SUMMARY OF GROUND-WATER CONDITIONS IN THE JAFFNA PENINSULA, REPUBLIC OF SRI LANKA

WITH A PLAN FOR INVESTIGATING FEASIBILITY OF GROUND-WATER DEVELOPMENT

U.S. GEOLOGICAL SURVEY

OPEN-FILE REPORT 77-558

Prepared in cooperation with

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CONVERSION FACTORS

The following factors may be used to convert the International System of Units (SI) published herein to the English units. Although given below to four significant figures, in the text the English equivalents are shown only to the number of significant figures consistent with the values for the metric units.

Multiply SI (metric) units	By	To obtain English units
millimeters (mm)	0.0394	inches (in)
meters (m)	3.281	feet (ft)
kilometers (km)	.6215	miles (mi)
square meters (m^2)	2.471×10^{-4}	acres
square kilometers (km^2)	.3861	square miles (mi^2)
cubic meters (m^3)	8.110×10^{-4}	acre-feet (acre-ft)
cubic meters per year per square kilometer [(m^3/yr)/km^2]	.0021	acre-feet per year per square mile [(acre-ft/yr)/mi^2]
cubic meters per second (m^3/s)	35.31	cubic feet per second (ft^3/s)
liters per second (L/s)	13.20	Imperial gallons per minute (I gal/min)
square meters per day (m^2/d)	10.76	square feet per day (ft^2/d)

SUMMARY OF GROUND-WATER CONDITIONS IN THE JAFFNA PENINSULA, REPUBLIC OF SRI LANKA

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ABSTRACT

Ground water in the Jaffna Peninsula, an area of 1,065 square kilometers (411 square miles) located at the northern tip of Sri Lanka (Ceylon), occurs within solution openings of the Jaffna Limestone of Miocene age. The freshwater forms a complex of lenses up to 25 meters (80 feet) thick overlying saline water derived from the sea that nearly surrounds the Peninsula.

Recharge to the aquifer is from monsoonal rains during October-December. Known discharge from the aquifer is primarily from withdrawal of water from about 100,000 wells and by discharge to the sea through springs and seeps along the north coast. Discharge through springs and seeps, which takes place primarily during and shortly after the monsoon, appears to be small compared to withdrawal from wells. Pumping from more than 19,000 shallow dug wells in an intensively studied 142 square kilometer (55 square miles) area of the Peninsula was 55.5 million cubic meters (45,000 acre-feet) in 1976 whereas discharge to visible seeps and springs within that area is estimated at 9.3 million cubic meters (7,500 acre-feet) per year.

Pumping, which takes place largely during January-September, removes water from storage causing heads to decline and the salt water-freshwater interface to rise. The storage is replenished as heads increase and the interface is depressed during the following monsoon in October-December. Consequently, most of the recharge goes into storage rather than discharging to the sea.

Salt water intrusion and upconing of the interface has occurred in the western tip of the Peninsula and at several locations along the coast. Salinities vary seasonally, being lowest during the monsoon and increasing during the dry season. However, leaching of salt from the soil appears to affect salinity locally during the early monsoon period. In the intensively studied area, chloride concentrations of greater than 1,000 milligrams per liter occur in shallow dug wells in 23 percent of the area in August and in 10 percent of the area in January. Generally low salinities occur beneath topographic highs and high salinities occur beneath topographic lows.

A systematic program of data collection, consisting principally of water levels and salinity determinations from shallow dug wells, was started in 1966. The program is still in operation. Expansion of this program to include data collection from deeper parts of the aquifer is required in order to evaluate the entire hydrologic system and to develop a water-management plan that will control salt-water intrusion and maximize the amount of freshwater that can be extracted. The management plan should evaluate techniques for controlling discharge to the sea, identify areas of the greatest potential supply, and establish optimum well spacing and pumping rates. Consideration should be given to transfer of water from one area to another.

INTRODUCTION

The Jaffna Problem

The Jaffna Limestone is the principal source of water for domestic and public supply and for extensive irrigation in the Jaffna Peninsula of the Republic of Sri Lanka (fig. 1). Fresh ground water occurs in the aquifer as lenses overlying salt water. Largely because of low freshwater heads in the aquifer and withdrawals from wells, saltwater intrusion and upconing of the saline water have occurred in several areas of the Peninsula. Recharge to the aquifer and build-up of ground-water storage occur predominantly during a 3-month monsoonal period (October-December) each year. Rapid decline in water levels and ground-water storage generally starts in January. Previous investigators believed that this decline is primarily a result of ground-water discharge to the sea through an extensive network of solution channels in the limestone and secondarily a result of withdrawal from wells. Wijesinghe (1975b, p. 33) states "75 percent of this water is lost to the sea due to rapid flow out from ground-water mound as a result of the numerous karst conduits in the limestone." Within three months of the end of the monsoon the storage of fresh ground water is so depleted and, in some areas, salinity increased as to limit severely the amount of usable water.

Purpose and Scope

This report was prepared by the U.S. Geological Survey under a "Participating Agency Service Agreement" with the U.S. Agency for International Development. The purpose of the report is to present a detailed work plan for a subsequent feasibility study that would develop analyses, designs, and cost estimates for the utilization of ground water presently being discharged to the sea from the Jaffna Peninsula of the Republic of Sri Lanka.

The report describes the many ground-water investigations that have been conducted in the Jaffna Peninsula. It evaluates the data available as well as the present state of knowledge of the hydrology in order to determine the kinds of additional data and interpretive study needed for wise ground-water development and management in the Peninsula. Also considered is the availability within the Irrigation Department of Sri Lanka of staff and equipment to perform the subsequent feasibility study.

Location and Geographic Setting

The Jaffna Peninsula is an area of 1,065 km^2 (411 mi^2) forming the northern tip of Sri Lanka (fig. 1). It is bounded by the Palk Strait on its western and northern sides, by the Bay of Bengal on the east, and by the Jaffna Lagoon on the south. Several saline water lagoons occur on the Peninsula and other lagoons separate the Peninsula from islands lying to the west.

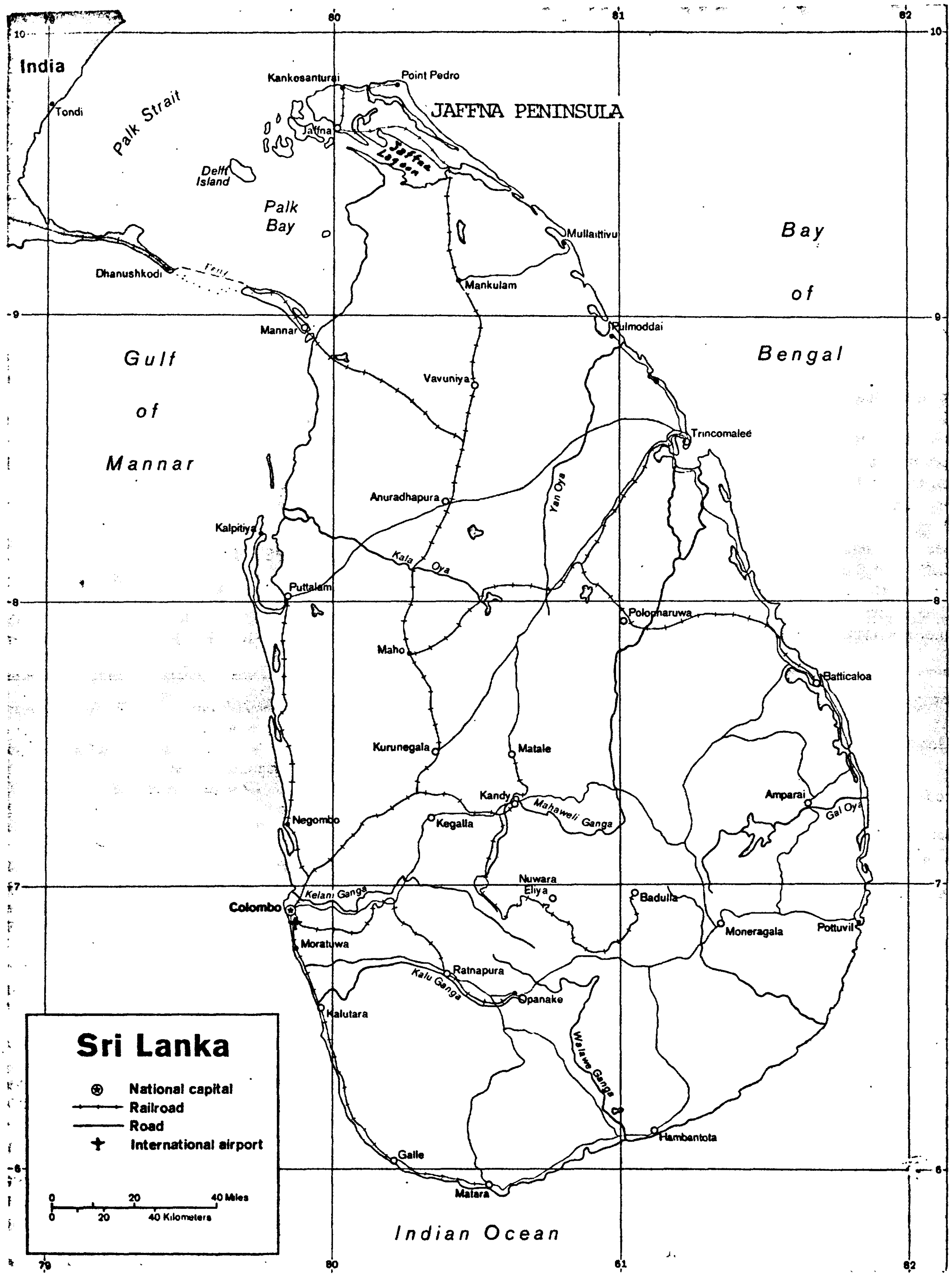


Figure 1.—Map of Sri Lanka and the adjacent southern part of India, showing the Jaffna Peninsula (from Background Notes, Sri Lanka: U.S. Dept. of State Publ. 7757, Dec. 1976).

The area is relatively flat and low-lying, altitudes ranging from sea level to about 11 m (35 ft) above mean sea level. Natural surface drainage is relatively undeveloped. Except for the lagoons, the only surface-water body is the Valukai Aru, a small stream 13 km (8 mi) in length that drains the southwestern part of the Peninsula (fig. 2).

Most of the Jaffna Peninsula is intensively cultivated, agriculture forming the basis of the economy. Chili peppers, onions, tobacco, and other cash crops requiring extensive irrigation with ground water are grown in home gardens and 1000 m^2 (quarter-acre) plots. The area under cultivation has increased considerably in recent years, particularly since 1971.

Geology

The Jaffna Peninsula is underlain by the Jaffna Limestone of early Miocene age (Balendran and others, 1968). The limestone is typically a compact, hard, partly crystalline rock. It is massive in places but some layers are fossiliferous and weather into a honeycombed mass (Cooray, 1967). Coralline limestones appear to be abundant along the north coast of the Peninsula (T. Gunasegaram, oral commun., 1977). Some of the coralline limestones are of Quaternary age. A coral reef extends along part of the northern shore about 60-90 m (200-300 ft) from the shore. The limestones have not been mapped in detail and both surface and subsurface distribution of the various lithologies are unknown.

The Jaffna Limestone is believed to be greater than 75 m (250 ft) thick. At one drilling site in the southeastern part of the Peninsula it was found to be 82 m (270 ft) thick (Balendran and others, 1968). The formation is almost flat-bedded but may have a slight regional dip to the west. The limestone is well jointed; aerial photographs indicate a rectangular fracture pattern with the principal directions being NW-SE and NE-SW (Cooray, 1967; Sirimanne and Vaidya, 1958).

Soil overlies the limestone nearly everywhere in the Peninsula and is generally 0.6 to 2.1 m (2 to 7 ft) thick. Sand deposits, generally 3 to 6 m (10 to 20 ft) thick, and sand dune deposits as much as 20 m (70 ft) thick overlie the limestone along the eastern edge of the Peninsula (T. Ganesarlingam, oral commun., 1977).

Previous Investigations and Present Efforts

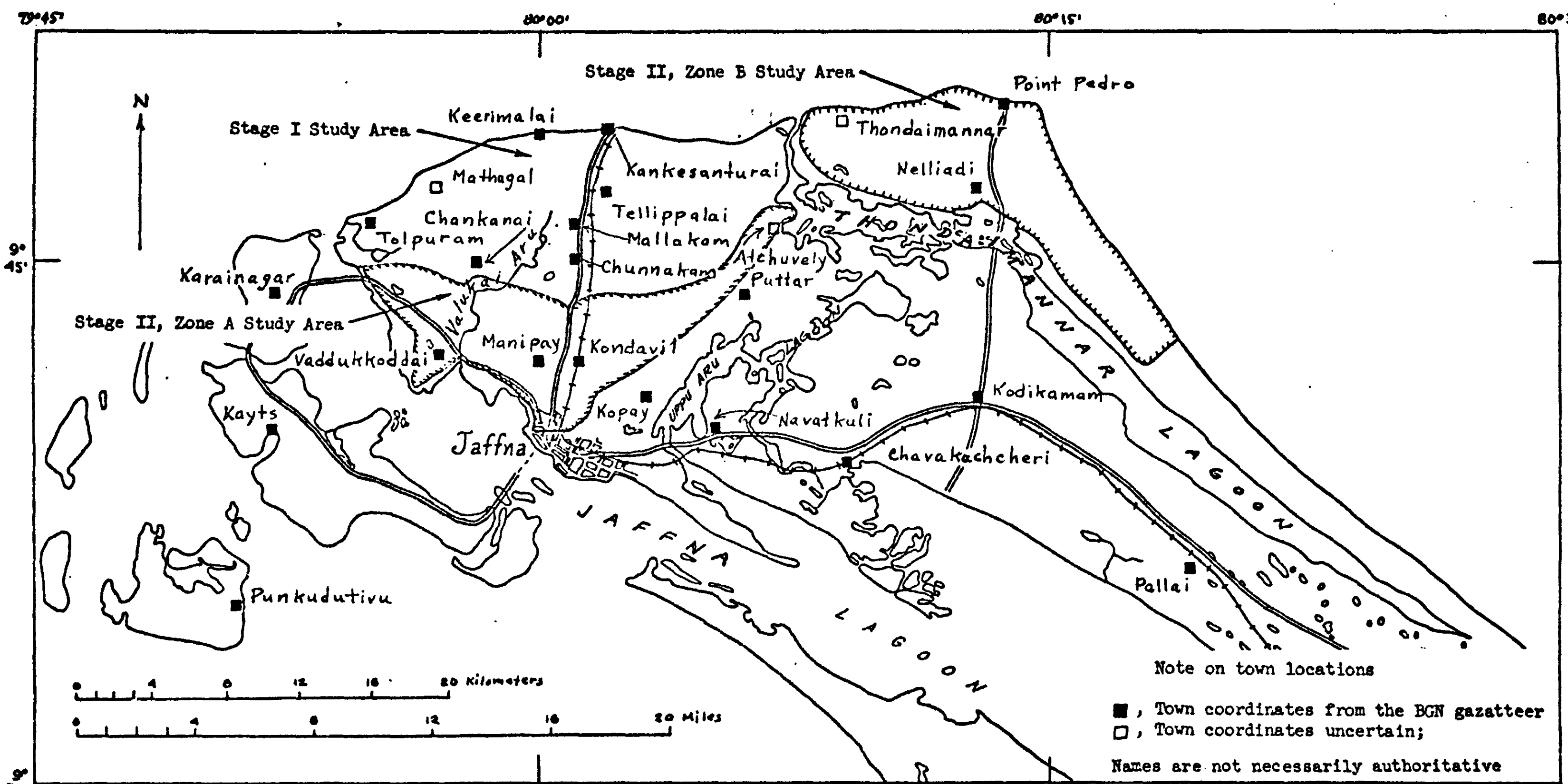
The Hydrogeology Branch was established within the Irrigation Department of the Sri Lankan Ministry of Irrigation, Power, and Highways in 1965. In that year a ground-water investigation of the Jaffna Peninsula was initiated upon the advice of a team of Israeli hydrologists. A systematic program of data collection from 411 wells throughout the Peninsula was started in August 1966. This program was concluded at the end of 1972. A summary of some results of the data collection program and a description of the hydrogeology of the area are given in a paper by Balendran and others (1968).

An intensive data-collection program, utilizing 725 shallow dug wells in an area of 142 km^2 (55 mi^2) in the northwestern part of the Peninsula (Stage I in fig. 2), was initiated in January 1973 and concluded in December 1976. A manuscript describing the results of this program is being prepared by T. Gunasegaram, and was discussed with the present author.

In July-August 1973 G. F. A. Goldberg visited Sri Lanka under the auspices of the United Nations Economic Commission for Asia and the Far East for the purpose of "defining the scope of the work required for future investigations of the ground-water potential and development work" in Sri Lanka (Goldberg, 1974). In reference to the Jaffa Peninsula, Goldberg (1974, p. 1) concludes "there appears to be no economic means of controlling or reducing this loss [ground-water discharge to the sea] . . . optimum utilization of the available resources has already been passed and that more detailed investigations would be of academic value; however, a limited program of data collection . . . should be undertaken."

A reconnaissance survey of natural wells formed by collapse of cavern roofs (called freak wells) was made by Patkunan (1974). In 1974-75 core drilling of 14 bore holes ranging in depth from 8 to 30 m (25 to 100 ft) was carried out for the Water Resources Board.

During February-May 1976 a mission sponsored by the British Ministry of Overseas Development made a study of areas of ground water and land potential in Sri Lanka. A report on the Jaffna Peninsula has been prepared (Foster, 1976) but has not been made available to either the Irrigation Department, the British High Commission in Sri Lanka, or the author.



Base from Geological Survey Department, Ceylon, Sheet 1, 1965. Scale: 1:253 440

Figure 2—Map of the Jaffna Peninsula, Sri Lanka, showing intensive study areas.

An intensive data-collection program in two other areas of the Peninsula (Stage II, Zones A and B in fig. 2) totaling 200 km^2 (77 mi^2) was initiated in January 1977. This program will be similar to that in the previously studied area of 142 km^2 (55 mi^2).

Acknowledgments

The author is indebted to the Irrigation Department of the Ministry of Irrigation, Power and Highways of Sri Lanka for its invaluable assistance in this study. Individuals who provided the author with considerable information and data are M. W. P. Wijesinghe, Divisional Irrigation Engineer, and A. D. Millevitanatchy of the Colombo headquarters office and M. Ganesarlingam and T. Gunasegaram of the Jaffna field office.

HYDROLOGY

General Features

The Jaffna Limestone is the principal source of water supply in the Jaffna Peninsula. The water generally occurs within secondary openings along bedding planes and fractures that have been enlarged by solution of the limestone. Visible karst features include sink holes and solution caverns. Freshwater occurs as a complex of lenses overlying saltwater. The lenses are controlled in gross aspect by the Lagoons that nearly split the Peninsula into separate land masses (fig. 2).

The sand overlying the Jaffna Limestone in the extreme eastern part of the Peninsula is water-bearing and, where it is sufficiently saturated, is the principal source of water supply.

Rainfall is the source of all ground water in the Jaffna Peninsula. The rainfall infiltrates the thin, well-drained soil and moves down into the rock openings and to the zone of saturation. Recharge to the aquifer occurs mainly during the northeast monsoon (September-December). Water-table levels rise from a low in August, ranging typically from 0 to 1 m (0 to 3 ft) below mean sea level, to a high in January that ranges typically from 0 to 2.5 m (0 to 8 ft) above mean sea level. Previous investigators (Goldberg, 1974; Wijesinghe, 1975b) indicate that discharge to the sea through innumerable solution openings causes the water table to decline rapidly to levels approaching those of the previous August. The author's views on this point are discussed in a subsequent section of the report.

Although this report discusses the hydrology of the entire Jaffna Peninsula, much of the report focuses on an area of 142 km^2 (55 mi^2) in the northwestern part of the Peninsula called the Stage I study area (fig. 2). It is in this area that most of the visible discharge to the sea is taking place and for that reason has been the focus of intense data collection by the Irrigation Department.

Rainfall and Infiltration Capacity

The Jaffna Peninsula lies in the dry climatic zone of Sri Lanka. Considerable information is available on rainfall in the area. One station in Jaffna has been operated by the Department of Meteorology since 1871. In addition, the Irrigation Department has measured daily rainfall at eight locations since 1966 (A. D. Millevitanatchy, oral commun., 1977). These data are tabulated on a daily and monthly basis.

Balendran and others (1968, p. 4-5) present a summary of rainfall data for the years 1955-66 based upon data from nine stations. Rainfall for that period averaged 1,212 mm (47.7 in) per year. About 80 percent of this rainfall fell during the northeast monsoon in the months September-December. Rainfall varies considerable from year to year; the two lowest recorded annual precipitation totals since 1871 being 625 mm (24.6 in) in 1963 and 591 mm (23.27 in) in 1974. According to Balendran and others (1968, p. 5) long-term trends in rainfall, based on the single Jaffna record, indicate a cyclical pattern of 20 year-periods each of a dry phase and a wet phase. No "tendency to increase or decrease over the period 1871-1966" is discernible.

A soil survey of part of the Jaffna Peninsula is nearing completion and information on soil types and infiltration rates is available (W. D. Joshua, written commun. 1976). The infiltration rate of the most prominent soil type, a dark reddish brown to dark red clay loam is 360 mm/hr (14 in/hr) and that of the second most prominent soil type, a brownish clay loam, is estimated to be 125 to 200 mm/hr (5 to 8 in/hr). Rainfall intensities in the Jaffna Peninsula determined for the period 1968-73 are less than 50 mm/hr (2 in/hr) for 88 percent of the rainfall. Maximum recorded intensity is 89 mm/hr (3.5 in/hr) (W. D. Joshua, written commun., 1976). Comparison of infiltration rates and rainfall intensities would suggest that surface runoff is insignificant. Indeed, Goldberg (1974, p. 5) states that surface runoff is meager. Maheswaran (Director of the Irrigation Department, oral commun., 1977) believes that runoff is approximately 10 percent of rainfall.

No study of evapotranspiration in the area has been made. Two evaporation pan stations are operated by the Meteorological Department and data from these stations are available for evaluation of plans for surface water storage in ponds and lagoons.

Well Inventory and Ground-water Withdrawal

An inventory of all domestic and agricultural wells reported by Balendran and others (1968, p. 6) indicates that there were more than 84,000 dug wells in the Jaffna Peninsula. Of these about 66,000 were domestic wells and 18,000 were agricultural wells. Ground-water withdrawal as computed for the entire Peninsula by the Agricultural Department (Balendran and others, 1968, p. 6) was 34.5 million m^3 (28,000 acre-ft) per year, most of which is from the agricultural wells. Balendran and others (1968, p. 8) in a water balance study estimated ground-water consumption at 49.3 million m^3 (40,000 acre-ft) in 1968. Goldberg (1974, p. 6) estimates that there were 100,000 dug wells in 1974. The wells are typically about 3 m (10 ft) in diameter, 4.5 to 7.5 m (15 to 25 ft) deep, and when used for irrigation, they are pumped at rates of 4 to 5 L/s (50 to 70 I gal/min).

A detailed inventory by the Irrigation Department of more than 19,600 wells in the Stage I study area of 142 km^2 (55 mi^2) indicates that 55.5 million m^3 (45,000 acre-ft) of water per year are presently being withdrawn for an average of 0.391 million $(m^3/yr)/km^2$ [(818 acre-ft/yr)/mi^2]. A detailed breakdown of ground-water withdrawal within the Stage I study area is given later in table 2. As part of the inventory of the 19,600 wells, data were collected on the length of time each well took to recover (called recuperation rates by the Irrigation Department) after being pumped dry. As these data are not presently in a form suitable for interpretation, the author has not attempted any analysis in order to evaluate areas of high and low aquifer transmissivity.

Collection of Ground-Water Data

Data were collected from 411 shallow dug wells throughout the Jaffna Peninsula during the period August 1966 to December 1972 and the altitude and location of all the wells were surveyed. Water levels were measured twice monthly, usually in the morning prior to pumping, and monthly water-table contour maps (1:63,360 scale) were constructed. Examination of these maps by the author indicates that some wells had already been pumped prior to measurement and that the contours were constructed somewhat mechanically without considering the validity of the measurements.

Hydrographs of individual wells have not been constructed. However, based upon the water-table contour maps and using a specific yield of 0.15 (Balendran and others, 1968, p. 5), monthly calculations of ground-water storage above mean sea level have been made for the entire Peninsula and for each of four islands. Balendran and others (1968) include such a storage graph for 1966 and 1967. The author examined the storage graphs for the years 1967-71. Peak storage in January appears to be a function of rainfall occurring during the monsoon but storage in August does not differ significantly from year to year regardless of the magnitude of the previous peak. Hence, no long-term change in ground-water storage is discernible.

Water samples from the 411 wells were collected monthly and analyzed for chloride (called salinity by the Irrigation Department), total hardness as calcium carbonate, and total dissolved solids. Chloride concentrations were plotted on maps (1:63,360 scale) for 2 months (August and either December or January) each year representing months of highest and lowest water levels. The chloride concentrations were contoured using a 500 mg/L contour interval. A small-scale chloride map for the average August concentrations in 1965-67 is given in Balendran and others (1968). No evaluation of hardness or total dissolved solids has been made.

Upon termination of the Peninsula-wide program of data collection, intensive data collection from 725 dug wells was conducted from January 1973 to December 1976 in the Stage I study area of 142 km^2 (55 mi^2) in the northwestern part of the Peninsula (fig. 2). Here are located most of the visible springs discharging to the sea and their contributing drainage areas. The types of data collected here are essentially the same as those collected during the earlier Peninsula-wide program. However, the monthly chloride-concentration and water-table maps (scale 1:31,680) produced appear to be more suitable for interpretive study. Monthly storage calculations of freshwater above mean sea level were also made. In addition, locations of visible discharge to the sea were noted and the discharge either measured or estimated. Collection of data from 100 wells is continuing in the Stage I study area.

In January 1977 intensive study of two new areas having a total of 200 km^2 (77 mi^2) was started in the southwestern and northeastern parts of the Peninsula. These areas are shown in figure 2 as zones A and B of the Stage II study area. The collection of data from 850 wells in the Stage II study area will be identical to that in the Stage I study area.

The data collection program of the Irrigation Department is summarized in table 1.

Other types of information available, in addition to the material on soils, infiltration capacity, rainfall, geology and ground water already discussed include: aerial photography; topographic maps at a scale of 1:6,336 and 1-foot (0.3-m) contour interval; a survey of ponds; daily water-level measurements in three ponds; and drillers' logs and salinity profiles for 14 drill holes 64 mm (2.5 in) in diameter and 8 to 30 m (25 to 100 ft) deep. Several of these drill holes were pumped for 1 hour at generally small pumping rates while drawdown and subsequent recovery were measured. The Irrigation Department began a core-boring program in December 1976. About 10 core holes, 20 to 25 m (70 to 80 ft) deep and 64 mm (2.5 in) in diameter are planned. Water samples will be collected at 1.5 m (5 ft) intervals, and periodic determinations made of vertical salinity using a conductivity probe. As of January 30, one core hole has been completed but the data are not yet available.

Table 1.--Data-collection programs of the Irrigation Department in the Jaffna Peninsula

Location	Area, mi^2 (km^2)	Period	Number of wells	Water-level measurements	Water-table maps	Water-quality sampling	Chloride concentration maps	Status
Entire Peninsula	414 (1,065)	1966-72	411	Twice monthly	Monthly, 1:63,360	Monthly	Aug. and Dec. or Jan. 1:63,360	Completed
Northwest Stage I	55 (142)	1973-76	725	Twice monthly	Monthly, 1:31,680	Monthly	Monthly, 1:31,680	Completed. 100 wells to be continued
Southwest and Northeast, Stage II, Zones A and B	77 (200)	1977-Continuing	850	Twice monthly	Monthly, 1:31,680	Monthly	Monthly, 1:31,680	Initiated January 1977

Other planned programs of ground-water data collection include the drilling of several 152 mm (6 in) diameter wells, approximately 18 m (60 ft) deep and smaller diameter observation wells for the purpose of conducting pumping tests to determine the aquifer transmissivity and storage coefficients (M. W. P. Wijesinghe, oral commun., 1977).

Thickness of the Freshwater Lens

The thicknesses and shape of the freshwater lenses in the Jaffna Peninsula have not been adquately defined. Wijesinghe (1975a, p. 1-2) states that "good quality ground water exists only in the form of scattered lenses ranging in depths down to about 25 m (80 ft) in most parts of the Peninsula . . . even during the height of the drought."

Examination of data from the 14 core holes drilled largely during a period of high water levels provides additional understanding of the nature of the lenses and of the freshwater-saltwater interface. In most of the holes a sharp increase in chloride concentration from less than 400 mg/L to more than 900 mg/L takes place with increasing depth. This has been called the freshwater-saltwater interface but is more precisely the upper boundary of the zone of diffusion. A thickness of the zone of diffusion of 6 to 8 m (20 to 25 ft) was identified in three wells containing water with chloride concentrations similar to that of sea water.

In one of the islands west of the Peninsula, the top of the zone of diffusion was typically 8 to 17 m (25 to 55 ft) below mean sea level at the time the water table was 3 m (9 ft) below mean sea level. On an adjacent island the top of the zone of diffusion was 6 m (20 ft) below mean sea level and the water table was 0.1 m (0.3 ft) above mean sea level. This latter position of the interface accords fairly well with Ghyben-Herzberg (Herzberg, 1901) prediction. The seeming discrepancy between the two islands is probably a function of aquifer permeability, particularly the relation of lateral to vertical permeability and of the additional complexity caused by intermittent pumping of ground water in the area. Furthermore, the freshwater head at the interface is unknown.

In the southwestern part of the Peninsula and at Thondaimannar in the north-central part, the location of the top of the zone of diffusion also accords reasonably well with a Ghyben-Herzberg prediction. In the southwest, the interface was at or below 21 m (70 ft) below mean sea level and the water table ranged from 0.3 to 0.6 m (1 to 2 ft) above mean sea level. At Thondaimanar the interface was located at 10 m (33 ft) below mean sea level and the water-table altitude was 0.2 m (0.7 ft) above mean sea level.

Data from four additional bore holes identify the position of the interface as ranging from 48 feet below mean sea level (water table unknown) at Kankesanturai in the northwest to deeper than 23 m (77 ft) below mean sea level (water level was 0.9 m (3 ft) below mean sea level) in an upland area near Kopay west of the Uppu Aru lagoon.

Salinity maps to be discussed in the next section of this report show areas where the thickness of the fresh-water lens appears to be negligible and water is being pumped from the zone of diffusion in shallow dug wells.

Because of the karstic nature of the aquifer and the unpredictability of both its vertical and horizontal permeability, additional subsurface borings and observation wells are required to define the shape of the lenses and for monitoring fluctuations of the interface, particularly in areas of heavy pumping.

Salinity Distribution

General Features

Two major areas of low-salinity ground water (less than 500 mg/L chloride) occur in the Jaffna Peninsula. One coincides with the southeastern part of the Peninsula and is approximately 390 km^2 (150 mi^2) in size. The Jaffna Limestone is overlain by sand in this area and groundwater withdrawals are generally from the sand. The other area is centered in the western part of the Peninsula and is approximately 18 km^2 (60 mi^2) in size. Smaller areas of low salinity ground water occur elsewhere on the Peninsula and on two of the islands to the west of the Peninsula.

Areas containing water with high chloride concentrations occur generally in close proximity to bodies of saline water where pumping of wells has caused upward movement of the lower boundary of the thin freshwater lens. Water with chloride concentrations of 1,000 to more than 3,000 mg/L occurs at the western end of the Peninsula (discussed in greater detail later in this report), along the southwest coast (near Jaffna), and northeast coast (near Point Pedro). Other areas of high salinity with concentations ranging from 500 to 2,000 mg/L of chloride occur adjacent to the Uppu Aru lagoon and western part of the Thondaimannar lagoon in an area (including the lagoons) of about 260 km^2 (100 mi^2). Areas of salinity or those apt to be saline in the dry season amount to 23 percent of the total area (Balendran, 1968, p. 7). In the Stage I study area in the northwestern part of the Peninsula, salinity maps show that areas of chloride concentrations of greater than 1,000 mg/L in shallow wells occupied 23 percent of the total area in August 1975 and 10 percent in January 1976 (T. Gunasegaram, written commun., 1976).

Salinity in the Stage I Study Area

Salinity in the Stage I study area in the northwestern part of the Peninsula and its relation to water levels and topography can be discussed in some detail based upon data from shallow dug wells. For the purpose of discussion the area can be divided into four north-south trending strips called here, from west to east: (1) high salinity subarea, (2) western low salinity subarea, (3) variable salinity subarea, and (4) eastern low salinity subarea. Table 2 summarizes salinity (chloride in mg/L) and static water-level conditions (water levels measured under non-pumping conditions) in each of these subareas for four separate months during the period August 1975 to April 1976. Topographic and soil characteristics and ground-water withdrawals for each subarea are also given in table 2.

Several general relationships may be observed from table 2. Areas of low salinity occur in higher topographic areas where the limestone crops out or is overlain by well-drained to excessively-drained red clay loam. High salinity occurs in lower topographic areas and locally along the north shore of the Peninsula where soils are more characteristically imperfectly-drained to well-drained brown clay loam.

Table 2.--Ground-water salinity in the northwestern part of the Jaffna Peninsula

Subarea	Size of area (mi^2)	Generalized chloride concentrations (mg/L) and water table levels (feet above (+) or below (-) mean sea level): August 1975	November 1975	January 1976	April 1976	Topography generalized altitudes in ft. above msl	Soils	Ground-water withdrawal in 1976
(1) High Salinity	9.58	1000 to 3000; locally 500 to 1000 and >3000 (-5 to 0)	1000 to 3000; locally <500, 500 to 1000, and > 3000 (+4 to +6)	< 500 to 1000; locally 1000 to 6000 (+4 to +6)	1000 to 3000; locally < 500 to 1000 and >3000 (0 to +2)	Low area 5 to 10	Well drained & imperfectly drained brown clay loams	8000 acre-feet per year 835 acre-feet per year per mi^2
(2) Western low salinity	7	< 500; locally 1000 to 5000 along North Coast (-2 to +1)	< 500; locally 500 to 3000 along North Coast (+3 to +7)	< 500; locally 500 to 3000 along North Coast (+1 to +5)	<500; locally 500 to 4000 along North Coast (0 to +2)	High area 10 to 30	Excessively drained red clay loams & well drained brown clay loams	4000 acre-feet per year 571 acre-feet per year per mi^2
(3) Variable salinity	9.5	500 to 1500; locally< 500 (-4 to 0)	1000 to 2500; locally< 500 and 500 to 1000 (+2 to +8)	< 500; locally 500 to 3000 (+1 to +4)	< 500 to 1000; locally 1000 3000 (-2 to +1; locally +4)	Low Northeast-Southwest trending valley 8 to 15	Well drained & imperfectly drained brown clay loams	8800 acre-feet per year 926 acre-feet per year per mi^2
(4) Eastern low salinity	29	< 500; locally 500 to 5000 along North Coast and Lagoon (-1 to -2)	< 500; locally 500 to 5000 along North Coast & Lagoon (+1 to +3)	< 500; locally 1000 to 2500 along North Coast & Lagoon (+2 to +4)	< 500; locally 500 to 3000 along North Coast & Lagoon (-1 to +2)	High area 20 to 35	Excessively drained red clay loam & lime-stone out-crops	24,200 acre-feet per year 834 acre-feet per year per mi^2

Soil data provided by W. D. Joshua, Irrigation Department
Salinity and water-table contour maps by T. Gunasegaram, Irrigation Department.

To convert English units to the International System of Units (SI) multiply feet (ft) by 0.3048 to obtain meters (m), multiply square miles (mi^2) by 2.59 to obtain square kilometers (km^2), multiply acre-feet (acre-ft) by 1233 to obtain cubic meters (m^3), and multiply acre-feet per year per square mile [(acre-ft/yr)/mi^2] by 476.3 to obtain cubic meters per year per square kilometer [(m^3/yr)/km^2].

Seasonal changes in salinity and water levels can be seen in table 2 data. In August, water levels were generally below sea level in all subareas and chloride concentrations were at their seasonal peak in all subareas except in the variable salinity subarea. Generally the water table also was lower in the subareas of high and variable salinity than in adjacent subareas. With the onset of monsoonal rains, water levels rose rapidly and the water table was above sea level in all subareas in November and January. Although considerable recharge took place between August and November, little significant change in salinity pattern can be seen in most subareas, and in the variable salinity subarea, the increase in salinity from August to November was notable. This increase will be discussed later in this report. By January, however, salinity was generally lower in all subareas as a result of recharge of freshwater. Locally, water with chloride concentrations of greater than 1,000 mg/L can still be found even where the water table is a few meters above mean sea level. By April the water table had declined to levels at or near mean sea level and salinity was generally higher than in January, especially in the high salinity area, although even here static water levels were still generally above mean sea level. In August 1976 (not shown in table 2) salinity and water level conditions were generally similar to those of August 1975.

Salinity and water-level data in the high-salinity subarea, where the fresh-water lens is very thin, suggest a relatively thick zone of diffusion resulting from large fluctuations in the water table and upconing of the saltwater-freshwater interface caused by overpumping of wells. The position of the interface in the vicinity of a pumping well is a function of several factors including amount of recharge contributing to that well, vertical head profile, rate of pumping, and the ratio of horizontal to vertical hydraulic conductivity of the aquifer. Under the existing conditions of head, hydraulic conductivity, recharge, and spacing of wells, the pumping rate in most wells in this subarea is too great to achieve stabilization of the interface beneath the well. Such stabilization and resulting improvement in quality of the pumped water could probably be achieved by reduction of pumping from each well. Optimum utilization of the aquifer probably could be accomplished by pumping a larger number of shallow wells at a lower rate per well. Pumping of individual wells at lower discharge rates for longer periods of time each day may also be beneficial. The use of collecting galleries also may permit maximum withdrawals while minimizing drawdown and upconing. Optimum development of the aquifer could also include additional withdrawal of water from wells in the western low-salinity subarea, which has a lower groundwater withdrawal rate, for the purpose of transmitting the water to the high-salinity subarea.

The withdrawal rate in the variable-salinity subarea is significantly higher than that of the western low-salinity subarea but is only slightly higher than that of the eastern low-salinity subarea. Although the variable salinity subarea occupies a stream valley, it forms a water-table high during the recharge period and a water-table low during the ground-water withdrawal period, suggesting the probability of lower aquifer transmissivity here than an adjacent subareas. Indeed, T. Gunasegaram (oral commun., 1977) states that recuperation rates of dug wells in this subarea are lower than in adjacent subareas. Hence, the higher salinity values in this subarea appear to result from local overpumping of a less permeable aquifer. Optimum development of the water resources and reduction of upconing of the interface should be accomplished by methods similar to those described for the high-salinity subarea.

The spread of high salinity in the variable-salinity subarea at the beginning of the monsoon period has been the subject of much speculation in the Irrigation Department. M. W. P. Wijesinghe (oral commun., 1977) attributes the phenomenon to leaching of salt from the soil during the first monsoonal rains. The occurrence of brown clay loam that is less well drained in this subarea may account for a greater buildup of salt in the soil. The same type of soil also occurs in the high salinity subarea but an increase in salinity here may be masked by the widespread occurrence of saline water prior to the monsoonal rains. However, the lack of significant change in salinity pattern from August to November nearly everywhere in the Stage I study area suggests that leaching of salt from the soil may be offsetting the general reduction in salinity over a wide area.

Ground-Water Recharge and Discharge

Belendran and others (1968, p. 6-7) have calculated an average recharge of 140 million m^3 (113,000 acre-ft) per year to the aquifers underlying the entire Jaffna Peninsula for the period 1965-67. The present author believes that those figures are significantly too small as they do not represent recharge but rather an approximations of the measurable increase in storage above mean sea level from August to January. They do not account for ground water being discharged to the sea and lagoons during the monsoonal rains, nor do they consider the increase in ground-water storage that occurs as the saltwater-freshwater interface is depressed.

Known ground-water discharge from the Jaffna Limestone is primarily to pumping wells and to springs and seeps discharging to the sea. Withdrawal from wells in the Stage I study area was 55.5 million m^3 (45,000 acre-ft) in 1976 and is considered by T. Gunasegaram (oral commun., 1977) to have taken place essentially during a 9-month period, at a rate of 6.2 million m^3 (5,000 acre-ft) per month. Visible springs and seeps are located primarily along a 4-mile stretch of the north shore of the Stage I study area between Keerimalai and a point about 2 miles east of Kankesanturai. Total flow of these visible springs and seeps is estimated to be 9.3 million m^3/yr (7,500 acre-ft) (T. Gunasegaran and M. Ganesarlingam, oral commun., 1977).

The spring at Keerimalai, which flows from an observable solution opening, is perennial. Its flow is reported to be about 0.1 m^3/s (4 ft^3/s) during the monsoon and to average about 0.05 m^3/s (2 ft^3/s) during the year (T. Gunasegaram, oral commun., 1977). Hence, estimated annual discharge of this spring is 1.8 million m^3 (1,500 acre-ft). Examination of water-table contour maps for January 1, and February 1, 1976, a period when withdrawal from wells is minimal, indicates that the probable drainage area contributing to the Keerimalai Spring is about 2.5 km^2 (1 mi^2). The average water-table decline in the area from January 1 to February 1, 1976 was about 1 m (3 ft). Assuming a specific yield of 0.15 and disregarding changes in the position of the freshwater-saltwater interface, the rate of depletion of ground-water storage is 0.13 m^3/s (4.7 ft^3/s) a figure that is quite close to the reported January spring flow at Keerimalai. The water-table map for August shows that a water-table mound persists throughout the dry period immediately south of the spring, thus explaining why Keerimalai continues to flow when virtually all other seeps and springs are dry.

The other springs and seeps flow only during a few months of the year. The total flow of the ephemeral springs and seeps has been estimated to be about 7.4 million m^3/yr (6,000 acre-ft/yr) (M. Ganesarlingam, oral commun., 1977). Water-table maps for November 1, 1975 and January 1, 1976 indicate that a drainage area of about 8 km^2 (3 mi^2) contributes to the discharge of these springs and seeps. The drainage area appears to be a 0.8 km (0.5 mi) wide strip along the coast.

Calculations of ground-water storage above mean sea level made for the Stage I study area, based upon changes in water-table levels and a specific yield of 0.15, show that freshwater storage increased from 1.17 million m^3 (950 acre-ft) on August 1, 1975 to 14.9 million m^3 (12,100 acre-ft) on January 1, 1976. By August 1, 1976 freshwater in storage was back down to 1.23 million m^3 (1,000 acre-ft). Hence, seasonal change in storage above mean sea level was approximately 13.7 million m^3 (11,000 acre-ft).

A seasonal decline in storage above mean sea level of 13.7 million m^3 (11,000 acre-ft) during a period when withdrawal from wells was 55.5 million m^3 (45,000 acre-ft) and discharge to known springs and seeps was 9.3 million m^3 (7,500 acre-ft) suggests that most of the water being pumped is coming from storage below sea level as the freshwater-saltwater interface rises. Storage, both above and below sea level, is replenished, however, during the monsoonal rains when water levels rise back to a peak and the fresh water-saltwater interface is lowered. If recharge to the freshwater lens each year is less than the discharge from the previous irrigation season, the long-term position of the interface will rise and wells will become increasingly saline. Salinity graphs prepared by the Irrigation Department show no clear trend for the 4 year period 1972-76 in the Stage I study area.

Configuration of the water table in November 1975 and January 1976 tends to support the contention that most of the recharge to the aquifer during the monsoon replenishes ground-water storage rather than discharges to the sea. South of the drainage areas for the springs and seeps the water table is a nearly flat surface averaging 0.6 to 0.9 m (2 to 3 ft) above mean sea level and containing very shallow mounds and depressions. As pumping during this period is reported to be insignificant, the low heads and hydraulic gradients coupled with transmissivity values of 600-1,200 m^2/d (6,500-13,000 ft^2/d) suggested by C. H. L. Sirimanne (T. Gunasegaram, written commun., 1977) indicate that the major flow component is downward as the interface is depressed and that lateral discharge to the sea is relatively small. More thorough analysis of the water-table data is required as well as the acquisition of head data and salinity data with depth in order to evaluate the three-dimensional flow pattern and change in storage within the aquifer. Furthermore, monitoring of the position of the interface should continue as part of a sound water management program in the Peninsula.

A generalized annual water balance for the Stage I study area is presented in table 3. Evaluations of precipitation, withdrawal from wells, ground-water discharge to the sea, and direct surface runoff as already discussed in this report form the basis of the water balance. Evapotranspiration, the remaining component of the balance, was determined in two ways. The first method assumes an evapotranspiration rate of 25 mm (1 in) per week (this is the water application rate on croplands during the irrigation period) for the entire area during the monsoon period. Evapotranspiration is assumed to constitute 90 percent of the rainfall during the dry period. This method gives an annual evapotranspiration of 80 million m^3 (65,000 acre-ft). The second method assumes that all other values in the water balance are correct; hence, evapotranspiration was calculated as the difference between the input (rainfall) and all known outputs. An evapotranspiration value of 85 million m^3 (70,000 acre-ft) computed using this method is shown on the water balance in table 3. Ground-water recharge is shown on the table to be equivalent to ground-water discharge to wells and to the sea. This equivalence assumes that annual change in ground-water storage is insignificant. The quantitative difference between the two modes of ground-water discharge underscores the fact that most of the available ground-water recharge is presently being utilized.

Discussion of Future Studies

Introduction

In this report the author has described the history of hydrologic investigations in the Jaffna Peninsula and has presented a summary and partial analysis of the extensive data that are available. Nevertheless, several types of data and hydrologic analysis required for mitigation of Jaffna's ground-water problems are lacking. These include: salinity profiles, definition of the freshwater lenses in both space and time, subsurface distribution of solution channels, hydraulic properties of the aquifer and their vertical and horizontal distribution, and accurate determination of ground-water discharge and changes in fresh ground-water storage. This information and its interpretation should be used to evaluate the feasibility of various structures proposed for utilizing ground water presently being discharged to the sea but, more importantly, to develop a water-management plan that will optimize utilization of the available freshwater and minimize saltwater intrusion.

Table 3.--Generalized annual water balance for the Stage I study area.

	Millions of cubic meters	Acre-feet	
Input:			
Rainfall	170	140,000	
Output:			
Evapotranspiration	85	70,000	
Direct runoff	18	15,000	
Ground-water discharge			
to wells	55	45,000	Ground-water recharge
to the sea	12	10,000	

The author believes that a hydrologically sound system of shallow wells, pumped at limited rates, and having optimum spacing, will be far more significant in achieving maximum aquifer utilization than construction of cut-off walls or dams to block ground-water discharge. Consequently, the author does not recommend a feasibility study solely for the purpose of controlling springs that discharge to the sea. The proposed study is for development of a water-management program appropriate to the hydrology of the area. It would consider control of salt-water intrusion as well as evaluation of the feasibility of both structural approaches to minimizing discharge to the sea, and approaches involving aquifer development and management.

Lagoon Scheme

Proposals for the closure of saltwater lagoons and creation of freshwater bodies are under study within the Irrigation Department. The proposals call for importation of fresh surface water from the mainland to the south. Consideration of these proposals is beyond the scope of the present report. Nevertheless, if such a scheme is successful, its impact upon a ground-water management plan could be significant. In addition to the availability of surface water directly for irrigation, the lagoons could be a source of water for artificial recharge in areas of heavy pumpage and where there is a relatively thin freshwater lens. If sufficient freshwater head can be maintained by importation of water into the lagoons, improvement in the water quality of areas adjacent to the lagoons should occur. However, significant subsurface discharge to the sea may also occur and such water loss must be weighed against the expected gains.

The program of investigation proposed here should provide considerable knowledge of the hydrology of the Peninsula to aid in evaluation of ground-water gains and losses resulting from a lagoon management scheme. Evaluation of the scheme, however, is beyond the scope of the proposed study.

Resources of the Irrigation Department

The Hydrogeology Branch of the Irrigation Department was set up in 1965 for the purpose of the investigation and utilization of ground-water resources. The Branch is under the direction of Mr. M. W. P. Wijesinghe, an engineer with considerable knowledge and experience in ground-water hydrology. The staff of the Hydrogeology Branch in Colombo consists presently of two junior civil engineers, four senior technicians, one junior technician, two draftsmen, and a typist. The engineers are university graduates but are relatively inexperienced in ground-water hydrology. On the other hand, the senior technicians appear to have practical experience in both irrigation projects and ground-water hydrology. A separate office set up in Jaffna expressly for the data-collection program described in this report is under the direction of Mr. M. Ganesarlingam, an engineer with experience primarily in irrigation projects. Also working in the Jaffna office are two technicians, five draftsmen, five laboratory assistants, and a large number of laborers. One of the technicians, Mr. T. Gunasegaram, has an extensive knowledge of the available data and of the ground-water conditions in the Peninsula.

Also within the Hydrogeology Branch is a drilling unit employing a superintendent, five drilling foremen, ten assistant drilling foremen, and 30 to 40 drilling assistants. Equipment includes seven rotary well drills capable of drilling up to 406-mm (16-in) diameter wells, one percussion rig, and 40 core drills (up to 76-mm (3-in) diameter cores). The drilling unit is used for both engineering, geologic, and hydrogeologic investigations.

The Hydrogeology Branch has demonstrated outstanding ability to design and carry out effectively a program of data collection. The makeup of the staff and the availability of drilling equipment make possible intensive data collection tailored to meet the needs of the Jaffna investigation. Also available within the Irrigation Department is considerable expertise in the design, construction and cost estimation of water-supply and irrigation projects. However, it is also clear that experienced ground-water hydrologists are in relatively short supply and that the existing professional hydrologic know-how is spread rather thinly over several projects throughout the nation. The author believes that the proposed investigation requires the addition of one full-time experienced ground-water hydrologist capable of making the necessary analysis and developing water-management techniques appropriate to the Jaffna Peninsula.

If only the more limited objective of reducing spring discharge to the sea by structural means - such as a cut-off wall or a series of wells - is pursued, the author believes such an undertaking and the preliminary feasibility study could be accomplished with the resources of the Irrigation Department with, at most, intermittent outside support. In the author's view such an undertaking ignores the larger problem of controlling salt-water intrusion and maximizing the utilization of the water resources.

Plan for Investigating Feasibility of Ground-water Development

Project Title - Feasibility study of development of ground water in the Jaffna Peninsula

Objectives

The objective of this study is to develop sound water management practices for the fullest practicable utilization of the limited fresh-water supplies within selected areas of the Jaffna Peninsula. Consideration would be given to minimizing salt-water intrusion and to appraising the feasibility of utilizing water that is presently being discharged to the sea. Techniques developed should have transfer value to other parts of the Peninsula.

Approach

Study and interpretation of the existing data in the early phase of the investigation would be supplemented by collection of essential data not presently available. The present data collection program of the Irrigation Department should continue until knowledge gained in this investigation suggests appropriate changes. Both structural and conventional techniques for utilizing water being discharged to the sea would be considered. A program of monitoring would be established to evaluate the effectiveness of measures taken. Structural techniques to be evaluated would include construction of cut-off walls, damming solution openings, and development of a series of control wells.

Area Covered

Intensive study of existing data and feasibility study for utilizing discharge to the sea would be in the Stage I study area of 142 km ($55\ mi^2$) in northwestern Jaffna Peninsula. The present data collection program of the Irrigation Department includes the Stage II study area of 200 km^2 ($77\ mi^2$) in southwestern Jaffna Peninsula and northeastern Jaffna Peninsula. Supplementary data collected during this investigation would be concentrated in the Study I study area but would also be carried out on a more limited basis in the Study II study area.

Data Collection

1. Monthly measurement of water levels and analysis of water samples in 100 dug wells in the Stage I study area and 850 dug wells in the Stage II study area: Part of present Irrigation Department program.
2. Rainfall data collection: Part of present Irrigation Department program.
3. Ground-water withdrawal from wells: Part of present Irrigation Department program.
4. Core drilling: Initiated in January 1977 by the Irrigation Department.
5. Periodic measurement of flow of springs and seeps.
6. Well drilling and pumping tests.
7. Specific capacity pumping tests of selected dug wells.
8. Periodic salinity and potentiometric head profiles in bore holes.
9. Soil salinity data.

Analysis

1. Evaluation of fracture traces on aerial photographs as indicators of the occurrence of solution channels.
2. Evaluation, where feasible, of the hydraulic properties of the limestone aquifer.
3. Preparation and interpretation of water-table maps and evaluation of the three-dimensional flow pattern within the aquifer.
4. Definition of the subsurface lithology of the Jaffna Limestone and, where feasible, the vertical distribution of solution openings.
5. Determination, where feasible, of the distribution of major solution channels.
6. Evaluation of salinity maps, soil salinity data, and salinity profiles, and definition of the fresh-water lenses.
7. Development of water balance to evaluate recharge, discharge, and change in storage within the fresh-water lenses.
8. Evaluation of feasibility of utilizing discharge to the sea by structural techniques.
9. Development of water-management plan including identifying areas of greater potential supply, recommended withdrawal rates and well spacing, and feasibility of water transfer.
10. Determination of construction costs for structural methods of controlling discharge to the sea.
11. Preparation of a final report.

Estimated Costs of Personnel and Equipment

	Cost in Sri Lankan rupees
Jaffna Office Staff	200,000 per annum
Ground Water Hydrologist Consultant	440,000 per annum
Additional Irrigation Dept. Staff	5,000 per annum
Well Drilling, 6 Wells, 50 to 80 feet deep @ 150 rupees per foot	60,000
Core Drilling of 30 Bore Holes, 60 to 100 feet deep @ 50 rupees per foot	120,000
Two Pumps	60,000

Total cost for a 3-year study 2,175,000 rupees

Bank quotation of exchange rate on June 30, 1977: U.S. $1 = 8.68 S.L. rupees

Time Required

The project is planned for 3 years. A generalized estimate of the timing of the project by half year increments is as follows:

		Years of investigation					
	Data collection	1		2		3	
1.	Monthly measurements	x	x	x	x	x	x
2.	Rainfall data	x	x	x	x	x	x
3.	Ground-water withdrawal	x	x	x	x	x	x
4.	Core drilling	x	x				
5.	Measurement of springs	x	x				
6.	Well drilling and pumping tests			x	x		
7.	Specific capacity tests		x	x			
8.	Salinity profiles	x	x	x	x		
9.	Soil salinity	x	x				
	Analysis						
1.	Aerial photographs	x	x				
2.	Hydraulic properties		x	x	x		
3.	Water-table maps and flow patterns	x	x	x	x	x	
4.	Subsurface geology	x	x	x			
5.	Distribution of solution openings	x	x	x	x		
6.	Salinity maps and profiles	x	x	x	x		
7.	Hydrologic budget		x	x			
8.	Feasibility of structural techniques			x			
9.	Water management				x	x	x
10.	Construction costs			x			
11.	Final report					x	x

Reports

Three reports would appear to be appropriate:

1. Feasibility and cost of structural means of controlling discharge to the sea.
2. Water management practices for the Jaffna Peninsula.
3. Final summary report of data and interpretation.

CONCLUSIONS

The ground-water resources of the Jaffna Peninsula have been the subject of considerable discussion and investigation for many years. The main problem concerning ground water in the Jaffna Peninsula, as considered in the past, contains three elements: recharge occurs during a 3-month monsoonal period each year; most of this water is lost to the sea through a network of solution channels in the limestone aquifer; and saltwater intrusion and upconing of the freshwater-saltwater interface occur at many locations. Ambitious and intensive programs of data collection have been designed and carried out by the Irrigation Department in order to solve the Jaffna problem.

The author believes that recharge to the Jaffna Limestone is considerably greater than has previously been thought, that most of the recharge is stored in the aquifer as the saltwater-freshwater interface is depressed, and that discharge to the sea is a less significant part of the water balance. Most of the water recharging the aquifer is later withdrawn by wells. However, more data, particularly relating to hydrologic and salinity conditions at greater depths, are required in order to make a definitive evaluation.

The development of a water-management plan is needed in order to control saltwater intrusion and upconing of the saltwater-freshwater interface while maximizing the amount of fresh water that can be extracted. A study to determine the feasibility of controlling discharge to the sea should be developed within the context of the overall management plan. The management plan should delineate areas where increased withdrawal of ground water is possible and areas where present withdrawal rates are excessive. It should provide also for continuing surveillance of the interface position.

In areas of high salinity the pumping rates of individual wells are too great to achieve a stabilization of the interface beneath the well. The quality of the water being pumped could be improved by reduction of pumping from individual wells. Maximum utilization of the aquifer in such areas could be accomplished by pumping a larger number of shallow, large-diameter wells at lower rates per well or possibly by the utilization of collecting galleries. The proposed study should determine optimum well spacing and pumping rates based upon local hydrologic conditions. The study should also consider the transfer of water from "water rich" to "water poor" areas.

The proposed 3-year study should utilize the Irrigation Department's demonstrated ability to design and carry out an effective program of data collection and subsurface exploration. The Department's expertise in designing, construction, and estimating costs of water-supply projects should be integrated into the feasibility aspects of the study. Because of a shortage of experienced ground-water hydrologists within the Department, the addition of one full-time, experienced ground-water hydrologist to the project is essential.

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