A BIBLIOGRAPHY AND LITERATURE REVIEW OF GROUNDWATER GEOLOGY STUDIES IN THE INDUS RIVER BASIN

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by

Alfred J. Tamburi

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ABSTRACT

A bibliography of studies of groundwater geology in the Indus Basin is presented, together with discussions of the regional geology and geography. A review of historic trends in groundwater development in the area is presented, and major contributions are indicated.

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INTRODUCTION TO A BIBLIOGRAPHY OF GROUNDWATER GEOLOGY STUDIES IN THE INDUS RIVER BASIN

Pakistan is a country built around a river. The Indus River is basic to Pakistan, and the waters of the Indus system give it life. Groundwater is an important part of the water resource of the basin, and its optimum use is necessary to improve farm yields on irrigated lands.

Due to the dislocations caused by the Indus Water Treaty of 1960, and the ill effects of salinity, water logging, and underwatering of cultivated lands, the groundwater resource must be developed rapidly during the next few decades.

This bibliography has been assembled both as an introduction to the available material, and as a guide to landmark papers and research trends over the years. It should also serve to give water resource planners and engineers an appreciation of the need for an understanding of the geologic and geographic setting. Both the geologic and geographic factors have played a role in the historical development of the water resource, and even now influence trends in groundwater development.

Ultimately, a knowledge of geology and geography are an essential ingredient of long-term success in water resource management in the region.

GEOGRAPHY OF THE INDUS BASIN

Location

The Indus Basin occupies the western half of the Indogangetic plain, and extends from the inner Himalayas in China, to the Arabian Sea, over 800 miles to the southwest. A major part of Pakistan is included in the basin, as well as portions of Afghanistan, China, and India. The most important part of the basin is the Indus plain of Pakistan.

The Indus plain occupies the lowest and driest region of the basin. It is bounded on the north by the Salt Range, on the west by the Suliman and Kirthar Ranges, on the south by the Arabian Sea, and on the east by the Thar Desert.

This is the region of greatest agricultural development, and consequently the greatest water resource need and development. As a result, groundwater development in the Indus Basin, has predominantly occurred in this area.

Physiography

The Indus Basin may be divided into five physiographic regions (Ahmad 1964):

1. The Northern Mountains
2. The Western Bordering Mountains
3. The Salt Range and Potwar Plateau
4. The Upper Indus Plain
5. The Lower Indus Plain

The Northern Mountains are a portion of the Himalayan range, and extend across northern Pakistan in four major ranges. From north to south these are the Trans-Himalayan ranges, the Central Himalayas, the Outer Himalayas, and the Siwaliks. The Trans-Himalayas contain peaks as high as 28,000 feet, with elevations generally decreasing to the south.

The Western Bordering Mountains are a series of lower ranges west of and generally parallel to the Indus River and lie in the western portion of the basin. These are the Safed Koh, Suliman, and Kirthar ranges with elevations of twelve, eleven, and seven thousand feet, respectively. The Western Mountains lie outside the path of the monsoons, and are consequently far drier than the Himalayas.

The Salt Range and Potwar Plateau. South of the Siwaliks lies the dissected Potwar Plateau, with elevations ranging from one to two thousand feet above sea level. South of the Potwar lies the Salt Range, consisting of two parallel ridges with elevations ranging from two to five thousand feet.

The Upper Indus Plain. South of the Salt Range begins the unrelieved monotony of the Indus Plain. The Upper Indus Plain consists of tertiary and recent alluvium from five rivers tributary to the Indus, and the Indus itself. The Punjab, or land of five rivers, has historically been one of the most productive regions of the Indus Basin. The northern part of the plain has

elevations of one thousand feet, with a gradient of one foot per mile to the southwest and minimum elevations of less than 600 feet. The land between rivers is called Doab, and consists of active and inactive flood plains, and bar uplands, as much as fifty feet above the flood plains. Most of the ground-water development potential exists in this area.

The Lower Indus Plain. The Lower Indus Plain is the alluvial plain of the Indus River, having elevations between 600 feet and sea level. The river is aggrading, and the countryside is protected from floods by levees, or bunds. The low gradients and elevation of the region have combined to help make the waterlogging and salinity problem the worst in the basin. Water development in this region must largely be a salvage operation.

Climate

The climate of Pakistan is characterized by arid continental conditions. Like most arid regions, spring and fall are almost nonexistent. However, from July to September a rainy season exists as the monsoons travel north.

The mean July temperatures range from 100°F near Jacobabad, to lows of 80°F in the Himalayan foothills. Mean January temperatures range from 65°F along the Arabian Sea, to lows of 40°F in the Himalayan foothills.

Rainfall is generally greatest in the Himalayan foothills, decreasing to a minimum in the central portions of the Indus plain, then increasing slightly near the coast. The mean annual rainfall of Sialkot in the foothills is 31.8". Moving south, Lahore has 19.2", Multan 7", Jacobabad 3.6", Hyderabad 7", and Karachi 7.7". Although 32" may seem a reasonable amount of rainfall, most of it is concentrated in the monsoon season. Evaporation rates are much higher at these latitudes (34°N) and the country consequently appears dryer than the total rainfall figure would indicate. Thus, the Climate of Pakistan can only be described as arid or semi arid.

GEOLOGY OF THE INDUS BASIN

The geology of the Indus Basin is closely tied to the concept of continental drift. As early as 1937, West applied Wegener's 1910 concept of continental drift to the Indian subcontinent. India was understood to have been part of a 200 million year old supercontinent which broke up with the parts drifting north. The Himalayas were seen as the wreckage of a head-on collision between what was then south Asia and the Indian subcontinent.

The past two decades have seen a fantastic amount of data collected which confirms in detail this seemingly preposterous hypothesis. Let us reconstruct in brief, a history of the geologic events producing the Indus Basin.

Prior to the impingement of the Indian subcontinent, the southern coast of Asia lay approximately along the southern front of the present Himalayas. Afghanistan and what is now largely China, poured sediment into the sea in the arc now occupied by the Indo-Gangetic plain. As the Indian subcontinent moved north and began to interact with the Asian continent at depth, the Himalayas began to form. However, at the same time, downwarping produced the Himalayan fore-deep, a 25,000 foot trench between Asia and India. Even as the trench developed, it was being filled with sediment, sometimes marine, sometimes continental. Occasionally lakes were found in the continental deposits, and with the passage of time marine deposits were more and more restricted to the extremeties of what is now the Indo-Gangetic plain, near Karachi and Calcutta.

Deposition was so continuous in some parts of the trough that one of the most nearly continuous records of sediments from pre-Cambrian to the present exists in the Salt Range. However, as noted earlier, the type of sediment and depositional environment frequently changed in haphazard fashion. Deltaic deposits were replaced by channel alluvium or great saline lakes which were replaced in turn. The vast amounts of salt water and salt deposits now found in the rocks and alluvium of the Indus Basin are a legacy of this period in large part, and are derived from saline lake deposits, and connate, or sea water left in the interstices of marine deposits.

Deep freshwater zones in the Indus plain are largely in fluvial deposts of the early Indus River or its tributaries. Much of the fresh or brackish water nearer the surface of the present plain owes its existence to the flushing effect of groundwater moving from the Himalayas towards the Arabian Sea over low gradients. This flow may locally be interfered with by the presence of a buried portion of the Indian subcontinent overlain by Indus Valley alluvium.

This buried basement rock, the Aravalli Range, lies between the Himalayan trough and the shallower sediments of the lower Indus plain. It is largely buried by at least 600 feet of sediments, and according to USGS findings, cannot be considered a major barrier to useable groundwater flow.

Concurrent with sedimentation, tectonic adjustment continued to take place throughout this period. The Himalayas grow younger in the southwesterly direction, and faults grow progressingly younger in the same direction. As early as 1937 Lahiri recognized recent or subrecent faults in the Punjab.

During the past two hundred years, earthquakes have been felt in every portion of the basin with the western ranges being most active. Recent work has suggested that the Indus basin is underlain by a left lateral fault, along which the Indian subcontinent is still moving north.

Thus, the Indus basin is still an area of tectonic instability, and water development projects in the basin must consider this factor. Also, the extent and quality of groundwater resources are affected by a complex stratigraphic history, as well as the locations of present sources of recharge.

WATER DEVELOPMENT IN THE INDUS BASIN

Civilization and water development have gone hand in hand in the Indus Valley for over four thousand, five hundred years. Although in the early millenniums the region was apparently wetter than it is now, it has always been necessary to develop irrigation agriculture to support civilization. Thus the extent and sophistication of the irrigation systems is closely related to the size and sophistication of the associated civilization.

The earliest major civilization was that of the Mohenjo-Daro and Harappan culture. This first of the great Indus civilizations lasted over a thousand years, from 2500 B.C. to 1500 B.C. An extensive system of flood control levees were produced along the 1000 mile length of the Indus controlled by this culture.

It is likely (Wheeler, 1950) that this civilization was largely destroyed by the Aryan invasion chronicle in the Rigveda. And with the arrival of Indra, the Aryan god of war, civilization and the written work disappeared from the Indus plain. In about 500 B.C. the Jumna River was diverted by tectonic activity from the Indus to Ganges drainage, but no civilization marked its passing. After the passage of Alexander the Great in 326 B.C., a succession of empires and kingdoms ruled parts of the Indus plain, but never approached social development on the scale of the Harappan culture. The Mauryan dynasty was followed by the Bactrians, who in turn were overrun by the Scytho-Parthians in the first century B.C. The Parthians remained, with their city of Taxila until about 450 A.D. when the kingdom was destroyed by the Ephthalites, or White Huns.

The first Muslim-Hindu War occurred in 711-12 A.D. in the lower Indus plain. Sind fell to Muslims in the eighth century, but the conquest of the Punjab was not completed until the eleventh century. Repeated wars extended Islamic territory into Hindustan until the Sultanate of Delhi was established in 1206. The Samma-Rajputs, accepted Islam between 1351 and 1517, and used reservoirs and canals to irrigate the eastern part of the Indus lowlands (Wilhelmy, 1967).

Babar defeated the last of the Delhi Sultans, and became the first of the Moghul emperors in 1526. With the advent of the Moghuls, water development again expanded, with more extensive irrigation. In addition, the Moghuls, to support their road and communication network, began the construction of wells, or bāolis, ideally spaced at three mile intervals on all roads. Considering the extent of the empire which included all of the northern part of the Indian subcontinent, the undertaking was extensive.

By the death of Aurangzēb, in 1707, the irrigation system was probably the most extensive the valley had yet seen. However, the Moghul empire was in decline, and many local states were gaining power.

Many canals were built by the Kalhora dynasty (1747-1783) and the subsequent Talpur dynasty (1783-1843). These canals often took advantage of the dry beds of former stream courses, but still depended directly or indirectly on high water flow. Thus many canals existed before the British arrived.

The British began to move into the balkanized region, and from the beginning of the nineteenth century on, developed and applied engineering techniques for water development throughout the basin. As early as the thirties of the nineteenth century, as many as nine papers or treatises on flow in the Indus or its tributaries had been completed by the British. Some of the earlier surveys date from the 1840's. Much effort during the century was also put into flood control, as a consequence of a number of catastrophic floods apparently caused by the collapse of glacial dams in the Himalayan headwaters. In general, the dams failed due to melting, but interestingly enough from 1852 on, at least one major earthquake per decade has been described in the Indus Basin literature.

As early as 1857, Jacob investigated the possibility of restoring the eastern Nara River using subsurface sources of water. Occasional papers dealing with the groundwater resource appeared during the remainder of the nineteenth century, often dealing with areas inaccessible to Indus River

water. Simpson (1903) and Barnes (1917) describe the beginnings of serious development of groundwater in the Punjab with the extensive use of tubewells. During the first half of the twentieth century, the British concentrated water development efforts on conversion of older seasonal canals to year round sources of water with the construction of control dams or barrages on the Indus and its tributaries. During the same period, Lacey was developing an empirical approach to the design of stable canals, thus allowing expansion of the irrigation system beyond any prior scale.

However, the most important events affecting water development in this century have been partition in 1947 without any sane regard for the importance of water in this arid region, and the conclusion of the Indus Water Treaty in 1960.

The Indus Water Treaty gives India sole right to the waters of the Beas, Sutlej, and Ravi Rivers, while Pakistan retains the water of the Indus, Jhelum, and Chenab. Although the treaty is probably a bad solution to the water problems produced by a poorly drawn boundary, Pakistan must live with it. Consequently, an extensive system of link canals has been built to transfer water from the three western rivers to the Ravi and Sutlej Rivers. The vast extent of the system can be hinted at with a few figures: The inter-river canals are approximately a total of 400 miles in length, and several carry up to 22,500 cfs, a flow equal to that of the Colorado River. The total transferred flow is on the order of 100,000 cfs. A series of new barrages, and storage dams are also part of the system, with the Tarbela Dam on the Indus probably the largest single undertaking. The completion of this system will produce enough water to adequately irrigate the lands provided with water prior to the Indus Water Treaty and diversion by India. The entire system then, primarily represents not an expansion of irrigation in Pakistan, but a readjustment of water supply dictated by political facts.

Intensive development of groundwater for on-farm irrigaion is currently necessary for several reasons. The development of projects which expand the water resource base for agriculture has not kept pace with the increasing population. Also, the proper development of groundwater can minimize waterlogging, and can help to control salinity.

TRENDS IN STUDIES OF GROUNDWATER GEOLOGY

Water in the Indus Basin has always been so important that water development technology here has always kept pace with, or even led, global developments. Thus, as early as the 1850's groundwater in Sind was being seriously eyed for systematic development. However, in broad outline, the period 1857-1900 was a census era with the geology and extent of the groundwater resource being mapped. This was also the period of easy development of surface and artesian waters, such as those at Sabzulkot in the Punjab. Occasional papers within and outside the basin describe development of the groundwater resource for local use, especially in the Quetta region. It should be remembered, however, that Baluchistan has used groundwater for thousands of years in the form of "Karez", underground canals which tap groundwater near impervious mountain fronts and conduct it out into the plains. The practice was extensive in the region and Karez are still active here, as well as in Iran to the west.

1900 to 1925 saw early study of artesian waters described by Vredensburg, 1901, and an important paper by Barnes and Singh, 1917, describing tubewell development in the Punjab. During this period, an interest was evinced in groundwater by several municipalities, notably Karachi.

After 1925 tubewell development, especially in the Punjab, had progressed to the point that serious interest was expressed in rising water table levels by Wilsdon and Sarathy, 1928. Local problems of the same nature were investigated in the Upper Chenab Bund area by Taylor and others, 1933. During the early thirties gravitometers were being extensively used on the Indian subcontinent by Glennie, and in 1934, Wilsdon and Bose used gravity to study waterlogging in the Jhelum, Chenab, and Ravi Doabs.

Following Lacey's classic work on stable channels in 1935, Midha and others investigated canal seepage in areas of high water table in the Punjab. During the immediate prewar period, numerous groundwater supply papers were completed, many centered in the Punjab, but with an extensive study of the Peshawar District by Coulston in 1939. An extensive paper by Mehta, 1940, describes the current practices used to reclaim "Thur" lands in the

Punjab. Finally, throughout the entire interwar period, Karachi seemed to face one water crisis after another, with numerous attempts to use groundwater as an additional water source.

The war period marked a sharp decrease in the number of groundwater papers devoted to research. Most work was devoted to water supply, with state geologic surveys increasingly active.

After partition in 1947, the new Pakistan Geologic Survey faced a period of organization. However, an early paper by Kazmi (1947-49) was an intensive investigation of groundwater in Baluchistan. Although largely outside the basin, the study reflects the current level of investigation, and the approach to integration of ground and surface water. During the formative period, Crookshank was the head of the Geologic Survey of Pakistan. During the years 1947 through 1953 many extensive narrative reports on groundwater investigations were contained in the record as a result of Crookshank's sponsorship. Pithawalla, 1949, presented the first inclusive study of water resources in the dry regions of the new nation, and Moosa, 1949, worked on Karachi's perennial water supply problem. One is bemused by the rapid, uncontrolled growth of Karachi, and its effect on water supply. There is a temptation to call it "Denver-by-the-Sea."

A highly useful paper by Heron, 1951, is a summary of geological surveys in Pakistan, and contains an extensive bibliography of all prior work. Starting in 1951, another concise source of geologic and groundwater investigations is available in the annual report of the Geologic Survey of Pakistan (G. S. P.), normally contained in the Record of the G. S. P.

A major paper by Pithawalla in 1952 is an integrated study of water resources, soils, and natural vegetation in Baluchistan. 1952 was also the start of the first major international effort on water development in the Indus Basin. The U. S. Bureau of Reclamation, U. N. E. S. C. O., and the F. A. O. were all involved in water studies in Pakistan in the period 1952-56, with the most extensive report being that of Paver and Scholtz, 1955.

1956 saw the first use of geophysical methods really suited to groundwater exploration. Although gravity had been used by Glennie as a groundwater

exploration tool in the thirties, it did not have the sensitivity necessary to be a development tool. The advent of electrical resistivity, discussed by Farah, 1956, enabled the groundwater geologist to estimate both the depth to, and quality of near surface groundwater. A report by Auden, 1956, on a geologic reconnaissance of dam sites in Pakistan, indirectly produced information on the location and extent of groundwater in the river valleys.

Also, in the period 1956 to the formation of WAPDA (Water and Power Development Authority, 1958) Pakistan Geologic Survey Administration Reports contained frequent groundwater studies. In 1958, the Colombo Plan Cooperative Project (Pakistan and Canada) produced an extensive survey of the land forms, soils, and land use of the Indus plain (Fraser), which was to serve as an aid in future planning of water use. During this period heavy use was made of the electrical resistivity technique, and it has since been a standard tool for groundwater investigations.

1958 saw the formation of WAPDA with the beginning of the implementation of the Indus Water Treaty in 1960. All aspects of water development are within the scope of WAPDA investigations, and it is interesting to note that more than half of all groundwater studies completed in Pakistan have been undertaken since 1960.

During the early sixties, the emphasis of the new organization was in the Punjab, with a new emphasis on the quality as well as quantity of groundwater. Hints of a dynamic approach to groundwater occur in studies of precipitation (Sheikh, 1960), records of changes in groundwater levels (Shakur, 1960) and river flows (Qureshi, 1960).

Extensive soil surveys were also carried out (Asghar, 1960; Zaidi and Rehman, 1961) and a program for waterlogging and salinity control in the irrigated areas was devised (WAPDA, 1961). A summary of each year's work is also available in the WAPDA Annual Reports.

Starting in 1961 the scale of groundwater investigations was both increased to basin wide extent (Nagvi, 1961) and decreased to the laboratory (Kazmi, 1961). Several papers by the U.S.G.S. containing studies of the Hydraulic regime in the Punjab were completed during 1962, with the traditional boundary between geology and engineering beginning to disappear.

A series of geologic studies of the doab areas was undertaken by WAPDA (Kidwai, 1962, Siddiqi, 1963; Kidwai, 1963) to determine the influence of the geology on groundwater flow.

A 1963 landmark paper by Karpov outlines future water development in the Indus Basin on a scale unmatched except perhaps by the N. A. W. A. P. A. dreamers in the U. S. Although many of Karpov's suggestions may never materialize, his ideas will influence a generation of water development planners in the Indus Basin.

Pakistan, with its planned economy, was one of the early targets of systems analysis. Fiering, 1963, applied the technique to water control in the Indus River Basin, and the method was used repeatedly by the World Bank throughout the sixties. During the same period, however, studies at the local level proceeded apace, as evidenced by the work of such men as Wood, 1964; Young, 1964; Hussain, 1963; and Shamsi, 1964. Shamsi's paper is one of the earlier papers dealing with the potential of deep (thousands of feet) groundwater.

In 1965 Offield completed a preliminary bibliography and index of the geology of Pakistan under the auspices of the Pakistan Geological Survey. Although covering all aspects of geology, the bibliography is still a service to groundwater investigators, as references on that topic as well as stratigraphy and economic deposits formed by groundwater are included. Also in 1965, Gilani used electric analog analysis to model groundwater flow in Chaj Doab. The dynamics of groundwater systems were also studied by Malmberg, 1966.

The single most important source of information for groundwater studies in the Indus Basin is the Geohydrology of the Indus, by A. K. Snelgrove, published by the Sind University Press in 1967. This book integrates local studies in a way that produces a clear idea of the state of knowledge of groundwater in the Indus Basin in 1967. In addition, apart from this report, the most extensive bibliography of groundwater investigations in Pakistan is included. Another excellent source of information on the Geohydrology of the Indus River is the published symposium produced by A. I. M. E. (American Institute of Mining Metallurgical and Petroleum Engineers) in 1967.

The Pakistanis during the late sixties received professional assistance from the Soviets on the structure and tectonics of West Pakistan (Voskresenski, 1968). These reports contain some material of value to the study of groundwater in a regional context.

Electric analog studies are more frequent in the late sixties, with sophisticated well logging equipment also in use (Bhatti, 1969). However, the most recent trend in groundwater investigations has been the total involvement of the WAPDA resource base in applied development of the water resources of Pakistan. The groundwater studies are dynamic, and the consumption of groundwater is integrated into the agricultural and economic context using systems analysis.

Two major trends can be foreseen in the near future. First, there will be a trend towards depletion use of groundwater, both to lower water tables, and to expand the water base until the link and storage system is completed. Further into the future, using systems analysis, the equilibrium use of groundwater will be integrated into the water resource needs of the economy, as it becomes increasingly industrialized.

The scope of irrigation in the Indus Basin has no equivalent elsewhere in the world. It is not surprising then, to encounter corrolary development of a massive groundwater resource. The following bibliography is an introduction to that resource.

USE OF THE BIBLIOGRAPHY

The bibliography of groundwater geology in the Indus Basin contains materials dating from 1971 to 1857. This bibliography is chronological, with the entries for each year in alphabetical order. An effort was made to extend the bibliography to portions of Pakistan outside the Indus Basin to increase its value. Also, entries in fields peripheral to groundwater geology are included to enable the researcher to enter those literatures. Areas thus included are: soils, structural geology, stratigraphy, economic geology, physiography, geomorphology, and hydrology.

The review of groundwater geology in the Indus Basin is an attempt to outline trends in groundwater studies over the years, both in research and application. It also attempts to include landmark events and articles affecting the nature and direction of groundwater research in the Basin.

Ultimately, the bibliography should serve as a reminder to those involved in groundwater studies, that geology is an important element in all groundwater development, and the growing knowledge of regional geology is implicitly reflected in groundwater studies.

Alfred J. Tamburi
Water Resources Group
Civil Engineering Department
Colorado State University
Fort Collins, Colorado
July 30, 1972

A BIBLIOGRAPHY OF GROUNDWATER GEOLOGY STUDIES

IN THE INDUS RIVER BASIN

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