpage in SCARP–I from public tubewells has ranged from a high of 2.76 maf/y in 1962–63 to a low of 1.55 maf/y in 1966–67. Total pumpage during the 9 years of full operation, 1962–71, was about 19.4 maf. For comparison, gross canal diversion to SCARP–I during the same period was 16.3 maf. Assuming a loss of 33 percent between the canal head and the field watercourse, the net available canal supply would have been 11.0 maf or about 57 percent of the tubewell pumpage.

SCARP–II.—Because start of operations in the various schemes covered a long span of time, it is not possible to give a consolidated account of ground-water utilization in SCARP–II. Utilization in the individual schemes of SCARP–II, however, is described in following paragraphs.

In Lāliān Scheme the total pumping capacity was 0.49 maf/y at time of commission in 1963. This capacity had declined by 14 percent to 0.42 maf/y in 1969–70. Average utilization during the period 1963–70 was 43 percent, and the annual range in utilization was 30 to 72 percent of installed capacity. Total pumpage for the 8-year period was about 1.6 maf. The gross canal diversion to the

Lāliān Scheme for 1969–70 and 1970–71 and was 0.18 maf each year, about 11 percent more than tubewell pumpage. The net amount of canal water delivered to field watercourses, however, probably was less than tubewell pumpage.

In the Mona Scheme the installed capacity in 1965 was 0.33 maf/y, which had declined 10 percent to 0.30 maf/y in 1970 (Rehman, 1961, p. 22). Average annual utilization of capacity has ranged from 39 percent in 1966–67 to 70 percent in 1969–70. Pumpage from project wells has ranged from 0.088 maf in 1965–66 (not full operation) to 0.204 maf in 1969–70. Total pumpage in the period 1965–71 (6 years) was about 0.93 maf. Total canal diversion to the Mona Scheme during that period was 0.95 maf. Ground water pumped during the past 3 years of operation, however, has exceeded gross canal diversion by nearly 20 percent.

In the Khādir Scheme the installed tubewell capacity at time of acceptance tests in 1966 was 0.71 maf/y. This had declined about 6 percent, to 0.67 maf/y in 1969–70. Total ground-water withdrawal during the period, 1967–71, was 0.90 maf. The average withdrawal for 4 years of full operation was 0.22 maf/y. Utilization of capacity ranged from about 35 to 40 percent. Ground-water withdrawal for the 2-year period, 1969–71, was 0.50 maf as compared to 0.32 maf gross canal diversion for the same period.

In Upper Jhelum subproject (Phālia, Sohāwa, and Busāl Schemes) the initial installed tubewell capacity (1968) was 3.04 maf/y. The capacity had declined about 18 percent to 2.49 maf/y in 1970–71. Ground-water withdrawals totaled about 1.87 maf during the 2-year period 1969–71. Utilization of capacity was 34 percent in 1969–70 and 46 percent in 1970–71. Gross canal diversion for the same period was about 1.9 maf.

In Lower Hujjan Scheme the tubewell capacity at time of acceptance tests in 1968 was 0.158 maf/y. By 1969–70 the capacity had declined to 0.128 maf/y, a reduction of 19 percent. Utilization of capacity was about 30 to 35 percent from 1969–71. Total ground-water withdrawal was 0.078 maf for the 2-year period 1969–71, as compared to gross canal diversions of about 0.074 maf for the same period.

WATER LEVELS

The Punjab Irrigation Department with the beginning of irrigation in 19th century and CMO of WASID since the beginning of the SCARP program, have maintained a comprehensive network of observation points for determining changes in ground-water levels. The network includes open wells and observation pipes. At present (1972), WASID has about 1,350 measuring points in its water-level network in Thal, Bāri, Chaj, and Rechna Doābs, including about 50 wells with continuous water-stage recorders. Based on measurements in these wells, and in production wells while they are idle, the CMO has prepared water-level change and depth-to-water maps annually for most SCARP areas during the past decade. General opinions among WASID, WAPDA, and the Punjab Irrigation Department hydrologists and engineers indicate that there no longer is a waterlogging problem in the SCARP areas. Water-level trends in SCARPs I, II, and III are briefly described in the following paragraphs.

SCARP–I.—The water table had been lowered by an average of 10.7 feet as of June 1971 since the initiation in 1961–62 of pumping for reclamation in SCARP–I. The depth-to-water map for June 1971 shows that the water table lay within 10 feet of the land surface in less than 40,000 acres (about 3 percent of the SCARP area). Nowhere, except possibly in narrow strips along the Qādirābād-Balloki Link was the water table within 5 feet of the land surface in June 1971. Temporarily, however, after the monsoon rains, the position of the water generally is 1 to 3 feet higher.

SCARP–II.—As of June 1971, the water table had been lowered about 2 to 5 feet since beginning in 1963 of reclamation in this SCARP. The greatest decline has occurred in those schemes where pumping started first (1963). The water table, however, was at depths greater than 5 feet below land surface in all but about 1 percent of SCARP–II in June 1971. The water table was more than 10 feet below land surface in about 70 percent of the SCARP where pumping of SCARP tubewells had begun in 1963–65.

SCARP–III.—From June 1969 to June 1971, the water table was lowered about 1.85 feet by pumping in Rangpur Scheme, 2.8 feet in Kot Addu Scheme, and 5.7 feet in Alīpur Scheme, all in SCARP–III. The smaller declines in Kot Addu and Rangpur Schemes can be attributed to the fact that they lie in long narrow strips adjacent, respectively, to the Indus and the Chenāb-Panjnad Rivers. Data on the depth to the water have been obtained through June 1972 for all of SCARP–III but were not at hand for the present evaluation. As of June 1969, however, the water table was within 5 feet of the land surface in about 40 percent of SCARP–III. Undoubtedly, the water-table lowering from pumping since June 1969 has greatly reduced this area.

WATER QUALITY

During the late 1950's and early 1960's, WASID and its predecessor agencies initiated a basic water-quality sampling program directed toward obtaining systematic areal coverage of the chemical quality of water in the alluvial aquifer of the entire Punjab region and also in the streams of the Indus River system. During this time about 120,000 shallow dug or driven wells were inventoried, and the electrical conductivity and pH of the well waters were measured. In addition, complete chemical analyses of a large number of samples were made in the Quality of Water Laboratory of WASID. The quality of the shallow ground water—that is, the water in the zone between the water table and a depth of 20 to 100 feet below the water table—has been described for Rechna Doāb by Shamsi and Hamid (1960), and for Chaj Doāb by Gilani and Hamid (1960). Other comparable WASID reports have been prepared for Thal and Bāri Doābs and the Bahāwalpur area. Somewhat later Greenman, Swarzenski, and Bennett (1967) described areally the chemical quality of the native ground water of the Punjab region based on about 2,600 complete chemical analyses of water samples taken from some 800 test holes drilled between 1955 and 1962. This work was followed by a more detailed evaluation and delineation of the fresh and saline ground-water zones of the region by Swarzenski (1968).

Since initiation of the SCARP program in 1961–62, WASID has undertaken water-quality monitoring of the Punjab aquifer to evaluate the effects (1) of reclamation leaching of salinized soils and (2) of pumping withdrawals for water-table control and supplemental water supply. To date (1972) WASID has concentrated its change-with-time water-quality evaluations in SCARP–I and in the Mona Scheme of SCARP II, commissioned in 1961 and 1964, respectively.

SCARP–I.—Three recent WASID reports (Malmberg and others, 1968; Shamsi and Abdullah, 1970; and Abdullah, 1972) have evaluated water-quality changes in SCARP–I. In all cases these evaluations compare two or more time increments and were based on data for relatively deep public tubewells with screens set several tens of feet or more below the water table. Observed water-quality changes in these wells, thus, may not reflect the changes in water quality of the shallow ground-water zone that could result from reclamation leaching. Malmberg, Khan, and Abdullah (1968, p. 52), however, emphasized the need for water-quality monitoring of the shallow ground water from dug and driven wells or shallow tubewells screened 10 to 30 feet below the water table.

Malmberg, Khan, and Abdullah (1968) compared water-quality changes in SCARP–I as of 1960–62 versus 1967. They concluded that pumping during this 6-year interval had caused widespread changes in the chemical quality of the ground water by changing the rate and direction of flow, inducing infiltration from canals, and mixing indigenous waters of different chemical quality. Most of the observed water-quality changes, however, were quantitatively small. Near canals, total dissolved solids and the sodium absorption ratio (*SAR*) of most of the ground water had changed little since pumping began. On the other hand, waters in many wells remote from canals and the southwestern part of SCARP–I had increased in dissolved solids, electrical conductivity, and in sodium ion concentration. As of the end of 1967 there was no substantial evidence that recycling of irrigation water had affected the chemical quality of the water pumped from project tubewells.

Shamsi and Abdullah (1970) compared water-quality changes for 1967 versus 1968. They concluded, however, that the 2-year interval was too short for assessment of long-term trends in ground-water quality. Abdullah (1972) made a more comprehensive study and compared 1963 data versus 1969–70 data using computer analysis and a base of 1,079 SCARP tubewells for his study. The findings of this study are summarized below:

	1963	1969–70
Number of wells yielding water of quality usable without dilution [1]	337	301
Number of wells yielding water of marginal quality requiring 1:1 dilution with high-quality canal water [2]	406	432
Number of wells yielding water of hazardous quality requiring greater canal-water dilution and also chemical soil amendments [3]	336	346
Total	1,079	1,079

[1] Waters in this category fall generally in classes 1 and 2 of the standards of the U.S. Salinity Laboratory (1954).
[2] Waters in classes 3 and 4.
[3] Water in class 5.

As indicated in the foregoing summary, 11 percent of the SCARP well waters of usable quality in 1963 had deteriorated to waters of poorer quality by 1969–70. During the same period wells yielding waters of marginal quality had increased by 6 percent and wells yielding waters of hazardous quality had increased by 3 percent.

Mona Scheme.—Two WASID reports have evaluated water-quality changes in 138 SCARP wells in the Mona Scheme of

SCARP–II, which has now (1972) functioned for several years as a type-area research project. All these wells have screens set at depths of 80 to 260 feet below land surface or several tens of feet below the water table. Shamsi and Khan (1968) compared water quality for 1965 versus 1967. Quality data for four time increments (1964, 1966, 1968, and 1970) were evaluated by Shah and Seaber (1971). They identified eight geochemical types of water in the 138 SCARP wells of the Mona Scheme and evaluated changes with time for the four time increments as shown in the following summary:

Geochemical type of water	Number of tubewells producing each type of water			
	1964	1966	1968	1970
Calcium bicarbonate	14	21	7	5
Magnesium bicarbonate	39	18	24	17
Sodium bicarbonate	62	80	87	94
Magnesium sulphate	1	--	--	--
Sodium sulphate	9	5	7	6
Calcium chloride	1	1	1	1
Magnesium chloride	2	--	2	--
Sodium chloride	10	13	10	15
Total	138	138	138	138

As noted in the foregoing summary, waters of magnesium sulphate, calcium chloride and magnesium chloride types are not significantly present in the Mona Scheme. Pumping, however, has induced a marked reduction in the volume of calcium and magnesium bicarbonate type waters since 1964, whereas in the same period it has induced an increase in the volume of sodium bicarbonate type water. The number of tubewells yielding sodium chloride type waters has also increased somewhat during the same period. As the freshest (less than 500 mg/l dissolved solids) ground waters of the Punjab region are commonly of calcium and magnesium bicarbonate type, it might be inferred from these changes in chemical type that pumping is bringing about a replacement of these waters by sodium bicarbonate or mixed type (bicarbonate, sulphate, and chloride) water. Shah and Seaber (1971) point out, however, that the dissolved solids of most of the well waters or their usability for irrigation did not change significantly during the period of observation. They attribute the decrease in calcium and magnesium and the increase in sodium to a combination of leaching of salts from the land surface, precipitation of calcium carbonate, ion exchange, decline of the water table, and lateral or vertical inflow of sodium-rich ground water.

Historical data for both the Mona Scheme (SCARP–II) and for all the schemes in SCARP–I need to be analyzed in greater detail, in order to evaluate more quantitatively areal variability and any changes in overall water quality or in chemical composition over time. Deficiencies of historical data need to be minimized in future data-collection programs, where the objectives of the information to be obtained are clearly defined. More emphasis should be given to increasing sampling frequency in time with some reduction in the density of tubewell sampling network. Where several water-quality variables can be correlated with an index variable, such as specific conductance, regression analysis of the historical data should be carried out. When regression equations can supply information with special levels of accuracy, continued laboratory analyses of variables can undoubtedly be reduced. Several points in a time series representing equivalent satistical-sampling basis (generally annual or seasonal means) must be available before proper detection and assessment of long-term trends in quality can be made. In addition, the effects of variable hydrologic conditions (wet year, dry year, or seasonal effects) must be accounted for before an absolute trend over and above that covered by variable hydrology can be determined.

SOIL SALINITY

Monitoring of soil salinity in SCARP–I began with soils surveys conducted during 1955–56. These surveys indicated that about 33 percent of the 1.2 million-acre area of SCARP–I was affected at that time by salinity problems, as evidenced in the salinity of surface soils. Chemical analyses of 1,944 auger-hole (6 feet deep) samples collected during these same surveys indicated about 63 percent of area to be affected by salinity. In these surveys, four samples were taken in the 6-foot interval of each auger hole. If any one of the samples indicated salinity, the entire 6-foot interval was considered as having a salinity problem. The difference, that is, 33 percent versus 63 percent, is a result of the differences in criteria used to judge the severity of the salinity problem. Probably neither the evidence of surficial salt accumulation or damaged crops, nor the evidence based on analyses of the soil profiles can be considered entirely adequate.

Specific monitoring studies were initiated by WASID in 1961 to determine soil salinity conditions by chemical tests of soils samples from 390 sites distributed throughout SCARP–I. These sites were selected to sample normal soils and saline or alkaline soils on which five different classes of tubewell irrigation water were applied from 1961 through 1967. The qualities of the applied waters ranged from very good (class 1) to very hazardous (class 5) as classified by U.S. Salinity Laboratory Staff standards (1954). A summary of the tests from 302 of the sites is given in table 6. Generally, there appears to be less improvement of soil salinity through leaching with poorer quality of applied waters. Decreases in soil salinity occurred at some places, however, even where poor-quality water was applied. In some instances part of the change may be attributed to application of high-quality canal water together with the poor-quality tubewell water. At 50 of these sampling sites, later tests in 1969 generally suggested the same trends in improvement of the soil salinity conditions as those indicated in table 6.

TABLE 6.—*Trends in improvement of soil salinity conditions in SCARP–I between 1961 and 1967*

Quality of applied tubewell water				Normal soils		Saline or alkaline soils	
Class [1]	Range in specific conductance (micromhos per centimetre at 25°C)	Sodium adsorption ratio (*SAR*)	Residual sodium carbonate (meq/1) [2]	Number of sites tested	Number of sites where *SAR* increased [3]	Number of sites tested	Number of sites where salinity improved
1	0–750	0.3–5.2	<2.74	35	0	49	4
2	750–1,500	2.1–12	.3–7.0	76	12	71	56
3	1,500–2,250	4.8–15	.6–7.3	17	11	22	12
4	2,250–3,000	11–19	3.1–10.2	5	4	6	4
5	>3,000	11–23	>11.2	10	10	11	5
Total				143	37	159	81

[1] Class 1 is usable for irrigation with most crops on most soils. Some leaching is required, but leaching incidental to normal irrigation is sufficient. Class 2 can be used for irrigation if there is moderate leaching. Plants having a moderate salt tolerance generally can be grown without special salinity control. Class 3 cannot be used on soils having poor drainage. Special management for salinity control may be required, even with adequate drainage, and the plants should have good salt tolerance. Class 4 ordinarily is not suitable for irrigation but may be used occasionally if the soils are permeable, the drainage is adequate, the irrigation water is applied in excess to provide considerable leaching, and very salt tolerant crops are grown.
[2] Milliequivalents per litre.
[3] Other sites show no change or decrease.

The evidence so far obtained in tests related to improving soil salinity conditions is not considered conclusive, because there are too few data with which represent any one combination of the variables of initial soil salinity, quality of applied tubewell water, and quantity of canal water mixed with tubewell water. Many combinations of these variables are represented by only one test plot. Thus additional research is needed.

SOILS, LAND CLASSIFICATION, AND LAND USE

Evaluations of the effects of reclamation measures have been included in soils and land-classification surveys of the *Indus Plain undertaken by both WASID and the Soil Survey Project of Pakistan. Work by WASID included the Upper *Indus Plain (about 30 million acres), Bahāwalpur, and 40 areas, designated small schemes. The work by the Soil Survey Project covered about 57.6 million acres, including the Upper *Indus Plain.

The Soil Survey Project has prepared four types of maps in the report of its soils survey. These include soils associations, present land use, land-capability associations, and geomorphology. The soils association mapping forms the basic means for differentiating and classifying the land's potential productivity. A soils association is a grouping of two or more soils series which have a defined proportional and repetitive pattern over an area.

Currently (1972), WASID is preparing soils survey maps which identify the textural characteristics, salinity status, degree of surface relief, and drainage of the soils. Each of these factors is weighed to obtain a numerical rating of land classification, evaluating the potential agricultural productivity of the land.

Random-sampling techniques have been used by WASID to make land-use surveys in SCARP–I. Since the beginning of this reclamation project in 1959–60 the proportion of land under cultivation and under irrigation has significantly increased by about 10 and 7 percent, respectively.

AGRICULTURAL CROPPING PRACTICES

The agricultural economy of the Punjab region is based on two crop seasons, the "kharif" (April to October), which includes the monsoon (wet) season, and the "rabi" or dry season (October to April). Full year-around irrigation intensity on cultivation is considered 200 percent (100 percent kharif and 100 percent rabi). The principal kharif crops are cotton, sugar cane, rice, and maize. Wheat is the chief crop during the relatively dry winter (rabi) season.

Agricultural production statistics in SCARP–I, SCARP–IIA, and Khairpur SCARP have been compared to initial targets established for these projects at the time of their commissioning. In SCARP–I the grains and cash crops are below target levels, whereas fodder and other crops are above the levels; cropping intensity is now (1972) about 10 percent below the target. In SCARP–IIA, underproduction occurs for cash crops, fodder and other crops, whereas grains are overproduced; intensity of production is only about 2 percent below target levels. Khairpur SCARP is about 15 to 20 percent below targets in grains, cash crops, and intensity; fodder and other crops are almost on target.

If the history of SCARP–I can be used as a precedent, reclamation efforts in the SCARPs seem to have slowed down within a few years after project implementation. In SCARP–I about 52 percent of the initial target goal for reclaimed land area now (1972) has been achieved, but most of this improvement had already occurred by 1963. Various measures to improve agricultural production such as better seed, fertilizers, quantity and quality of seeds sown, insecticides, and weed control have been partly implemented, but much still remains to be done.

HYDROLOGIC PROBLEMS ASSOCIATED WITH RECLAMATION

Although most of the objectives of the SCARP programs have been or are being met, in part, or entirely, a number of hydrologic problems associated with reclamation have arisen. Most of these problems were foreseen, but some are more serious than originally anticipated. Those problems relating to tubewell performance, brackish water, the salt balance, and export of salt water are discussed in more detail in following sections.

TUBEWELL PERFORMANCE

Deterioration in tubewell performance is perhaps the most serious reclamation problem in the *Indus Plain. Decline in discharge of production wells, increased drawdowns, corrosion and encrustation of casings and screens, well sanding or sand pumping, and eventual failure of tubewells have long been problems. The severity and magnitude of these problems, however, have come into sharper focus since the beginning of the SCARP program.

Tubewell deterioration has been especially critical in SCARP–I which has now (1972) been in operation for more than 10 years, the last scheme having been completed in 1962. The discharges of many tubewells have fallen off since that time, reducing the supply of water available. During the same period, drawdowns also have increased, and the greater pumping lift has resulted in increased operational costs. A small part of the increased lift can be attributed to a general lowering of the water table, but a major part of increased drawdown has been caused by decrease in specific capacity.

The problems of corrosion and encrustation as related to tubewell deterioration were recognized as early as 1963, and the operating agency for SCARP–I, at that time the Land and Water Management Board, and WAPDA initiated research to determine causes and investigate remedial measures. US AID and WASID cooperated in study of water chemistry as related to the problem of corrosion and encrustation of mild-steel screens (Clarke and Barnes, 1969). As pointed out in this study (p. L–22), external carbonate encrustation is also known to have extended several inches into the gravel shroud (pack) outside well screens. Samples of gravel pack encrusted and cemented by deposition of calcium carbonate have been recovered from pulled wells (Clarke and Barnes, 1969, fig. 19). There is some evidence also that use of calcareous gravel for packing is at least partly responsible for such carbonate deposition.

Declines in discharge and specific capacity with time have been observed with all types of well design and screen materials thus far employed in some areas of the *Indus Plain. Thus, screen material and design, at least in some areas, may not necessarily be the only or paramount causes of decreasing well yield. For example, gradual reduction, with time, of permeability in the aquifer annulus around and in the gravel pack in the vicinity of the well screen could also result in diminished discharge. Such loss of permeability could occur through a process of gradual cementation by carbonate deposition in the aquifer annulus and gravel pack near the entrance zones adjacent to screen openings as water flows from the aquifer into the well during pumping. Also this process could be coupled with bridging and accumulation of fines in partly cemented zones of the aquifer annulus and gravel pack leading to further reduction in permeability. Thus, the causes of deterioration in tubewell performance must be sought in the interplay of several factors, among which are screen materials, well design, growth of micro-organisms, physical chemistry of the aquifer water, mineralogy of the aquifer material and the gravel pack, and pumping regimen of the well. It is seldom, if ever, possible to pinpoint any one of these factors as the sole cause of deterioration of the yield of a well.

DISCHARGE AND SPECIFIC CAPACITY MONITORING

The Land and Water Management Board and later the Irrigation Department have measured discharges and pumping water levels in tubewells from the beginning of operation of SCARP–I. WAPDA has monitored Mona and other schemes where it has had operational responsibility. Later, WASID was given the responsibility of coordinating the monitoring program within the Central Monitoring Organization of WASID. A manual of instructions for monitoring studies, which includes standardized methods and procedures for monitoring tubewell performance has been prepared by the Central Monitoring Organization (1968). Many WASID/CMO reports giving data on tubewell performance have been released in recent years.

SCARP–I.—In spite of an intensive program of rehabilitation, the latest WASID report (Bhatti, 1972), giving comparative data for 1,586 wells, indicated that average tubewell discharge in 1970–71 had decreased about 38 percent in the eight schemes which were constructed during 1961–62. In the Hāfizābād and Zafarwāl Schemes the decrease in discharge has been more than 50 percent. The unweighted average decrease in specific capacity for the eight schemes, for the same period, is about 46 percent. Casings from a number of tubewells have been pulled in SCARP–I; the only observed cause of deterioration is screen encrustation, aggravated by corrosion.

SCARP–II.—Tubewell performance in SCARP–II has been quite variable. In the Mona Scheme, where all 138 wells but one have mild-steel screens, since 1963 the average discharge had decreased 7 percent by 1967 and 9 percent by 1970. A report by Bhatti (1972) indicates that the decrease in discharge was 11 percent by 1971 and 11.8 percent by 1972.

In Lāliān Scheme all 163 tubewells were constructed with mild-steel screens. Between 1963 and 1970–71, the average discharge of 37 wells had decreased more than 20 percent. Of 96 wells showing decreases, average decrease in discharge was 16 percent. A breakdown by cause of decrease in discharge was: well deterioration, 9 percent; pump defect, 6 percent; water-level decline, 1 percent (Hussain, 1972). It should be noted, however, that 39 other wells showed no change or even an increase in discharge.

In the Khādir Scheme, 56 wells have mild-steel screens and 157 have fiberglass screens. Between time of completion (1965–66) and March 1970, average decrease in discharge in the mild-steel wells was 7 percent; in the fiberglass wells it was less than 6 percent. The average specific capacity of the fiberglass wells had reduced from 100 to 99 (gal/min)/ft (gallons per minute per foot) and for mild steel from 84 to 77 (gal/min)/ft decreases of 1 percent and 8 percent, respectively (Tarar, 1970).

In the Phālia, Sohāwa, and Busāl Schemes of SCARP–II, Ibrahim, Aziz, and Ali (1972) report that the average discharge has decreased 16.4 and 21.6 percent, respectively, for wells with fiberglass and mild-steel screens. In their analysis of the causes for decrease in discharge, the writers conclude that screen deterioration is the cause of reduction of 2.6 and 7.9 percent, respectively, for fiberglass and mild-steel screens. The average specific capacities had reduced by 19.3 and 35.7 percent, respectively, for wells with fiberglass and mild-steel screens. In computing the averages, for these schemes it should be noted that all increases initially indicated in discharge or specific capacity were later checked in the field and found to be incorrect. Consequently, they were eliminated from the statistical analysis as being inconsistent. The averages, thus, reflect only the wells showing decreases. In contrast with some other areas, the statistical averages include wells showing both increases and decreases. The 1970–71 data show 19 mild-steel wells and 52 fiberglass wells, out of a total of 544 wells tested in these three schemes of SCARP–II, in which specific capacities have decreased by more than 30 percent.

In the Lower Hujjan Scheme, monitoring tests were made in December 1970, about 4 years after construction. All 51 wells in this scheme have fiberglass screens. Average decrease in discharge was about 19 percent and in specific capacity about 12 percent.

The average decreases in discharge in various parts of SCARP–II generally do not appear to be as serious as in SCARP–I, even after making allowance for the shorter period of operation. The fact remains, however, that a substantial number of wells in SCARP–II have had decreases of more than 30 percent.

SCARP–III.—In 76 wells with fiberglass screens in the Alīpur Scheme, the average discharge had decreased 17 percent between September 1967 and May to July 1972. The average specific capacity had decreased about 14 percent during the same period. The specific capacity of 14 wells (18.5 percent of the scheme total) had decreased by more than 30 percent.

SCARP–IV.—Field performance testing of most tubewells in the Māngtānwāla Scheme has been completed, but the data were not yet available for analysis as of August 1972. In Murīdke Scheme performance testing of 222 fiberglass wells was completed during the winter of 1971–72 which was some 3 years after the scheme was commissioned. Specific capacities of 55 wells showed no changes or increases; for 131 wells there was a decrease of 1 to 10 percent, for 20 wells a decrease of 11 to 20 percent. Only 16 wells had a decrease in specific capacity of more than 20 percent.

Khairpur SCARP.—In Khairpur SCARP, data on 53 wells with fiberglass screens showed a decrease in the specific capacities of 47 of these wells between 1967 and 1970. Specific capacities of seven of these had decreased by more than 30 percent. Of 10 wells with stainless-steel screens tested in 1970, all 10 showed decreases in specific capacity since 1967, 5 of them by more than 10 percent, but only 1 by more than 20 percent.

SCREEN DETERIORATION

Mild-steel and brass screens from many deteriorated tubewells have been pulled and examined in SCARP–I. The most evident causes of failure have been found to be corrosion of the mild steel, particularly in and around screen slots, and plugging and encrustation of the slots with mineral deposits. In the case of mild-steel screens, the corrosion products formed a significant part of the plugging materials, which were chiefly iron oxides and hydroxides and iron and calcium carbonates. In the case of brass screens, the deposits were found to be chiefly calcium carbonate (Clarke and Barnes, 1969). Tipton and Kalmbach, consultants for WAPDA, have also investigated these problems extensively.

It seems probable that at least part of the deterioration in the fiberglass tubewells of SCARP–III has been caused by growth of micro-organisms in the gravel pack and screen. In SCARPs I and II, however, the only identified causes of tubewell deterioration are corrosion together with plugging and encrustation of screens with mineral deposits. In the mild-steel screens, the deterioration process is aggravated by corrosion which involves chemical reactions with metal screens and which probably accelerates the deposition of encrustants. Also, eventually, the slots are so enlarged by removal of metal that the well fails completely.

Use of fiberglass screens in later SCARPs has largely overcome the corrosion problem, but tubewell deterioration still continues. Thus far (1972), only one fiberglass casing and screen (AP–451 in SCARP–IV) has been pulled from a tubewell (Afzal, 1972; Badr-ud-Din and Afzal written commun., 1972). In this instance there was no evidence of corrosion and no encrusting deposits were found on this fiberglass screen. Some evidence of bacterial infestation (brown slimy filaments) was found. Thick crusts of reddish-brown material were found on the column pipe when the pump was removed. This material dissolved completely in 27 percent hydrochloric acid (HCl). Only 80 feet of the fiberglass screen could be removed, however, and this with great difficulty. The screen broke between slots as it was pulled from the well. If there was any external encrustation on the outside of the screen, it seems probable that the encrusting minerals did not adhere tightly to the fiberglass and that they came off and were left in the well during the rough handling the screen received during removal.

The record of tubewell performance clearly indicates that there is marked variation in the viability of different screen materials and in rates and severity of screen deterioration among different areas in the *Indus Plain. Performance of mild-steel screens has been particularly poor in the Hāfizābād and Zafarwāl Schemes of SCARP–I. In contrast, deterioration of mild-steel screens has been only moderate in the Mona and Khādir Schemes of SCARP–II even after 7 to 8 years of operation. So far, no specific water-quality or other hydrologic factor has been identified to explain these differences. Therefore, the following comparisons of performance of screens of different materials are based on behaviour within the same scheme where the different screen materials are both in use.

Mild steel versus brass.—In the Shāh Kot Scheme of SCARP–1, 222 tubewells were constructed with brass screens and 162 with mild-steel screens. During the period 1962–70, the average specific capacity of the wells with brass screens decreased 24 percent; in comparison the wells with mild-steel screens decreased 33 percent. The failure rate of brass screens, however, after passing the point of 30 percent decrease, seemed to accelerate. During the 7-year period 1962–69, seven wells with brass screens were pulled as compared to two wells with mild-steel screens.

In the Pindi Bhattiān Scheme, 10 of 21 wells with brass screens had an average decrease in specific capacity of 41 percent between 1963 and 1970–71. By comparison, the average decrease in specific capacities of wells with mild-steel screens in adjacent schemes ranged from 33 to 46 percent over approximately the same period.

Mild steel versus fiberglass.—In SCARP–II, three schemes have some wells wth mild-steel screens and some with fiberglass screens. Over a 3- to 5-year period, the average decrease in specific capacity was about 9.5 percent for mild-steel wells and 2.5 percent for fiberglass wells.

Fiberglass versus stainless steel.—Khairpur is the only SCARP having wells with stainless-steel screens. Comparative specifiic capacity data are available for eight wells with stainless-steel screens. The decline in specific capacity among these wells over the period 1967–72 averaged 9 percent as compared to a decline of nearly 33 percent for neighboring wells with fiberglass screens. (One stainless-steel screened well in highly saline water was not considered in this analysis.)

The above comparisons would seem to indicate that brass screens have not performed much better than mild-steel screens in the same environments, that fiberglass screens have performed better than mild steel, and that stainless-steel screens have performed the best of all. Not enough data, however, are as yet available on behavior of stainless steel to warrant firm conclusions. It is also obvious that there are great differences in performance of the same screen material between different areas, even though there are no obvious environmental differences. Continued research on the problem of tubewell deterioration is essential.

TUBEWELL REHABILITATION

An intensive program of rehabilitation of deteriorated mild-steel and brass screen tubewells has been carried out in SCARP–I during the past decade. The chief method used is to break up the mineral encrustation and clear the slots by blasting inside the screened section with primacord. The primacord is suspended inside a 20-foot length of 4-inch perforated pipe which absorbs some of the direct shock and minimizes danger of blowing holes in the screen. The entire length of screen is treated by blasting successive 20-foot sections. Blasting treatment is used successfully on both mild-steel and brass screens, many wells recovering to their original specific capacity after the first treatment. Through June 30, 1972, a total of 1,752 rehabilitations had been performed in SCARP–I, most of them by blasting. A few wells have been treated with hydrochloric or sulphamic acid, but mostly with only moderate success, generally recovering not more than 10 to 20 percent of the lost capacity.

Bhatti (1972) reports that a study of 100 wells in the Hāfizābād Scheme (SCARP–I) indicated a decreasing recovery in specific capacity and a progressively shorter period of useful operation between required treatments with successive rehabilitations. He states that the useful operational period after the first treatment averaged 21 months, after the second it was 9 months, and after the third only 6 months.

Attempts to restore the yields and specific capacities of the fiberglass tubewells by flushing, treating with calgon, and redevelopment have attained partial success (Afzal, 1972). In a 15-well rehabilitation program in the Alīpur Scheme of SCARP–III, treatment with heavy charges of acid along with many hours of surging resulted in some improvement in specific capacity of the first three wells treated. The last 12 wells were treated primarily with a mixture of about 220 pounds of calgon (sodium hexametaphosphate) and 110 pounds of bleaching powder (27 percent chlorine), followed by 20 to 30 hours of surging. Most of the wells treated in this manner made a substantial recovery; generally specific capacities in the range of 15 to 20 (gal/min)/ft before, increased to 35 to 50 (gal/min)/ft after treatment. A muddy brown effluent was commonly discharged for a short period after pumps were reinstalled.

Blasting of fiberglass screens has not yet (1972) been attempted. Mechanical and air surging, together with use of such chemicals as chlorine, sodium hexametaphosphate, and hydrochloric and sulphamic acid has been the usual rehabilitation practice. The one well showing the great recovery, in the Alīpur Scheme (SCARP–III), was treated with nearly 7,000 pounds of hydrochloric acid and was surged for 158 hours.

More effective techniques are needed for rehabilitation treatment of fiberglass wells. If the cause of deterioration is encrustation, as seems highly probable, it is apparent that the acid attacks the encrustation products at a very slow rate. If the screen slots are plugged, it may be that the acid has only a limited point of attack on the encrustation. Some method of breaking up the encrustation is needed; perhaps by mechanical means such as a down-the-hole hammer, a sonic, or vibratory device. Blasting has proved effective in mild-steel and brass screens; this has not yet been tried in fiberglass. A combination of light to moderate blasting followed by treatment with acid injected in screened sections under pressure should be tried. Acid injected under pressure would penetrate through screen slots and attack external encrustation in the gravel pack adjacent to the slots.

TUBEWELL LIFE

There has been much discussion during the past several years concerning the life span of the SCARP tubewell as well as the comparative life spans of SCARP versus private tubewells. Tubewell life, of course, is of major importance in projecting and comparing costs of water pumped. In the late 1950's some estimates suggested an average life of a SCARP tubewell of 40 years; later as more experience was gained this estimated average was reduced to 30 and then to 20 years. More recently, the present Special Committee on the Working of the SCARPs has set 12 years (1971) as the average life of a SCARP tubewell.

One of the major difficulties in arriving at a meaningful figure for average life is to reach consensus on criteria for deciding when the useful life of a tubewell has ended. If a tubewell fails suddenly, the termination of its life is evident. If, however, the discharge and specific capacity of a tubewell decline gradually, as is the case with most SCARP–I tubewells, at what point should its useful life be considered to be complete? Also, some wells have been rehabilitated as many as seven or eight times. A formula is needed for determining at what point it is more economical to put down a replacement well rather than to continue rehabilitation of an old well with diminishing return. Of course, after a certain number of rehabilitations, the well with a mild-steel screen may fail suddenly and completely, because of the coalescence or enlargement of slots into large holes as the blank areas between the slots are eaten away by corrosion.

For SCARP–I at present (1972), the simplest method, and perhaps the most realistic one, is to base the estimate of tubewell life on replacement. A tubewell's operational life could be considered ended when it is no longer pumped and is replaced. As of June 30, 1971, 138 wells had been replaced in SCARP–I, 60 were planned for replacement during 1971–72, and 115 were budgeted for replacement in 1972–73. Assuming that 150 wells will need replacement in 1973–74 and 200 in 1974–75, a curve is plotted in figure 3. This curve shows that approximately one-half of the wells in SCARP–I will have required replacement by 1976. Of the 138 wells replaced as of June 30, 1971, 52 were in the older schemes of SCARP–I which were completed between 1954 and 1960. The other eight schemes were completed by WAPDA in 1961–62, so the average tubewell life by 1976 will be at least 15 years. Actually, because of economic factors, it is doubtful that the projected rate of replacement can be maintained for the next 3 or 4 years.

In SCARP–II, few wells have yet (1972) been replaced. One criterion proposed for the useful end of life for a tubewell is that it should be replaced when its discharge and specific capacity can no longer be recovered by rehabilitation measures to 50 percent of original capacity. This may be too rigid a criterion. Using this criterion as a basis, however, and data on decline of discharge and specific capacity presented earlier in this summary would suggest that average tubewell life in SCARP–II may exceed 20 years. In

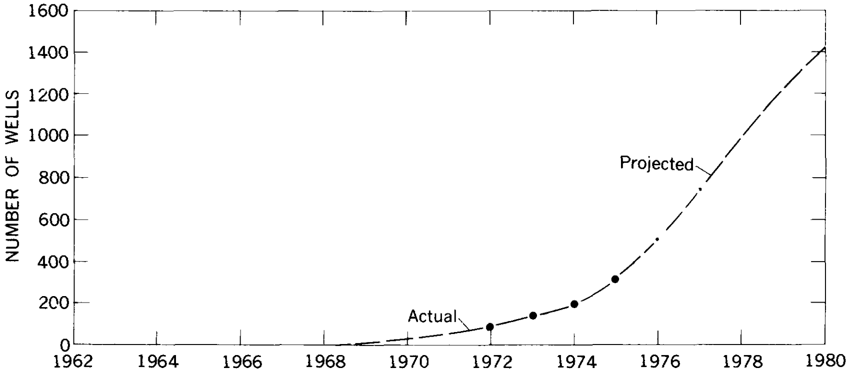

FIGURE 3.—Cumulative replacement of tubewells in SCARP–I.

the Mona and Khādir Schemes of SCARP–II, the average tubewell life may even exceed 30 years.

TUBEWELL DESIGN AND SANDING

The aquifer materials in the Upper Indus Plain generally are fine to medium sand, and the slot openings of screens must be comparatively narrow to prevent excessive movement of sand into tubewell screens. Excessive movement of sand into the well from the aquifer is harmful to pumping equipment and ultimately may lead to premature well failure by filling of the screened section with sand (sanding). The success or failure of the tubewell depends a great deal on the correct design of the slotted or screened section. Economic factors in tubewell design are closely related to selection of the optimum screen length. Other important factors include casing and screen diameter, and the type of material used in them, especially in the screened section.

An "ideal screen" might be considered to be one that would restrain the sand of the aquifer from moving into the tubewell but, at the same time, not in any way impede flow of water into the well. In fact no such screen exists, nor can it be constructed. By proper design of the screen, however, and with good well development, a tubewell and screen can be constructed that will have a higher specific capacity (discharge per unit drawdown) than an ideal screen without development. Under certain conditions an artificial filter a few inches thick of selectively sized gravel, known as shrouding or packing, is placed between the screen and the aquifer to help restrain entry of sand from the aquifer into the screen and to reduce drawdown in the vicinity of the tubewell.

A considerable number of tubewells in the Upper *Indus Plain are giving problems because of movement of sand through the gravel packing and screen into the well. As of 1972 at least 29 SCARP wells are known to have been partly or completely filled with sand. Sanding problems have been reported for many other wells. The affected wells have been found mostly in the Phālia, Sohāwa, Khādir, and Lāliān Schemes of SCARP–II. Serious sanding (sand pumping) problems also have been reported in a number of wells in the newly completed Murīdke Scheme of SCARP–IV. The sanding problem, however, may be more common in SCARP wells than has been heretofore recognized. Many wells with decreased specific capacity may in fact have screens which are partly blocked by accumulated sand inside screened sections. Repetitive soundings of deteriorating tubewells would serve to delineate further the magnitude of the sanding problem.

Based on available data for sand sizes in the Punjab aquifer and accepted criteria for gravel pack and screen design, gravel pack for well screens in the aquifer should be within the following size ranges: D_{15} size, 0.85–1.00 mm (0.034–0.044 inch); D_{50} size, 1.35–1.65 mm (0.054–0.0066 inch); D_{85} size, 2.0–2.5 mm (0.080–0.10 inch); D_{100} size, 6.4 mm (0.25 inch). (D_{15}, D_{50}, D_{85} and D_{100} are the sizes for which 15, 50, 85, and 100 percent of the aquifer material is finer.) The recommended slot width for use with this gravel pack is 1.0–1.25 mm, or 0.04–0.05 inch.

The specifications for the gravel pack used in SCARP–II, III and IV are as follows:

Size		Percentage passing
Inches	Millimetres	
0.039	1.0	0
.078	2.0	20–40
.185	4.7	60–80
.375	9.5	100

In SCARP–II a slot width of one-sixteenth of an inch (0.0625 inch) was used in all wells of the Khādir and Lāliān Schemes and slots of one-sixteenth and three thirty-seconds of an inch (0.0625 and 0.096 inch) were used in all wells of the Phālia and Sohāwa Schemes. All wells in the Murīdke Scheme of SCARP–IV have three thirty-seconds of an inch slots. It is evident then that too-coarse gravel pack and too-wide screen slots have contributed to the sanding problems in these scehmes.

BRACKISH WATER

Some 112 wells are not being used in SCARPs I and II, because the cultivators considered the water produced too brackish for irrigation. Most of the 72 wells shut down in SCARP–I are located in two areas, one lying north of Sāngla and the other west of Shāh Kot. Both areas are close to the bedrock hills and the zone of high salinity water shown on plate 1. There have been reports that the water in these wells had become brackish owing to encroachment of highly saline water from depth. Examination of the records, however, demonstrates that these wells produced brackish water even prior to initiation of SCARP–I. Furthermore, 30 wells, which are intimately interspersed with the shutdown wells, were selected and their records of chemical quality were examined. Although there has been considerable variation over the 10–11 year period since the early 1960's, only 3 of the 30 wells show a definite trend toward increasing salinity. In a much larger number the trend has been toward decreasing salinity.

About 40 wells have also been shut down in SCARP–II, and 33 of these are in Khādir Scheme, along Lāliān Distributary. All these wells, however, produced brackish water from the beginning of SCARP–II operations.

In some places in the Upper *Indus Plain underlain at depth by highly saline water, the shallower water is fresh. In one well drilled in the Mona Scheme of SCARP–II, it was found during testing that the salinity varied greatly with the length of time since pumping began. The pump was removed, and water samples were taken at different depths. It was found that water entered the well from two zones separated by a silty-clay layer. The deeper water was saline and the shallow water was fresh. After the well was backfilled to above the saline zone, the well produced fresh water. It is suggested that other shut-down wells be checked in the same way. Undoubtedly, in some of these, saline water is overlain by fresh water which could be utilized if the saline water were excluded by backfilling. Other wells with brackish water could be utilized if provision were made for adequate dilution of the well water with canal water.

SALT BALANCE AND EXPORT OF SALINE WATER

There are two separate problems involved here. One is pumpage and export of saline water from high-salinity zones in order to alleviate waterlogging, and the other is export of usable water from fresh-water zones in order to maintain a satisfactory salt balance. Export of salt water from the high-salinity zone will in no way help to maintain a salt balance in the usable aquifer.

From the inception of the SCARPs it was recognized that continued irrigation with recirculated ground water would result in a gradual buildup of salinity in the ground water, and that, if some remedial actions were not taken, the ground water eventually would become too saline for irrigation use. The solution offered seemed simple: Before the ground water reaches the upper limit of salinity tolerance for irrigation use, export a quantum of ground water from the system and replace it with an equal quantum of low-salinity canal or river water.

A salt-balance study was made for the White House Panel—Department of the Interior (1964) with the aid of a digital computer. One of the conclusions (1964, p. 305) was the following:

> Surface drainage (export) of about 10 percent of the tubewell pumping (pumpage?) over a 50-year period is needed to preclude eventual excessive

salt accumulation in the root zones of crops. More than 15 percent is unnecessary and less than 5 percent is ineffective. In many cases the pumps-to-drain flow can be delayed for 10 or even 20 years without excessive salt build-up, provided the total drainage in 50 years is equal to about 10 percent of the total pumpage.

WAPDA and its consultants appear to have used this statement as a basis for deferment of detailed study of the problem. It seems to be more or less assumed that 200 "export" tubewells with the same average capacity as the 2,000 production wells in SCARP–I would suffice to maintain a salt balance. If export of water is deferred for 25 years, however, then it will require 400 wells pumping the second 25 years to export 10 percent of the water in 50 years. More important than this, however, the problem of export is not that simple. For example, the pattern of ground-water flow in a SCARP of 2,000 wells, is a pattern of 2,000 individual cells of circulation. The water is recharged over a "circle" of radius 3,000 feet, is spread over the land within this radius and starts the cycle of land to well again. Of course, this model is greatly oversimplified. Major sources of recharge are the hundreds of canals, branches, distributaries, and other water courses. The principle, however, is clear, as there are many more or less independent cells of circulation in a SCARP, a few large capacity tubewells exporting 10 percent of the tubewell pumpage cannot possibly maintain a salt balance in all parts of a SCARP. The implications of this conclusion are rather alarming, that is, the task of exporting 10 percent of the effluent from each tubewell would be formidable indeed. No doubt the problem is somewhat overstated; however, 10 years have gone by since initiation of SCARP–I, and little research apparently has gone into identifying possible alternatives and reaching an appropriate solution.

Perhaps a partial solution is implied in statements of the Harvard Water Resources Group (1965). In referring to decreases in salinity of ground water indicated, after 30 years of operation, by some of the curves developed by computer for their salt model, they state (p. 1–15): "This decrease would have been even greater if the salt model had been run under the plausible assumption that with a low water table some of the salt leached below the root zone would be stored permanently in the soil pores above the water table." Also, (on page 1–10), "* * * when the water table is so deep that no throughputs from rain or irrigation water reach the ground water—this occurs when the ground water depths exceeds 20 or 30 feet—."

The water table is now (1972) more than 20 feet below land surface in large parts of SCARP–I and some parts of SCARP–II.

In the authors' opinion, intensive research is needed to verify whether the assumption of the foregoing statement is indeed plausible and to determine under what rates and timings of irrigation as well as what water-table depths and other conditions that this relation may hold true in various substrata of the Punjab region. If the salts could be leached from the root zone and "parked" or stored indefinitely in the substrata below the root zone, one of the most critical constraints on permanent irrigation in the Punjab region would be removed.

NON-SCARP AREAS

PRIVATE TUBEWELL DEVELOPMENT

The rapid growth in construction and use of private tubewells for irrigation in the Punjab region has been a remarkable phenomenon of the past decade. A report by the University of Engineering and Technology, Lahore (1970) gives detailed information on this growth. With only about 1,000 private tubewells in operation in the Punjab region and Bahāwalpur in 1954 and less than 7,500 by 1960, the total had reached 72,000 by 1969. The rate of growth for the Punjab region and Bahāwalpur area abstracted from the University's report (1970, table 5–1) is shown graphically in figure 4 of this report.

The numbers and distribution of private tubewells by political division and districts of the Punjab region as of June 30, 1971 (Agricultural Census, Pakistan), are shown in table 7.

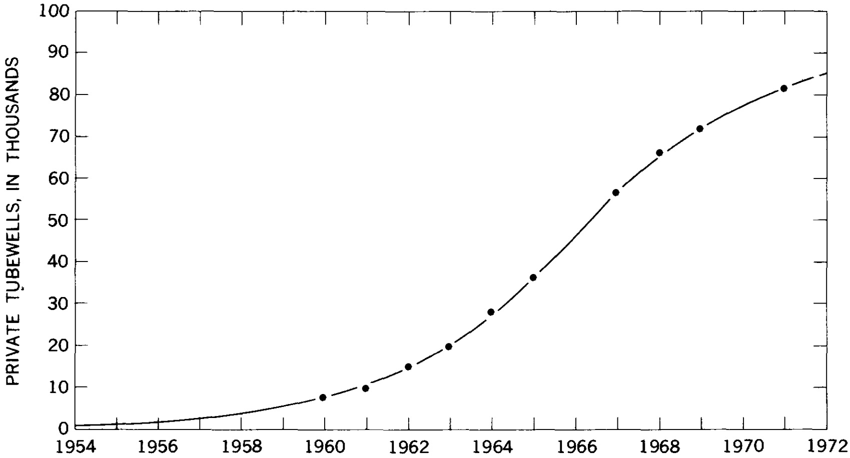

FIGURE 4.—Growth in use of private tubewells in the Punjab region and Bahāwalpur, 1954–72.

TABLE 7.—*Numbers and distribution of private tubewells by political divisions and districts of the Punjab region as of June 30, 1971*

Division and district	Electric power	Diesel power	Totals
Rāwalpindi Division:			
Gujrāt	1,173	1,082	2,255
Sargodha Division:			
Sargodha	319	244	563
Lyallpur	1,518	2,877	4,395
Jhang Maghiāna	1,983	2,812	4,795
Mīanwāli	722	628	1,350
Subtotal	5,715	6,561	11,103
Lahore Division:			
Siālkot	2,409	8,525	10,934
Gujrānwāla	3,819	7,609	11,428
Shekhūpura	1,433	1,302	2,735
Lahore	3,358	1,692	5,050
Subtotal	11,019	19,128	30,147
Multān Division:			
Sāhiwāl (Montgomery)	3,791	9,866	13,657
Multān	2,901	12,357	15,258
Muzaffargarh	151	1,887	2,038
Dera Ghāzi Khān	25	1,218	1,243
Subtotal	6,868	25,328	32,196
Bahāwalpur Division:			
Bahāwalpur	379	1,188	1,567
Bahāwalnagar	186	916	1,102
Rahīmyār Khān	387	2,363	2,750
Subtotal	952	4,467	5,419
Grand total	25,727	56,566	81,120

Some of the districts lie in more than one doāb, but by making adjustments a distribution was made by doāb and area as shown in table 8. No records of pumpage have been maintained, but several sample surveys have been made. It has been estimated that the average private tubewell has a discharge of 1.0 ft^3/s and is pumped 25 percent of the time. An average pumpage of 180 acre-feet per year per well was used in arriving at the estimated acre-feet pumped in each area of table 8. The total pumpage from about 81,000 privately owned tubewells in non-SCARP areas of the four doābs and adjacent districts of the Punjab region would have been at a rate of about 14.5 maf/y as of June 30, 1971. This compares with a total pumpage rate of less than 5 maf/y as of the same date from public tubewells in SCARPs I, II, III, and IV.

HYDROLOGIC CHANGES

The most obvious hydrologic change in the non-SCARP areas, and the one best documented, has been the general decline of the water table in those areas where there are concentrations of private wells. The average change in water level among a group of

TABLE 8.—*Private tubewells in operation as of June 30, 1971, estimated annual pumpage, and change in water level to June 30, 1972 in the non-SCARP areas since the early 1960's*

Doāb or area	Number of tubewells	Estimated pumpage (acre-feet per year)	Average change in water level (feet)
Chaj:			
Upper [1]	2,225	405,000	([2])
Central	420	75,000	+.2
Lower	1,200	225,000	−.05
Total	3,845	705,000	
Rechna:			
Upper	25,100	4,500,000	−6.25
Lower	6,800	1,200,000	−4.8
Total	31,900	5,700,000	
Bāri:			
Upper	18,707	3,350,000	−8.07
Lower	15,258	2,750,000	−8.37
Total	33,965	6,100,000	
Thal:			
Upper	2,744	490,000	([2])
Lower [3]	2,038	370,000	([2])
Total	4,782	860,000	
Bahāwalnagar District	1,102	195,000	
Bahāwalpur District	1,567	280,000	[4]+3.4
Rahīmyār Khān District	2,750	495,000	[4]−2.9
Total	5,419	970,000	
Dera Ghāzi Khān District	1,243	220,000	
Grand total	81,154	14,545,000	−1.4

[1] SCARP–II comprises most of area.
[2] Water-level data not available.
[3] SCARP–III comprises much of area.
[4] June 1966 to June 1972.

key wells in each non-SCARP area since the early 1960's is given in table 8. The correlation between large withdrawals (pumpage) and large declines in water level is evident. A small part of the decline may be due to slightly below-normal precipitation during the past 7 or 8 years. The fact, however, that the water level in the non-SCARP areas of Chaj Doāb, where there has been relatively little growth in use of private tubewells, has remained virtually unchanged, strongly suggests that most of the decline in other non-SCARP areas has been caused by pumping of private tubewells.

As indicated by a detailed tabulation of water-quality data in WASID files, only limited sampling of tubewells and shallow wells in non-SCARP areas has been carried out since 1964. No other water-quality data are known to have been collected by other agencies which would enable an evaluation to be made on the impact of private tubewell development, particularly in non-SCARP areas, on the hydrogeochemical regimen. No attempt was made by the USGS study team to assess changes in water-quality conditions in areas principally developed by private individuals, principally, because of lack of appropriate data or its unavailability to make such an evaluation.

ALTERNATIVES FOR THE FUTURE

PUBLIC COMPARED TO PRIVATE TUBEWELL DEVELOPMENT

Several feasibility and evaluation studies for reclamation of salinized waterlogged lands in the Indus River Basin have advocated the need for public tubewell projects (Tipton and Kalmbach, 1965, p. 11–10; Lieftenck, 1967, p. 157; and Hunting Technical Services and Sir Murdock MacDonald and Partners, 1965, p. 19–259). The last report cited above, however, gave some advantages of private tubewell development (Hunting Technical Services and Sir Murdock MacDonald and Partners, 1965, p. 19–262). Also, the Government of Pakistan's Fourth Five-Year Plan (1970) indicates the increasing reliance on private development of irrigated lands with corresponding decline in public expenditure for government-supported tubewell projects.

Hunting Technical Services and Sir Murdock MacDonald and Partners state that publicly-financed development tends to be more fully integrated and specifically designed to meet the requirements of particular areas. The Lieftenck report (1967, p. 157) states that "the distribution of surface and ground water under full public control (is) fundamental to the efficient long-term development of water resources, especially because of the need for integrated use of ground and surface water, particularly in mixing zones, and the requirements for effective water-table control." Other advantages of public development cited by Hunting Technical Services and Sir Murdock MacDonald and Partners are as follows:

1. Better utilization of tubewell water of marginal quality by mixing with canal water, because of greater areal coverage and inclusion of large distribution systems.
2. Better and larger drainage systems for tubewell pumping and export of saline waters, and
3. Concurrent development of electrification with tubewell drilling. (This, however, has not always been the case, in practice.)

Several arguments in favor of private tubewell development have been presented by Hunting Technical Services and Sir Murdock MacDonald and Partners; as examples, reduced foreign-exchange requirements through use of domestic materials, better scheduling of water deliveries, and the already rapid rate of private investment

Public tubewell development has been favored in areas where the ground water is more saline or where landowners do not have sufficient financial resources to undertake private tubewell development. The economics of public tubewell projects have not been wholly favorable thus far, because average tubewell life experienced to date (1972) has proved to be less than original estimates. Improved rehabilitation practices, however, as well as better knowledge and greater understanding of corrosion and encrustation processes may modify still further existing (1972) projections of the life of public tubewells.

Private tubewell development is an increasingly significant factor in the irrigation economy of the Punjab region, and the problems ensuing from this development must be tackled. Especially lacking is a code of national water law and water-development standards to protect water rights and to regulate water use. The current widespread practice of inducing recharge by tubewell pumping near stream channels or unlined canals makes this point especially critical. As a result the water supplies of downstream users of surface flows are being intercepted by increasing withdrawals from tubewell development near the rivers and canals. Also, over-concentration of private tubewells in some areas, due to lack of governmental regulation, may intercept recharge or lower water levels of existing wells.

REGULATION OF TUBEWELL DEVELOPMENT

In previous sections of this report it has been shown that private development has been tremendously accelerated during the past decade (1962–72). At the same time, public development has lagged far behind earlier proposed plans and schedules (Government of Pakistan, 1970; Tipton and Kalmbach, 1967, fig. 32). It seems likely that these two trends will continue. Several advantages and disadvantages of the increasing emphasis on private tubewell development were discussed in the preceding section. Because private tubewell development is and will continue to be a major factor in intensification of irrigated agriculture, this section of the report examines possible measures which may mitigate some of the disadvantages.

One disadvantage of private tubewells is that they are now drilled and utilized only in the fresh-water zones where water can be used on crops without mixing with canal water. According to the Northern Indus Plain Regional Plan report (Tipton and Kalmbach, 1967) 12 percent of the gross area of canal commands of the Northern Indus Plain is underlain by water of intermediate salinity which could be used, if it were diluted with canal water. It is quite possible that the landowners would drill wells and use ground water in this zone if some economic incentives were offered. A tax advantage and favorable electric power rates are possibilities. Another possibility is suggested by a statement in the feasibility report for SCARP–IV (Tipton and Kalmbach, 1965) as follows:

About 80 percent of the (private) tubewell-irrigated acreage also is canal commanded. Mixing, however, of tubewell water and canal water is not common. About three-fourths of the tubewell owners segregate the supplies, applying canal water to one-third of the irrigated acres and tubewell water to the remaining two-thirds. However, the historical amount of canal water is still being used, As canal irrigation rates are based on the number of acres irrigated, the farmers thus pay less than they did formerly for the same amount of canal water.

The farmers in the intermediate salinity zone cannot segregate supplies, because the ground water is too brackish for use without dilution. The Irrigation Department, however, could give them the same advantage by charging only for the percentage of canal water used, if the farmer were using a mixture of canal water and brackish ground water from his private tubewell. For example, if on a 20-acre plot, he used a mixture of 50 percent canal water and 50 percent brackish tubewell water, he would be charged only for canal irrigation of 50 percent of 20 acres.

Most nations consider their water resources as belonging to the people, therefore the government exercises control over the resources to protect the general public interest. First, for effective control the appropriate governmental agency or agencies need(s) to have legal authority to carry out its responsibilities and to enforce established policies of water development and management. Effective control also requires information; this is the second requisite. For example, the agency responsible for control over ground water must have adequate information on the number and location of wells, depths, discharges, water use, static and pumping levels and other hydrologic data. It is only when adequate information is available that intelligent decisions regarding utilization and control of the ground-water resource can be made.

SHALLOW COMPARED TO DEEP TUBEWELL DEVELOPMENT

Over the past two decades, differing views have been expressed with respect to the relative merits of shallow (less than 200 feet) as compared to deeper (200–400 feet) tubewells for irrigation water supply in the *Indus Plain. This debate is important and was examined in some detail during the present study, because major development programs depend on the outcome of decisions that may result. It is concluded that the long-term response of the water table to pumping depends entirely upon the total quantity of water pumped. Whether there are many shallow wells of small capacity or fewer deeper wells of large capacity has no direct bearing on the end result. Further, there is no definite advantage for either type of pumping regime as regards water quality. In some areas, shallow wells may yield the better quality water, but in other areas, the deeper wells yield better quality water. Except in the immediate vicinity of the high salinity zones, the average salt content of the shallow (less than 200 feet) and deeper (200–400 feet) waters is about the same.

The decision as to whether to use shallow, low-capacity wells should be based on other factors such as distribution system requirements, economic considerations, and whether, locally, the deep or shallow water is of better quality. Still another factor may be considered. Studies of the Harvard Water Resources Group showed that "the rate of salt build-up increases in inverse proportion to the depth" (White House-Department of the Interior Panel Report, 1964, p. 305). This is so because the gross volume of aquifer contributory to a shallow well is smaller than that to a deeper well. Any buildup of salt that might occur from recycling of water and leaching of salts from the soil would take place more rapidly in the smaller volume of water, hence there would be definite advantage to using deeper wells in this context.

UNDERGROUND STORAGE AND CONJUNCTIVE WATER USE

The water table has now (1972) lowered sufficiently so that waterlogging no longer is a problem in most of the Upper *Indus Plain (Punjab region). Moreover, there is a strong indication that the water level will continue to decline, although perhaps at a reduced rate; hence, the Punjab aquifer probably will have, within a few years, a considerable volume of usable storage capacity. Assuming a specific yield of 17 percent, an available layer of aquifer 10 feet thick over 25 million acres in the Punjab region could store more than 40 million acre-feet of water.

In the present (1972) hydrologic regimen, water in underground storage is being replenished by precipitation and seepage from canals, branches, distributaries, and some natural drainageways. As was described in a previous section, before canal irrigation began, the rivers served as line sources (lines supplying recharge to ground water). After the water table rose to near land surface, the rivers served as line sinks (lines receiving discharge from ground water). With a few more feet of water-table lowering, many reaches of the Punjab rivers will again serve as line sources. The magnitude of the recharge that will occur naturally is given in an estimate by Maasland, Priest, and Malick (1963). A condensed version of table 4 from that report is given in the following summary. This estimate of annual recharge in the Punjab region and Bahāwalpur assumes an irrigation intensity of 150 percent (60 percent in kharif and 90 percent in rabi) when tubewell pumping has evolved to full development.

	Million acre-feet per year
Links (canals)	3.7
Seepage from Punjab rivers	3.0
Rainfall penetration throughout to ground water	3.5
Leakage from canal system	13.0
Watercourse seepage	3.5
Recharge from irrigation return	9.6
Total	36.3

Whether or not some of the estimated components are too high or too low, it is obvious that the recharge is large indeed. To construct recharge works for deliberate artificial recharge that would be large enough to have an appreciable impact on the total volume of recharge would be very expensive; on the order of the cost of a link canal, for example. There are, however, a number of measures that can be taken to enhance natural recharge which would be relatively inexpensive.

1. Because of diversions in India of essentially all the headwater flows, the Rāvi and Sutlej Rivers are dry or have low flows much of the year. As these rivers again become line sources, every opportunity should be taken to divert excess water from the northern rivers, that is, the Chenāb and Jhelum, to the Rāvi and Sutlej.
2. Some of the link and irrigation canals are not always used to their full capacity at times when there is surplus flow, and thus do not realize their full potential as recharge vehicles. They should be utilized not only as channels for distribution of surface water, but also as line sources for recharge. Surplus water from the northern rivers can be diverted successively across doābs, into more southerly rivers, until it reaches the Rāvi and Sutlej and eventually returns to the

Indus River in its lower reaches. By this circuitous routing, recharge could be considerably enhanced.

3. As the water table declines, nālas and other surface drainageways that formerly served to drain off surplus water could be diverted into these channels for recharging the Punjab aquifer.

An important advantage of recharge through line sources, such as canals and rivers, in contrast to recharge through downward seepage from irrigated fields is that the water reaching the water table in this way will be of better quality. The chemical concentration of the water recharged from line sources will be essentially the same as that of the canals and rivers, whereas water percolating downward from irrigated fields will undoubtedly pick up large amounts of salts from the soil. As was pointed out in a previous section, the smaller the amount of water leaching down through the soil, the longer the water in the aquifer will remain of usable quality.

SURFACE STORAGE

Storage reservoirs are considered necessary in the Indus River Basin to control flood flows, to provide more dependable irrigation supplies, and to salvage some of the surface runoff presently wasted to the sea. Of the average annual flow of 53 million acre feet per year that passed through Ghulām Muhammed Barrage on the Indus during the period 1962–66 (water years), a large part was lost to the sea. Nevertheless, some wasting of water is needed to flush accumulated salts from the basin so as to maintain a favorable salt balance.

Several studies have been made of the storage potential in the Indus River Basin. Charles T. Main, International consulting engineers, surveyed Pakistan for possible damsites in 1961 (Lieftenck, 1967). Specific suggestions relating to development of storage reservoirs were made by Harza Engineering Co. International (1964). Lieftenck (1967) and a World Bank staff considered the benefits to be derived from various alternative reservoir sites and made a selection of promising projects. Major projects which seem to be the most promising, of those studied by Lieftenck and the World Bank staff, are listed in table 9 together with projects completed or underway (pl. 1).

TABLE 9.—*Completed and proposed storage reservoirs in Indus River Basin as of June 30, 1972*

River	Reservoir	Live capacity (million acre-feet)
Completed or under construction		
Indus	Tarbela	9.3
Jhelum	Mangla	5.36
Kābul	Warsak	2.8
Proposed for construction		
Indus	Skardu	8
Indus	*Kalabagh	6.4–8.0
Indus	Chasma	.5
Swāt	Ambahār	2.0
Kābul	Warsak [1]	8.0
Kunar (Chitral)	Mīrkhani	.6
Jhelum	Mangla [2]	9.1
Chenāb	Chiniot	1.4
Haro	*Gariala	4.6–8.0
Soān	*Dhok Pathān	8.3
Kahān	*Rohtas	5.8

[1] Raised for diversions to Swāt River.
[2] Raised.

Substantial sediment loads carried in the Jhelum and Indus Rivers upstream from Mangla and Tarbela Reservoirs estimated at 30,000 and 100,000 acre feet per year, respectively, by Harza Engineering Co. International (1964) will limit the useful life of these reservoirs. One proposal for counteracting the sediment problem is to construct satellite reservoirs, *Rohtas reservoir on the Kahān River and *Gariāla reservoir on the Haro River, which can eventually replace the lost storage in Mangla and Tarbela Reservoirs. Another means of compensating for losses in storage capacity is to raise at a future date the height of the dams forming Mangla and Tarbela Reservoirs.

An additional barrage of *Sehwan on the Lower Indus River has also been proposed that would divert surplus waters into Manchar Lake (capacity 1.8 maf).

A large off-channel reservoir has been proposed for construction in Thal Doāb (Lieftenck, 1967). The capacity would be 20 maf. Evaporation and seepage losses, however, would be large indeed—on the order of 5 maf/y.

Several other small reservoirs have been constructed, are in the active planning stage, or have been proposed. (See West Pakistan Water and Power Development Authority, 1969, and Directorate of Planning and Investigation, 1964).

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