AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523
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Batch 98 ARDA

1. SUBJECT CLASSIFICATION
A. PRIMARY: Food production and nutrition — AP10-0000-G582
B. SECONDARY: Water resources and management--Bahrain

2. TITLE AND SUBTITLE
Bahrain water resources management study; final report

3. AUTHOR(S)
(101) Metcalf & Eddy, Inc., Boston, Mass.

4. DOCUMENT DATE: 1977
5. NUMBER OF PAGES: 126p.
6. ARC NUMBER: ARC

7. REFERENCE ORGANIZATION NAME AND ADDRESS
M&E

8. SUPPLEMENTARY NOTES (Sponsoring Organization, Publishers, Availability)
(Final report)

9. ABSTRACT

10. CONTROL NUMBER
PN-AAG-369

11. PRICE OF DOCUMENT

12. DESCRIPTORS
Water supply
Water resources
Ground water
Waste water
Water use
Aquifers
Bahrain

13. PROJECT NUMBER

14. CONTRACT NUMBER
AID/otr-C-1301

15. TYPE OF DOCUMENT

AID 590-1 (4-74)

19

PN-AAG-369

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Metcalf & Eddy, Inc.

January 19, 1977

Mr. Juan Cabrero, Chief
General Engineering Branch
Office of Engineering
Department of State
Agency for International Development
Washington, D.C. 20523

Subject: Contract No. AID/OTR-C1301, Final Report
Bahrain Water Resources Management Study

Dear Mr. Cabrero:

In accordance with Work Order No. 3 under our contract No. AID/OTR-C1301, we have completed field studies in Bahrain and are pleased to submit this report on Management of Bahrain's Water Resources.

Included in the report are suggestions as to the type of USAID assistance which might be most helpful to the Government of Bahrain in management of their water resources.

Very truly yours,

METCALF & EDDY INTERNATIONAL, INC.

Stephen L. Bishop

Stephen L. Bishop
Vice President

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REPORT

CHAPTER 1

INTRODUCTION

General

On October 14, 1976, USAID entered into an agreement with Metcalf & Eddy, International to furnish the services of a Senior Waterworks Engineer and a Senior Groundwater Hydrologist for a six-week period in Bahrain. Mr. A. D. Moody and Mr. R. Lubke provided these services.

Purpose

The main purposes of their visit were to:

1. Make a general review of Bahrain's water resources, water usages, water supply and distribution systems, and planning for future water usage and distribution;
2. Suggest means of achieving a more beneficial use of available groundwater and reclaimed wastewater, and;
3. Indicate where AID-sponsored advisors could materially assist the Government of Bahrain in the following areas:
   a. Improving management of the total water resource;
   b. Implementing development of alternative water supplies other than groundwater;
   c. Controlling development and use of groundwater;
   d. Improving efficiency in use of irrigation water;
   e. Reducing loss and waste in the potable water distribution system;

f. Compiling, collecting and evaluating data which would lead to a better understanding of the ground water aquifer system allowing better forecasts of changes in either quality or volume of available flow;

g. Establishing a water accounting and billing system based on metered billing rates and manual or computer billing of water use;

h. Improving control of leakage reports, including reporting and evaluating procedures for repair of each leak and classification by type or evident cause;

i. Establishing detailed tie books for all valves, hydrants, main junctions, etc.;

j. Setting up and controlling system maintenance of valves blowoffs, tanks, pumps, etc.;

k. Establishing personnel requirements for improved system operation including preventative and corrective maintenance together with job descriptions and recommended position salary ranges competitive with the private sector.

Investigations

The team arrived in Bahrain on November 1, 1976; and on November 2, 1976 met with Shaikh Khalifa bin Salaman bin Mohamed Al-Khalifa, Assistant Under Secretary for Oil and Industries. At the close of this meeting, the team went to the Directorate

of Electricity where they met with Mr. Jamil Al-Alawi (Under Secretary for Power and Water Affairs) and were assigned temporary office space. On the following day, they met with Mr. Mahmoud Urrayed, Chemical Engineer at the power/desalination plant who ably assisted the team in collection of data by arranging interviews with the various Ministries and Directorates and assisted in procurring loans of various reports and engineering documents pertinent to the study.

Team investigations comprised the following:

1. A review of existing reports and records pertaining to water supply, usage, conservation, quality, distribution and production;
2. Field inspections of various water facilities including conductivity measurements of water supplied by various wells and the desalination plant at Sitra; and
3. Interviews with Government and Private Officials regarding additional data on present conditions, Government policy and planning and problems in their areas of responsibility or concern.

The following individuals were interviewed and provided valuable assistance and information to the team:

<u>Ministry of Development and Industries</u>

Sheikh Khalifa bin Sulman bin Mohammad Al-Khalifa

Mr. Mahmoud Urrayed*, Chemical Engineer, Power and Desalination Plant

Mr. Kaden Hashmi, Manager Generation and Desalination, Power and Desalination Plant

Mr. Hassan Mansoor, Public Relations Superintendent

Water Supply Directorate

Mr. Rasul Mussayab, Director of Planning

Mr. John N. M. Hutton, Chief Engineer

Public Works Directorate

Mr. Bjorn Nilsson

Ministry of Commerce and Agriculture

Directorate of Agriculture

Mr. Ibriham Lori, Manager of Water Resources Board

Mr. Mohammad Ayub, Agricultural Engineer

Dr. Edmund P. Wright, Advisor** to Agriculture Directorate in Hydrogeology, Institute of Geological Sciences, London U.K.

Ministry of Housing

Physical Planning Unit

Mr. Mohamad Nur-UN-Nabi, Director of Planning

(BAPCO) BAHRAN PETROLEUM COMPANY

Mr. Carl Helms, Lead Geologist

Mr. Jafir Masali

*Assigned as contact officer to assist the team in setting up further meetings and obtaining data pertinent to their study.
**On part-time basis including one or more short visits per year.

Ministry of Housing

Physical Planning Unit

Mr. Mohamad Nur-UN-Nabi, Director of Planning

(BAPCO) BAHRAN PETROLEUM COMPANY

Mr. Carl Helms, Lead Geologist

Mr. Jafir Masali

Rendel, Palmer & Tritton - Engineers

Mr. Stevens

Information on water supply was obtained from reports and studies prepared by numerous consulting engineers government and private agencies. Such reports are listed in the Table of References, page 2-3, which also includes other reports and information pertinent to Bahrain's water resources. Data was also made available for our evaluation by the Water Resources Board, Water Supply and Agricultural Directorates and the Bahrain Petroleum Company. The data includes current information on water abstraction rates, water supply system design and problems, water quality, aquifer pressure head, and borehole data.

Study Area. The area investigated in the State of Bahrain is limited primarily to the islands of Bahrain, Muharraq and Sitra on which nearly all of Bahrain's population reside. (See map, page 1-6). The islands comprise some 227 square miles and make up 89 percent of a total land mass of 256 square miles.* The

*Statistical Abstract, 1972, by Public Works Directorate, Bahrain.

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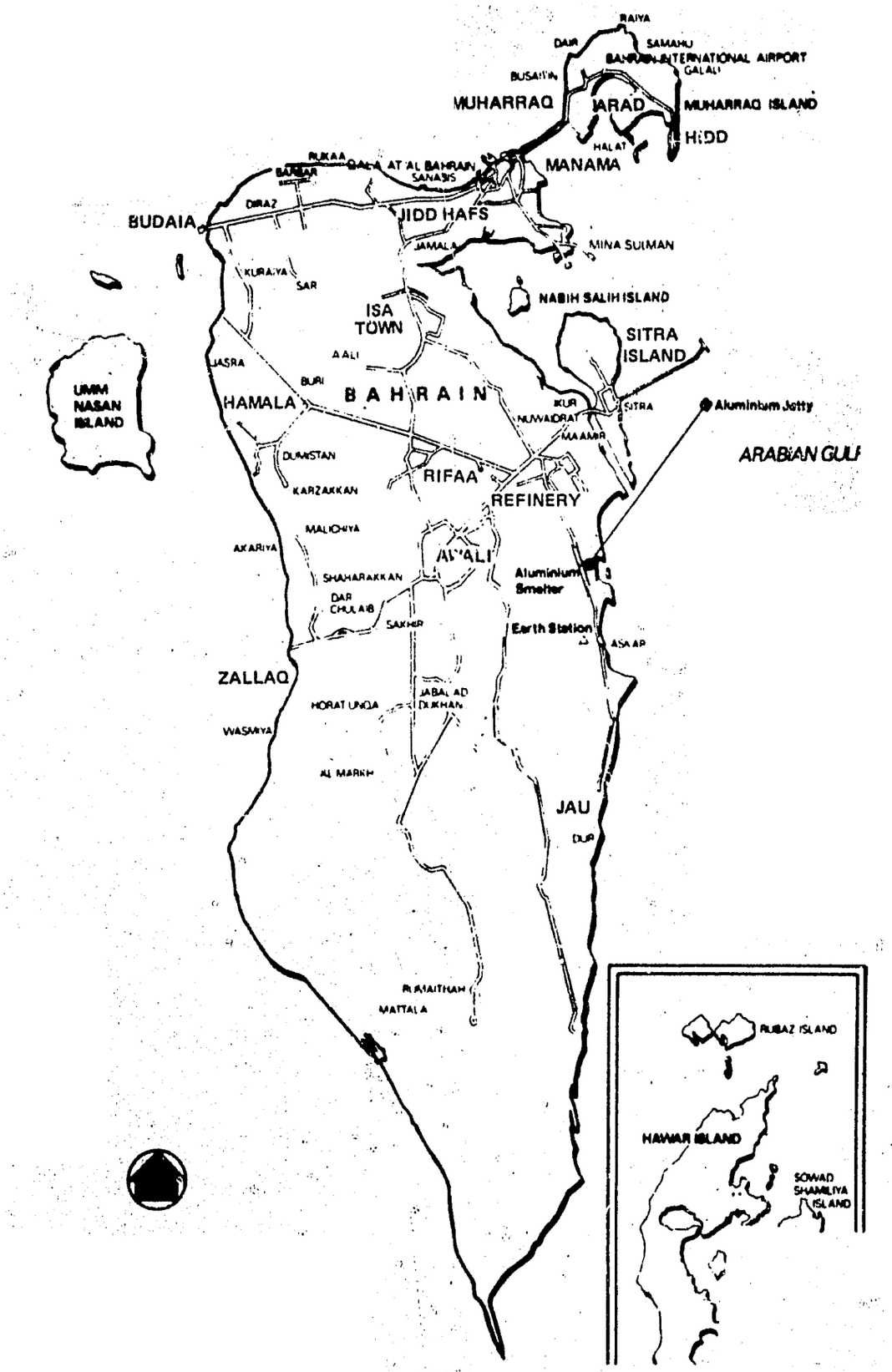

MAP 1

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remaining 11 percent comprise a number of islands of which Hawar, located 13 miles southeast of Bahrain Island, is the largest.

The islands are relatively flat and reach a maximum elevation of 440 feet on Bahrain Island. Drainage is generally poorly developed, and in some areas, as on Bahrain Island, is internal toward topographic depressions.

Population

The population of Bahrain is concentrated in the northerly one-third to one-half of the island of Bahrain and the adjoining islands of Muharraq and Sitra. About 70 percent of the population of the country reside in Muharraq, Manama Town and Greater Manama on the northeastern portion of Bahrain Island and the western portion of Muharraq which is connected to Manama by a causeway. Bahrain's population growth as indicated by census figures has been as follows:

Year	Total population*	Percent Bahrainis*
1941	89,970	82.3
1950	109,650	83.0
1959	143,135	83.0
1965	182,203	79.0
1971	216,078	82.5

This data has been plotted in Figure 1-1. The differentiation between Bahrainis and total population is made because the number of non-Bahraini residents is dependent upon government

From John Taylor & Sons 1974 report, Water Distribution Study, Reference No. 2.

policy and the degree of industrial and building activity in Bahrain. These factors will have a strong influence on labor requirements and the number of non-Bahraini workers needed and/or allowed in the country.

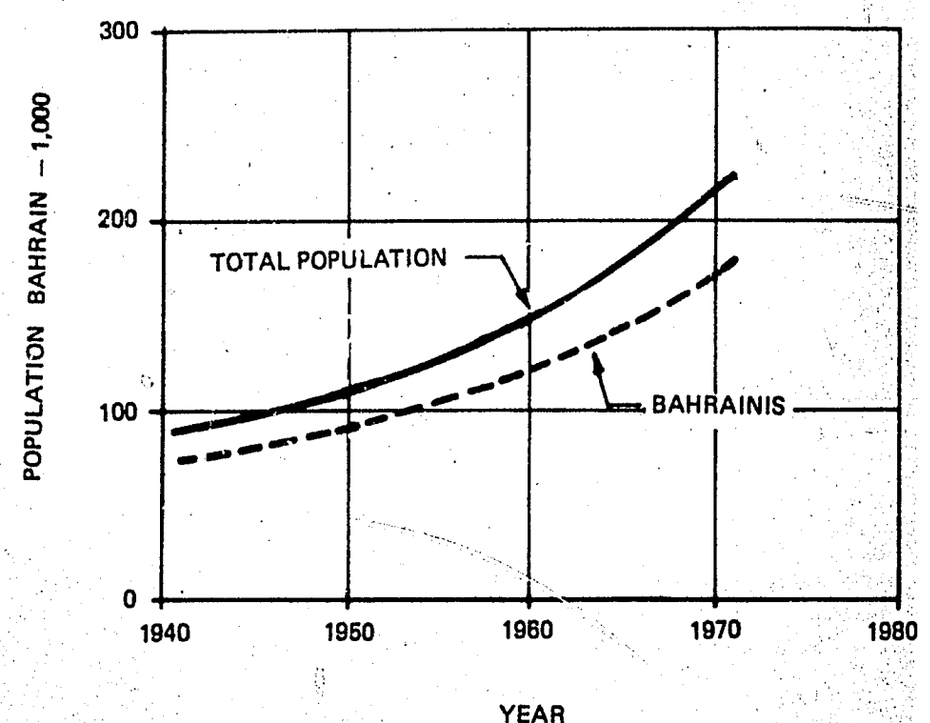

FIG. 1-1 HISTORICAL POPULATION TRENDS

The last census carried out in Bahrain was in 1971 before the present industrial-commercial growth. This growth has brought about housing shortages and consequently caused an increase in construction of houses, apartment buildings and hotels. As a result of the acceleration in building of all types, labor shortages have developed and additional foreign workers have been imported on a temporary basis. Consequently, a marked increase in total population has undoubtedly occurred.

In Taylors Rural Water report, Reference 2,* population increase is projected on the basis of a decreasing rate of growth shown in Figure 1-2.

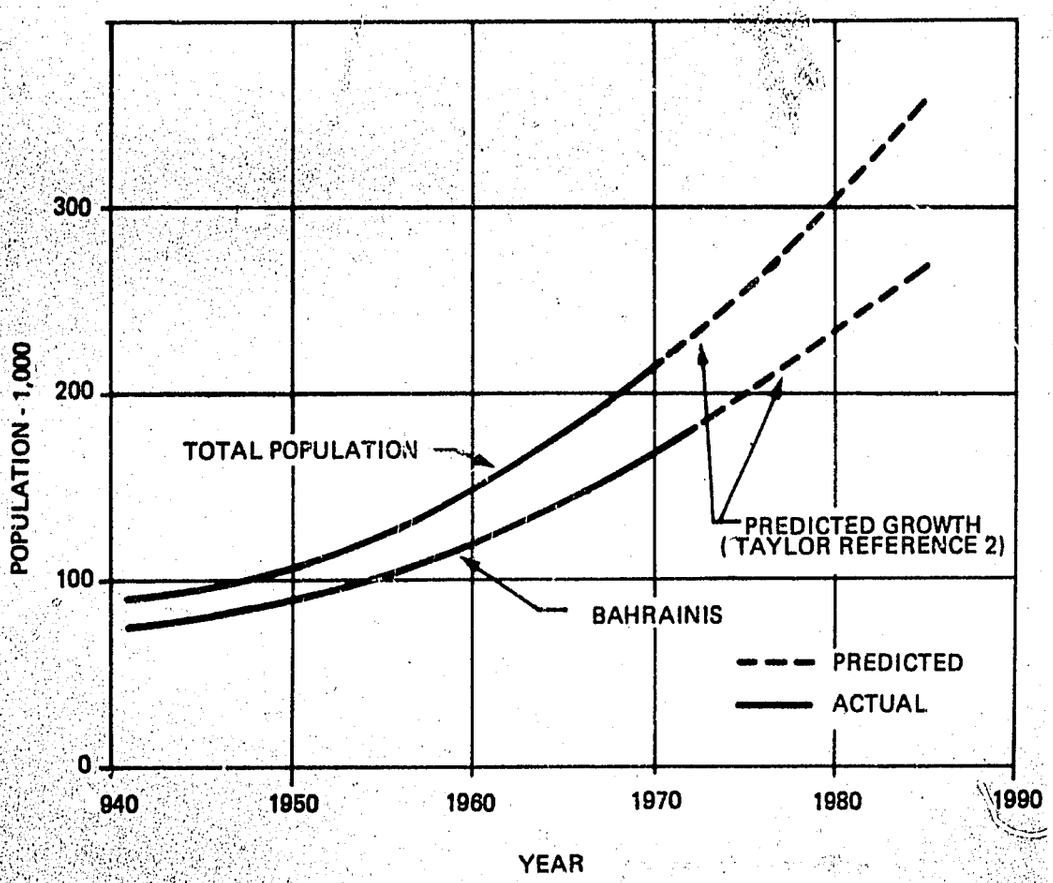

FIG. 1-2 PROJECTED POPULATION GROWTH

These projections still appear reasonable and since no subsequent census has been taken are, for planning purposes, as good as any which may now be estimated. The major metropolitan areas of Manama, Muharraq and Jidd Hafs area (also referred to

*References included on pages 2-3 through 2-5 of Chapter 2.

as Greater Manama) were expected by Taylor (Reference 1) to grow as indicated in Table 1-1.

TABLE 1-1. PROJECTED POPULATION DISTRIBUTION - URBAN AREA

Year	Manama[1]	Muharraq[1]	Jidd Hafs	Total major urban	Total Bahrain[2]	% of total in major urban areas
1975	100,618	42,139	23,458	162,215	249,400	66.6
1976					260,600	
1977	106,751	44,531	25,668	176,950	268,300	65.9
1978					284,500	
1979	113,251	47,059	28,079	188,389	296,700	63
1980					308,500	
1981	120,143	49,731	30,687	200,561	320,000	62.6
1982					330,900	
1983	127,465	52,556	33,489	213,510	341,000	62.6
1984					350,400	
1985	135,252	55,538	36,520	227,310	358,900	63

1. From Reference 1.
2. Reference 2 predicted growth for rural and urban areas combined.

If the projected urban totals are expanded to include Awali, Rifa'a Town, Sitra Town, and Isa Town, then the urban population as a percentage of total population rises to about 79 percent for the period from 1959 through 1971, the last census, and according to the projections shown in the Rural Report,

Reference 2, will increase to about 82 percent by 1985 (see Table 1-2).

TABLE 1-2. POPULATION IN URBAN AREAS

Urbanized area	1959	1965	1971	1975(1)	1985(2)
Manama	61,726	79,098	88,785	101,900	135,250
Muharraq(3)	31,555	39,660	43,001	47,410	72,140
Jidd Hafs	5,591	7,941	11,152	13,640	27,450
Isa Town	-	-	7,501	12,100	30,000
Sitra Town	3,926	5,071	6,663	7,590	10,420
Rifa'a Town	6,623	9,403	10,731	12,220	16,770
Awali	3,123	2,097	984	1,500	2,000
Total	112,544	143,270	168,817	196,360	294,030
Total Population	143,135	182,203	216,028	249,400	358,900
Percent Total	78.6	78.6	78.1	78.7	81.9

1. Estimated by John Taylor & Sons, Reference 1.
2. Projected by John Taylor & Sons, Reference 2.
3. Includes Hidd.

Again, these projections appear reasonable. It is possible that there may have been some increase in the rate of growth during the past two years. This increase may continue for a few more years. It is believed that most of any increase over projected population growth is primarily due to import of labor to meet shortages induced by the area economic growth.

Climate

Bahrain has a hot dry climate with high relative humidity for most of the year. During the period from May through October,

daily maximum temperatures are consistently above 30 deg C (86 deg F). The winter months are cooler with temperatures often 20 deg C (68 deg F) or lower.

Maximum daily humidities may exceed 95 percent quite regularly in the winter, but average humidities are usually lower allowing a rather high evaporation rate. Minimum daily humidity levels usually occur during the summer months and although ambient temperatures are high, the high evaporation rates make conditions fairly comfortable.

Rainfall in Bahrain is low with an average annual precipitation of about 75 mm (millimeters), less than 3 inches. Most of this rainfall occurs in the winter months. In fact, in 26 years of complete records, 1946 to 1971, no rainfall has been recorded during the months of June, July, August, and September.

The prevailing wind direction is NNW to WNW with the wind speed generally under 14 knots. However, wind gusts have been recorded up to 51 knots. Generally, there are calms less than 10 percent of the time with the greatest percentage during the summer months. The wind very seldom blows from directions outside the northwest quadrant.

Evaporation potential and rainfall are the major climatic factors on Bahrain which influence the hydrologic cycle and, therefore, groundwater availability and to a major extent, water use requirements. The former is estimated to be an important component of naturally occurring groundwater discharge via soil evaporation and also dictates agricultural water requirements for

crop irrigation. Such requirements, in turn, govern total groundwater abstraction rates of which nearly 90 percent is used for irrigation. Rainfall is inadequate to meet crop water requirements and does not contribute significantly to groundwater recharge. Such recharge, which does occur from rainfall, may permit only limited development of a relatively small freshwater supply within the Rimrock area.

Potential evaporation based on Class A Pan data and estimated for open-water bodies ranges from about 2,000 to 2,300 mm per annum. Periods of peak evaporation occur during the months of May through June as shown in Figure 1-3. Estimates made on evapo-transpiration or consumptive use by plants range from about 1,600 mm to 2,000 mm depending largely on type of crop.

Long-term rainfall records are available on Muharraq. These show a mean annual rainfall of 70 mm, nearly all of which falls during the months of November through May. Large variations in rainfall are normal with over 60 mm of rainfall recorded during one day, and practically no rainfall having been recorded for the months of June through September. Wide variations in rainfall are also suggested in Table 1-3 which lists total monthly and annual rainfall for the period of 1967 to 1972. Rainfall events are normally associated with high intensity, but are often localized showers of relatively short duration.

Salt Weathering

The climate of Bahrain is responsible for hazards primarily to masonry and concrete structures which are generally peculiar

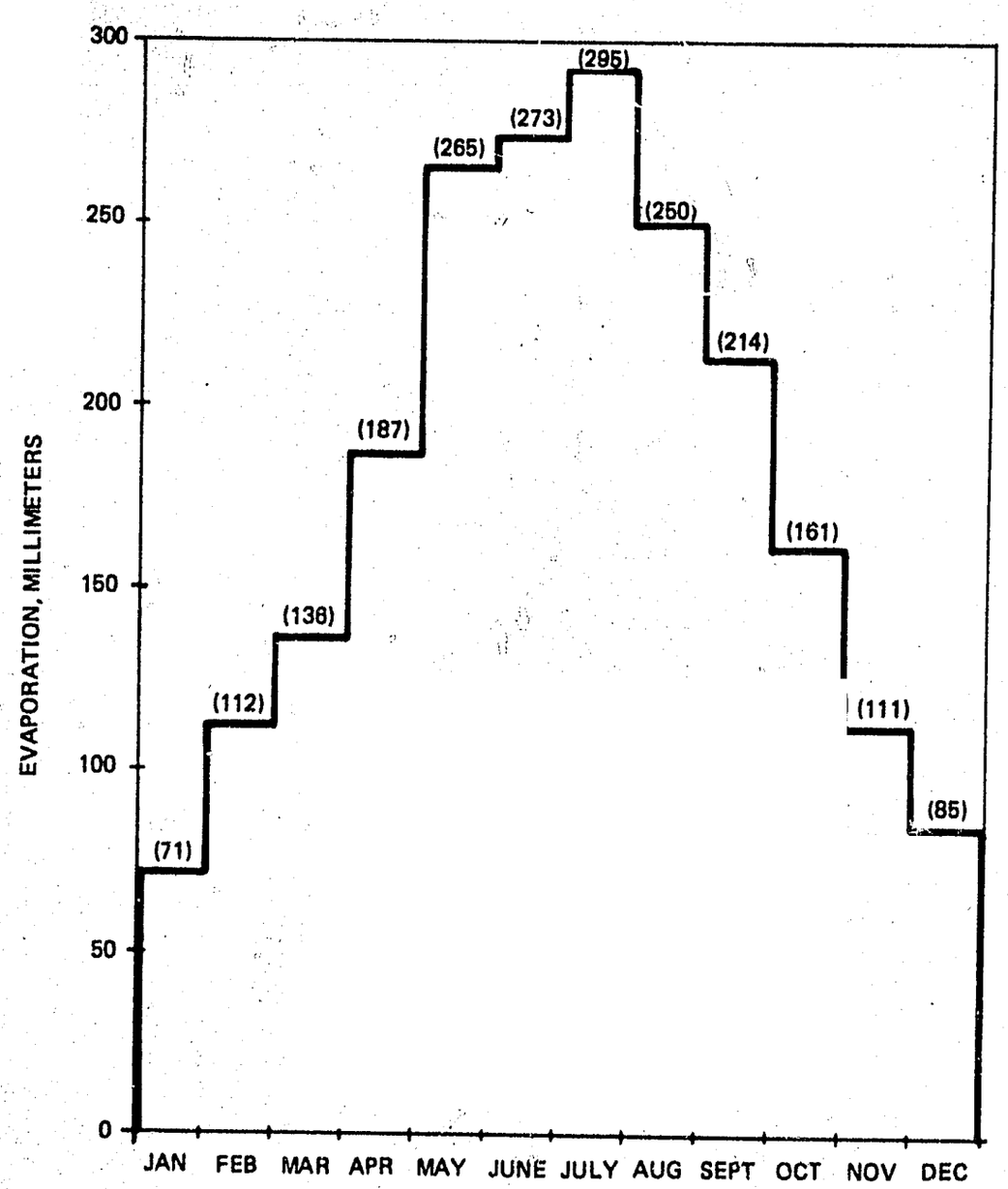

FIG. 1-3 AVERAGE MONTHLY CLASS A PAN EVAPORATION, MUHARRAQ PERIOD 1970–1972

TABLE 1-3. TOTAL MONTHLY AND ANNUAL RAINFALL, MUHARRAQ, IN mm

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Totals
1967	1.8	8.3	5.5	6.4	3.2	-	-	-	-	-	3.7	T	28.9
1968	T	52.7	1.4	14.3	0.1	-	-	-	-	-	2.7	5.1	76.3
1969	87.7	10.4	0.6	49.2	T	-	-	-	-	8.9	9.1	T	165.9
1970	7.4	T	1.2	T	T	-	-	-	-	-	-	0.3	8.9
1971	2.6	8.0	1.0	8.0	1.0	-	-	-	-	-	1.3	3.3	25.2
1972	19.5	10.0	42.0	3.1	0.1	-	-	-	-	-	4.0	6.1	84.8

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to arid zones. They include drying out of mortar and concrete before they are fully cured causing loss of strength and cracking. This is generally less serious than the complex salt weathering problems which may occur. Most of these problems stem from the presence of salts and saline solutions in construction materials or groundwater. The more serious are:

1. Changes in the chemical composition of materials which may reduce strength or resistance to normal weathering or result in volume changes such as the well known reaction of sulphates forming calcium aluminum sulphate in concrete which will result in failure of the concrete.
2. Changes in salts or saline solutions in stone, concrete, mortar or other materials which may cause weakening or complete disintegration. These changes may include, but are not necessarily limited to:
   a. Growth of salt crystals in pores due to capillary rise of saline groundwater in the structure and subsequent evaporation,
   b. Differential thermal expansion of salt in stone, concrete or other building materials, and
   c. Hydration of salts.

These problems involve changes in volumes of salt within the material and these changes, especially increases, may cause disintegration of the materials in which they occur or decreases

in volume such as solution of salts from fills may cause settlement and subsequent damage to structures.

Salt weathering of structures in Bahrain is evident in most areas, but appears most severe where saline groundwaters are sufficiently close to the surface to place the structures in the zone of capillary action. Most of the heavily built-up and growing areas of Manama and Muharraq fall in this zone. The high salt weathering hazard in these areas requires expensive special care in construction. Without it, the useful life of structures may be as little as 10 years. The hazard is most serious for those structures which must pass through the capillary zone from below the groundwater table such as building foundations, manholes in drains and sewers, pipelines, etc.

Water Supply. Present water use in Bahrain as reported by the Ministry of Works, Power and Water is estimated at 199 MCM (million cubic meters) per year. Of this amount, about 166 MCM per year is used for irrigation and the remainder for domestic, commercial, municipal, and industrial uses. At least 98 percent of the total water use is from groundwater sources while about 4 MCM per year is obtained for use from a desalination plant which uses sea water as its source of supply.

Groundwater sources, which presently supply nearly all of Bahrain's water requirements, include a sequence of essentially artesian carbonate aquifers whose source of recharge is in the interior of Saudi Arabia. In the Bahrain area, these aquifers are exposed at or near the land surface as a result of geological

deformation. The aquifers are tapped by numerous wells which are concentrated mostly in the northern half of Bahrain Island and on Muharraq Island where the best quality groundwater is found. Because of an increasing salinity gradient to the south, the groundwater throughout the remainder of Bahrain Island is generally unacceptable for most uses.

Water resources which originate on Bahrain are severely limited by a lack of rainfall. Runoff which originates from occasional rainfall, either rapidly runs off to the sea or accumulates in depressions where it either evaporates or infiltrates to the groundwater table. Such infiltration sustains a shallow fresh groundwater system in the interior parts of Bahrain Island, but in insufficient quantities to permit any major groundwater development.

The greater abundance of better quality groundwater has resulted since historic times in major population concentrations in the northern parts of Bahrain Island and the islands of Muharraq and Sitra. Present patterns of population growth to some extent continue to be controlled by or associated with the occurrence of better quality groundwater.

Increasing pumpage of groundwater as well as an overall reduction in recharge due to long-term climatic changes has resulted in a depleting groundwater resource as evident from regionally declining pressure heads in aquifers and associated salt water encroachment along the northeastern coast of Bahrain Island and on Sitra Island. Based on the trend of declining

pressure heads, continuing availability of fresh groundwater is estimated by others to last until about the year 2000 (References 7 and 8). As a result, the government is undertaking studies and projects which should result in conserving groundwater resources and also reducing the country's dependence on such resources.

Land-Use Planning and Zoning. Information on land-use planning and zoning is limited. A broad zoning plan is available for the Manama-Muharraq-Isa Town-Rifa'a area which permits mixed residential and commercial development and has set aside areas for industrial and green belt use. The latter allows either recreational or agricultural use or both. Most of the green belt areas are government owned, although some is under private ownership. There are three major areas which are zoned for green belts. These include an area just west of Manama which is privately owned and two government holdings, one of which is located between Isa Town and Rifa'a and the other between Rifa'a and Awali. Because of a burgeoning population, the need for increased housing reportedly has created a priority in terms of setting aside areas for residential use. This priority may infringe on both proposed green belt areas and on rural areas presently under cultivation where zoning does not exist.

Future population growth is expected to take place principally within and around existing population centers which include Rifa'a to the south and extends north through Isa Town and includes the peninsular area where Manama is located and then west to Muharraq. Other possible areas of future development and

population growth include the northwestern part of Bahrain Island where growth is likely to be associated with the completion of the causeway which will link Bahrain to Saudi Arabia. Additional developments include several proposed country clubs with a golf course on the southern end of Sitra Island and a proposed recreational-resort area, plans for which are presently understudy. The proposed area consists of about 3 square miles of land located along the west coast of Jazayir just south of Wasmiya. The area is to contain hotels, golf courses, beaches and other recreational facilities.

Generally, existing land-use zoning is reportedly flexible and not necessarily restrictive. In rural areas, present land-use controls permit residential development on one-fourth of privately owned land holdings. Such controls only apply to the northwestern part of Bahrain Island to the north of Awali and Zallaq where there is private land ownership. Areas to the south of Awali and Zallaq are largely controlled by the government and are unregulated.

There are no formal building codes in effect. Proposed development plans, however, require approval by the Ministry of Housing before construction can begin.

CHAPTER 2

PREVIOUS STUDIES AND REPORTS

The Government of Bahrain, over the past five to six years, has commissioned studies and reports concerned with or pertinent to water supply, distribution, management, conservation and reuse. Study reports were furnished to the water resources team and provided an important part of the data and information upon which this report is based.

These reports, listed hereinafter as references and referred to in this report, contain recommendations for:

1. Reduction in agricultural demand for and use of water through improved utilization of irrigation water and reduction of losses,
2. Reduction in commercial, industrial, sanitary and potable water, nonessential use and waste through metering, monitoring of system leakage and a realistic rate structure based on metered water use and the cost of providing water,
3. The means of supplying projected future demands for piped potable quality water for domestic, commercial, and industrial use with allowances for watering of gardens,
4. The best method for utilization of distilled water (produced at the Sitra power and desalination plant) to upgrade the quality of the piped water supply throughout the system as uniformly as possible,

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5. A wastewater collection, treatment and reuse system designed to collect all sanitary wastewater (sewage) from Manama, Muharraq, Greater Manama, and Isa Town; treat, disinfect, store and convey it to proposed government-operated demonstration farm land south of Isa Town and to roadside plantings for reuse as irrigation water, and
6. A program of constructing additional observation wells and continued collection of well pressure-head data and water quality with analysis and interpretation of data to improve understanding of the performance of the aquifer, the effect of pumping and the probable rate of degradation of the quality of the groundwater supply.

The study team reviewed the data, conclusions and recommendations in these reports and in some instance, suggested modifications to programs presently being implemented or in the planning stage.

Following is the list of references which were reviewed and have been referred to in this report. Following the references is a list of other pertinent studies collected and reviewed during the course of the field investigation.

LIST OF REFERENCES

1.	Water Distribution Study Report - January 1974	John Taylor & Sons, Consulting Civil Engineers, Artillery House, Artillery Row, London SW1P 1RY
2.	Water Distribution Study Rural Areas - September 1975	John Taylor & Sons, Consulting Civil Engineers
3.	Discussion papers for water. Rate schedule development. Interim Report 4 and 6. Interim 4 - Ten-year forecasts water consumption Interim 6 - Proposals relating to tariff structure	Price-Water House, Abu-Ghazaleh & Co.
4.	State of Bahrain Ministry of Works and Power, Bahrain Surface Materials Resources Survey, 6-volume report plus plates - February 1976	Survey team composed of geologists, engineering geologists, geomorphologists, civil engineers, soil surveyors, and a cartographer mostly from universities and colleges in Great Britain and lead by Senior Consultants, D. Brunsden, J. C. Doornkamp and D.K.C. Jones.
.	Bahrain Sewerage Project - Government of Bahrain, 5-volume report and preliminary design drawings for Manama and Muharraq - October 1975	J. D. and D. M. Watson, Terriers House, Amersham Road, High Wycombe, United Kingdom
6.	Groundwater Abstraction and Irrigation in Bahrain Undated, but during or after 1972	Dr. E. P. Wright, Institute of Geological Science, London, U.K. and Mohammed Ayub, Irrigation and Drainage Section, Directorate of Agriculture
7.	Water and Agricultural Studies in Bahrain, Kingdom of Saudi Arabia, Ministry of Agriculture and Water and Government of Bahrain, 2-volume report plus appendixes - September 1971	Italconsult, Rome, Italy

LIST OF REFERENCES (Continued)

8.	Report on Groundwater Resources of Bahrain, 1967	Dr. E. P. Wright, Institute of Geological Science, London, U.K.
9.	The Groundwater of North-eastern Saudi Arabia: Fifth Arab Petroleum Congress, 1965	Ali I. Naimi
10.	Geology of the Arabian Peninsula-Bahrain: U. S. Geol. Survey Prof. Paper 560E, 1967	R. P. Willis
11.	Geology of the Arabian Peninsula-Sedimentary Geology of Saudi Arabia: U. S. Geol. Survey Prof. Paper 560D, 1966	Powers and others
12.	Final Report, Feasibility Study on the Reuse of Sewage Effluent for Agricultural Purposes, Bahrain, August 1975	G. P. McGowan and Associates
13.	Irrigation Trials on Winter Vegetables 1973-1974, October 1974	UNDP report to the State of Bahrain
14.	Report on Rehabilitation of and Water Distribution from Five Wells Between and Including Gassari and Adari, August 1973	By ERCON, Consulting Engineers for the Ministry of Agriculture and Municipalities, Bahrain
15.	Feasibility Study on the Direction of Submarine Springs by Infra-Red Line Scanning, February 1974	By ERCON, Consulting Engineers for the Ministry of Agriculture and Municipalities, Bahrain
16.	Specific Study, Water Demineralization, Area IV, Kingdom of Saudi Arabia, Parts 1 and 2	Italconsult, Rome, Italy
17.	Land Spring Survey, January 1953	Report by BAPCO

18.	Groundwater Potential of Karst Aquifers in Saudi Arabia, 1969	D. J. Burden and G. Otkun
19.	Report on a Site Investigation for Sewerage and Sewage Treatment Works in the State of Bahrain, 3 volumes, March 1976	By Cementation Ground Engineering, Limited, for Ministry of Works, Power and Water
20.	Report for the Organization of Arabian Petroleum Exporting Countries on Proposed Arabian Gulf Repair Yard, Bahrain, September 1974	Wimpey Laboratories, Limited
21.	Report on Strengthening of the Department of Agricultural Services in Bahrain, October 1973, 2 volumes	By ERCON, Consulting Engineers for the Food and Agricultural Organization of the United Nations

Other Pertinent Studies

1.	Water Resources of Bahrain Island, 1940	P. Hurry, BAPCO
2.	Water Resources of Bahrain, 1941	G. W. Gulmon, BAPCO
3.	Water Resources of Bahrain Island, 1942	M. Steineke, BAPCO
4.	Water Resources - Bahrain Island, 1943	R. Godfrey, BAPCO
5.	Report on the Water Resources of Bahrain Island, 1948	R. Godfrey, BAPCO
6.	Artesian Well Survey - Bahrain, 1953	J. D. Porrit, BAPCO
7.	The Hydrology of Bahrain, 1958	R. E. DeMestre and P. A. T. Haines, BAPCO
8.	Water Resources of Bahrain, 1965	W. J. Hamilton, BAPCO
9.	Report on Groundwater Extraction of Bahrain Island and Coastal Hasa, 1967	J. W. Sutcliffe, U.K. Geological Service
10.	Groundwater of Eastern Saudi Arabia with Special Reference to Hasa Province, 1941	ARAMCO

11. Available maps:

    a. General map - at scale about 1:23600, revised 1966.

    b. Bahrain Island - 5 maps at scale of 1:50000, date 1956.

    c. Bahrain islands at scale of 63360, revised 1968.

CHAPTER 3

EXISTING CONDITIONS

General

Presently, at least 98 percent of the country's total water supply is extracted from a self-depleting groundwater aquifer system while 2 percent or less is desalted sea water. Generally, the quality of most of the extracted groundwater is unacceptable or but marginally acceptable for human consumption because of relatively high total dissolved solids. It is, however, in most cases acceptable for use in irrigating salt tolerant crops.

About 98 percent of the population is provided with piped water supply. About 99.2 percent of the population is provided with desalted potable water delivered by truck.

Responsibility for extraction of groundwater and supply to users is divided. Piped water for domestic and small commercial/industrial users is supplied by the Water Directorate with the exception of the old Juffair and Muharraq camp areas, and the Awali supply. The camp area systems are operated by the Directorate of Public Works and the Awali system by BAPCO.* Large commercial, industrial and agricultural users obtain their water from private wells. General control of abstractions and further development of groundwater lies with the Water Resources Board.

*Bahrain Petroleum Company.

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Water Use

General. As previously indicated, Bahrain is nearly entirely dependent on groundwater for its water supply. Present water use is estimated to total 199 MCM per year of which about 166 MCM is used for irrigation while the remainder is used for public supply and by industry. Information on past water use suggests a general increase since at least 1952, see Table 3-1. The data, although approximate, show that the largest component of water use is irrigation supply which has varied from 70 percent to 85 percent of total water use. Other major components of water use are domestic/municipal and industrial. The former supplies water for mostly household needs while the latter is used almost exclusively by oil and aluminum industries.

Sources of supply include numerous drilled wells and springs. The use of drilled wells, which presently total at least 1,000 in number, dates back to about 1924 at which time springs and shallow dug wells were the principal source of water supply. Reliance on drilled wells as a source of supply has been increasing since the early 1940's, and is in part due to declining spring yields resulting from an on-going depletion of aquifers and also on meeting the additional water requirements for a growing population and industrial base.

Although there is no clear record of historical water use, it has been suggested that the quantities of water use have decreased since at least the past 50 to 100 years as a result of

declining agricultural activity.* More recent data also suggest that since 1966, there has been no significant change in the quantities of water used other than in 1976. The values for 1976 are believed to be too high and may include consumptive use by date palms on abandoned agricultural lands.

TABLE 3-1. WATER USE

	In MCM/yr				
Year	Irrigation	Domestic and municipal	Industrial	Totals	
1952	86.9	5.1	10.1	102.1	Italconsult
1966	134.3	16.4	8.2	158.9	Wright, Reference 5
1971	104.3	20.9	8.2	133.4	Italconsult
1972	125.6	-	-	-	Wright, Reference 5
1973	98.0	31.9(1)	10.8	140.7	Watson
1976	166	20	13	199	Ministry of Works, Power and Water
1980	126	41	15	182	Ministry of Works, Power and Water
1985		48.0			

1. Includes 7 MCM/yr for private water supplies.

Nearly all water use and groundwater extraction is concentrated in the northern parts of Bahrain Island and on Muharraq Island. Some water is developed in the central part of Bahrain Island for industrial and stock use, the latter being relatively insignificant in terms of quantities abstracted. The preference

*Italconsult.

for concentrating water development in the northern part of Bahrain is based on the availability of better quality groundwater than elsewhere within the country.

Projected water use for at least the next 10 years is estimated to decrease slightly, primarily as a result of greater efficiency in irrigation practices with lesser application rates than used presently. During the same period, domestic/municipal demand is estimated to increase by about one-third while industrial demand will increase by 10 to 20 percent. A lesser reliance on groundwater sources, however, is anticipated by increased use of distilled sea water which now amounts to about 4 MCM per year, a reduction in total irrigation needs and the proposed reusal of municipal wastewater for irrigation.

Agricultural Supply. Agricultural activity is centered in the northwesterly and northerly parts of Bahrain Island and on the islands of Muharraq and Sitra. Such activities are mostly for growing crops which include dates, alfalfa and mixed vegetables, while some livestock is raised. During 1971, a total of 6,170 hectares was classified as agricultural land of which 2,220 hectares had been irrigated while the remainder was abandoned.* A report by McGowan and Associates (Reference 12) has shown no major change in irrigated area which in 1975 was estimated by them at about 2,000 hectares. Based on discussions with the Directorate of Agriculture, there are no long-term plans for

*Italconsult.

agricultural expansion. Indications are that agriculture is declining as a result of urban expansion. A continuing reductio in the agricultural labor force which presently amounts to about 1 percent of the population is due to the abandonment of land in areas of deteriorating groundwater quality. The loss of agricul tural land is, however, expected to be offset by proposed cultivation on government-owned lands in the Isa Town-Rifa'a area and locations south of Zallaq.

Water for agriculture use is primarily for the irrigation of crops and date palms, with a minor amount for raising stock. Total annual irrigation requirements during the past 24 years have reportedly ranged from about 87 to over 134 MCM per year. As of 1952, about one-half of these requirements were met by a spring flow which by 1971 only accounted for about 7 percent of the total irrigation supply. Presently, nearly all irrigation water is pumped from privately owned wells although some is obtained from public water supply sources.

It is estimated by Italconsult (Reference 7) that about 50 percent of the applied irrigation water is consumptively used by plants, while the remainder percolates to the water table. Application rates annually total about 5 meters per unit area* and are believed to be excessive in terms of both plant and soil leaching requirements. Studies being carried out at the Bahrain Agricultural Experiment Station indicate that as a rule, an

*Personal communication, M. Ayub, Directorate of Agriculture.

application rate of 3.4 meters per year is adequate for plant use and soil leaching. Future savings in the quantities of irrigation water used are anticipated once reductions in application rates can be implemented.

The overall quality of irrigation water ranges from about 2,000 to 8,000 ppm (parts per million) in total dissolved solids, although normally it is less than 4,000 ppm. An increase in the total dissolved solids content of groundwater resulting from saline water encroachment has forced the abandonment of numerous agricultural lands on and near Sitra Island. It is estimated that the landward encroachment of saline water, which is continuing at some unknown rate, will cause a further reduction in the area under cultivation.

Public Supply. Water for municipal and domestic use is obtained from drilled wells at individual pumping stations which generally discharge into an adjoining water tower from which it enters the distribution system. The Water Directorate presently operates about 63 pumping stations of which 25 are located in the Manama-Muharraq area. The rest of the stations supply water mostly to individual villages located in the northern half of Bahrain Island. Each pumping station typically consists of one or two wells which are pumped by a common suction header. Pump capacity at individual stations ranges from 650 to about 790 CMD (cubic meters per day). The wells are mostly of 6-inch diameter and are 30 feet to 410 feet deep. Presently, most of the pumping stations are operated at nearly their peak capacity throughout

the year. Construction of new wells since 1972 has been limited to two wells at the Hamala C pumping station and a well at the new Budaia pumping station which is not yet in service, but will serve the villages of Budaia, Bani, Jamra, Diraz, and Kuraiya. It has been estimated that an additional 10 wells are needed, mostly in rural areas, to serve as interim supply sources until distilled water becomes available.* At present, blended water consisting of distilled and well water obtained at Hamala and Sitra supplies Rifa'a, Isa Town, Sitra and the villages of Nuwaithdrat, Ikur and Ma'ameer.

In addition to the Water Directorate, BAPCO independently operates a separate system which supplies Awali, Askar and Jau in the east-central part of Bahrain Island. The BAPCO system is fed by three wells located in Zallaq. Pumping capacity of the wells totals 7,600 CMD. Other public supplies, but of small quantity, are obtained by wells at Wasmiya Beach and near Ras Noma from where water is pumped to Mattala Village.

The public water supply ranges from about 2,000 to 5,000 ppm total dissolved solids. The water is generally unsuitable as a source of potable supply although it is considered bacteriologically safe. The Water Directorate carries out routine analyses for bacteria, whereas chemical analyses are made randomly. Results of chemical analyses conducted since 1972 are listed in Table 3-2. Additional water quality data are listed in Table 3-3.

*Personal communication, John Hutton, Chief Engineer, Water Directorate.

TABLE 3-2. WATER QUALITY, MUNICIPAL WELLS

Well	Date sampled	In mg/L: Total alkalinity as $CaCO_3$	Total hardness as $CaCO_3$	Sulfate as SO_4	Chloride as Cl	Iron as Fe	Nitrate as NO_3	Total dissolved solids	Free CO_2	DO	pH
Zallaq	5-11-76	166	1,392	777	1,461	<0.02	2.42	3,763	10	2.4	7.1
Zallaq	7-30-73	160	1,225	755	1,460	0.10	3	3,620	7		7.6
Zallaq	1-18-71	157	1,254	780	1,410	<0.1	<0.1	3,604	20	0.2	7.1
Hamala	5-11-76	168	1,080	577	893	<0.02	10.78	2,586	12	2.6	7.1
Hamala	7-30-73	160	890	580	880	0.06	15	2,430	7		7.6
Hamala	8-13-70	168	926	590	907	<0.02	12.1	2,594	20	2.4	7.3
Isa Town 1	5-11-76	166	1,093	572	865	<0.02	10.56	2,525	8	0.7	7.2
Isa Town 1	8-12-70	168	1,179	440	1,496	<0.02	11.2	3,306	36	3.6	7.1
Isa Town 2	5-12-76	168	1,729	698	2,453	<0.02	9.24	5,275	9	2.0	7.0
Isa Town 2	8-01-73	160	1,470	660	2,360	0.12	13	4,950	7		7.6
Isa Town 2	8-12-70	170	1,407	640	2,176	<0.02	6.6	4,703	44	2.6	7.1
Sitra	5-12-76	167	1,200	468	1,475	<0.02	10.78	3,386	9	0.8	6.9
Sitra	7-30-73	160	1,020	445	1,460	0.12	17	3,200	5		7.7
Sitra	8-12-70	166	1,023	430	1,460	<0.02	12.5	3,254	20	2.0	7.1
Jidd Hafs	5-18-76	153	1,190	374	978	<0.02	10.56	2,366	4	1.4	7.5
Jidd Hafs	8-11-70	176	838	310	964	<0.02	12.8	2,302	32	1.2	7.2
Zahara	5-18-76	164	1,178	391	1,390	<0.02	12.76	3,105	8	3.0	7.4
Zahara	7-30-76	160	985	420	1,380	0.04	17	3,040	15		7.3
Zahara	8-09-70	169	1,005	400	1,361	<0.02	11.9	3,055	28	1.6	7.3
Hidd	5-18-76	166	1,244	395	950	<0.02	14.08	2,379	5	1.5	7.3
Hidd	7-30-73	155	850	440	980	0.08	20	2,410	7		7.6
Hidd	1-17-71	152	875	444	942	<0.02	14.1	2,401	20	0.6	7.3
Muharraq A	5-18-76	165	1,255	385	1,049	<0.02	14.96	2,501	4	1.4	7.6
Muharraq A	8-01-73	160	890	410	1,040	0.06	18	2,470	18		7.2
Muharraq A	1-17-71	154	907	431	1,041	<0.02	13.9	2,553	20	0.6	7.3
Muharraq A	8-10-70	164	958	400	1,035	<0.02	14.9	2,515	20	1.4	7.4
Muharraq B	7-30-73	160	850	395	980	0.06	18	2,350	6		7.6
Muharraq B	8-10-73	170	818	380	992	<0.02	14.7	2,454	32	0.8	7.2

TABLE 3-2 (Continued). WATER QUALITY, MUNICIPAL WELLS

Well	Date sampled	Total alkalinity as $CaCO_3$	Total hardness as $CaCO_3$	Sulfate as SO_4	Chloride as Cl	Iron as Fe	Nitrate as NO_3	Total dissolved solids	Free CO_2	DO	pH
		In mg/L									
Busateen	7-30-73	160	865	420	1,100	0.06	17	2,590	7		7.6
Busateen	8-10-70	174	912	440	1,070	<0.02	14.7	2,654	28	1.0	7.2
Mahooz	7-30-73	160	930	410	1,220	0.10	18	2,760	7		7.6
Mahooz	8-18-70	163	973	433	1,225	<0.02	14.3	2,924	42	1.0	7.3
Al Gufool	7-30-73	160	900	395	1,160	0.08	14	2,640	7		7.6
Al Gufool	1-14-71	153	909	431	1,146	<0.02	11.4	2,731	20	1.2	7.1
Budaia	7-30-73	170	775	410	840	0.64	18	2,150	17		7.3
Ras Rumman	1-14-71	151	1,005	449	1,350	<0.02	10.6	3,076	16	1.0	7.1
Muharja	1-14-71	151	1,003	437	1,336	<0.02	10.8	3,029	12	1.0	7.5
Zubhara	1-14-71	150	1,006	433	1,342	<0.02	10.6	3,026	12	1.8	7.1
Hura	1-14-71	152	1,009	436	1,325	<0.02	11.4	3,008	12	0.8	7.0
Salmaniya 2	1-14-71	154	965	431	1,225	<0.02	9.7	2,384	20	1.2	7.1
Jufair B	1-14-71	153	932	455	1,126	<0.02	12.1	2,716	20	0.8	7.1
Jufair A	1-14-71	154	956	447	1,183	<0.02	12.1	2,795	16	0.6	7.1
Hyde Park (Muharraq)	1-17-71	157	884	428	981	<0.02	14.3	2,464	20	0.8	7.3
Samahiy	1-17-71	146	876	478	845	<0.02	15.1	2,282	16	0.6	7.5
Malchya	1-18-71	153	998	618	987	<0.02	10.5	2,714	20	1.4	7.2
Khazzakhan	1-18-71	156	991	645	936	<0.02	10.5	2,674	20	0.6	7.3
Durmistan	1-18-71	157	964	619	913	<0.02	9.9	2,605	20	0.6	7.2
Jannusan	1-19-71	165	820	417	857	<0.02	13.2	2,265	20	1.0	7.1
Sihila	1-19-71	166	1,431	740	1,688	<0.02	9.9	4,038	20	0.4	7.1
Gudabia	8-08-70	145	965	434	1,301	<0.02	14.3	2,969	42	2.4	7.2
Mina Sulman	8-08-70	156	802	390	1,134	<0.02	14.9	2,661	40	1.4	7.2
Jufair C	8-08-70	157	941	400	1,220	<0.02	14.3	2,813	36	0.8	7.2
Hyde Park (Manama)	8-09-70	170	1,000	460	1,340	<0.02	12.8	3,109	28	2.4	7.2
Sulmaniya 1	8-09-70	174	970	400	1,226	<0.02	11.2	2,842	32	4.8	7.3
Delmon	8-09-70	171	950	440	1,205	<0.02	11.2	2,867	28	0.6	7.4

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TABLE 3-2 (Continued). WATER QUALITY, MUNICIPAL WELLS

Well	Date sampled	In mg/L									
		Total alkalinity as $CaCO_3$	Total hardness as $CaCO_3$	Sulfate as SO_4	Chloride as Cl	Iron as Fe	Nitrate as NO_3	Total dissolved solids	Free CO_2	DO	pH
Al Benali	8-10-70	165	885	430	1,006	<0.02	14.7	2,548	28	1.4	7.1
Al Khamis	8-11-70	170	913	440	1,127	<0.02	11.2	2,744	24	1.8	7.2
Sanabis	8-11-70	175	847	380	992	<0.02	12.8	2,447	32	0.8	7.2

TABLE 3-3. SELECTED WATER QUALITY ANALYSES, NOVEMBER 1976

Sampling station	Specific conductance, umhos/cm at 25 deg C	Total dissolved solids estimated in mg/L(1)	Remarks
Isa Town well	4,000	2,300	Second well on transmission line; well not in operation.
Isa Town well	5,950	3,400	First well on transmission line; well not in operation.
Isa Town system	1,750	1,000	Sample from tap at Public Works building.
Sitra Town system	1,100	600	Sample from tap at Municipal building.
Sitra - main pump station	5,200	2,900	
Rifa'a blending station	105	<100	Distillate water.
Hamala pump stations A & C	3,700	2,100	
Hamala pump station B	3,600	2,000	
Muharraq A	3,600	2,000	
Hyde Park (Muharraq)	3,500	2,000	
Muharraq B	3,400	1,900	
Hidd	3,600	2,000	
Galali	3,600	2,000	
Samahiy	3,600	2,000	

1. Specific conductance x 0.565 = total dissolved solids - (rounded to nearest 100 mg/L).

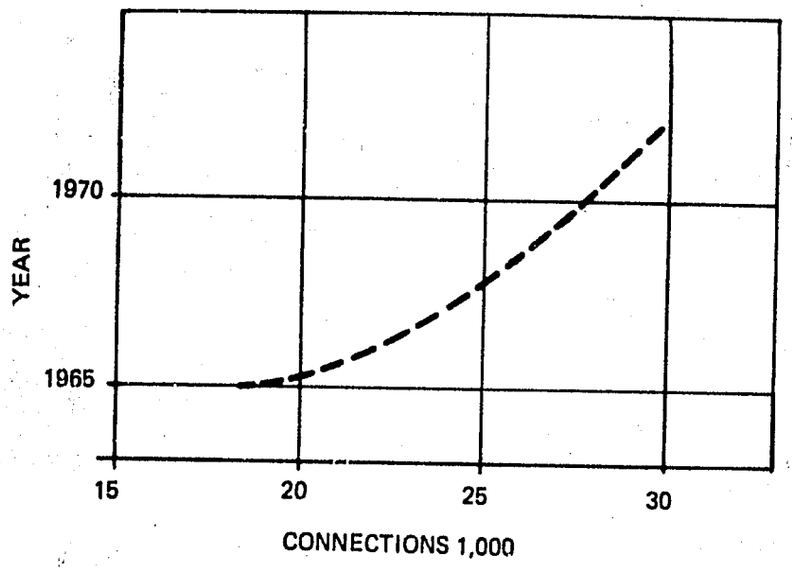
Source: Samples by M&E, November 22, 1976

These are based on the specific conductance of water taken at selected points in the distribution system or from supply wells. Samples of blended water taken from the distribution system at Isa Town and Sitra show total dissolved solids ranging from an estimated 600 to 1,000 ppm, whereas water from wells generally averaged 2,000 ppm. The Water Directorate has as its long-term objective to supply water having a total dissolved solids ranging from 700 to 1,000 ppm. Other than the blended water, water having less than 1,000 ppm total dissolved solids and suitable for drinking is available from a number of demineralization plants. One of these is operated by BAPCO and feeds directly into a dual-distribution system. Other private plants provide demineralized water which is sold and delivered to consumers by tanker.

In order to meet the objective of providing an island-wide public potable water supply, it is planned to expand the existing distillation plant to a 77,200 CMD capacity by the year 1981. The distilled water will be blended with well water to be obtained at five blending stations in addition to the existing ones at Rifa'a and Sitra. It is estimated that a total of 18 wells will be required for meeting the blending water requirements. As a matter of policy, new public supply wells are constructed with 10-inch diameter casings to minimize friction losses. The use of 10-inch diameter casings would also allow a deeper pump setting should yields fall off as a result of declining groundwater pressure heads. At present, the Water Directorate has not

experienced any noticeable loss in well yield caused by declining groundwater levels, nor have their wells experienced any significant deterioration in water quality, although the total dissolved solids content at the Sitra well is relatively high, and since 1972 has ranged from 3,200 to 3,386 ppm.

Population Served. Piped water presently serves about 29,836 dwelling units in Bahrain and about 98 percent of the population. The growth of the piped water system is indicated by the following summary of dwellings served. See Reference 5.



NOTE: 1965 AND 1971 DATA CONFIRMED BY CENSUS REPORTS

FIG. 3-1 WATER SYSTEM CONNECTIONS

The total piped water use in 1973 was about 24.57 MCM (from Watson, Reference 5), not including Awali use and uses from private wells. The estimated population in 1973 was about 240,000 people with about 95 percent of this total supplied with

piped water. It has been estimated that the total piped water use for 1974 was about 25 MCM.

Water Usage. Historical piped water use is shown in the following figure which is based on Statement 1 in Reference 3.

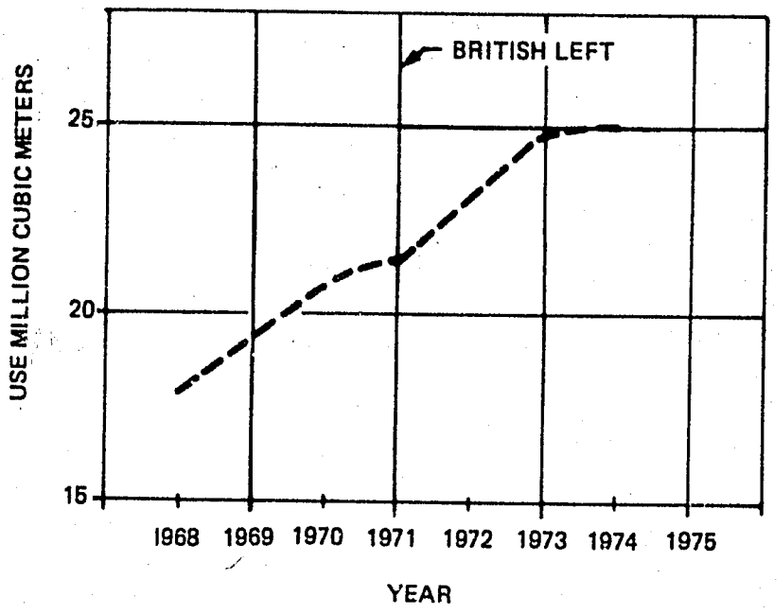


FIG. 3-2 PIPED WATER USE

The growth trend in 1971 dropped, no doubt, as a result of the reduction in total population due to the departure of the British forces. In the opinion of the team, the fall in the rate of growth of water use in 1974 may be due to system restraints on total use and may not reflect water demands.

The above water use figures are not based upon metered use but rather represent total production based on master meter readings. They, therefore, include system leakage. The water supplied to the water systems in 1973 amounted to about 298.6

liters per capita per day or 65.7 gcd (gallons per capita per day).* This is considered high for primarily domestic use.

A study for the U. S. Department of Housing and Urban Development** in 1963, 64 and 65 covered residential water use in various sections of the country. Water use for three sections of San Diego, California, in an arid area with about 178 mm (7 inches) of rainfall per year was included in this study. The average use and ratios of maximum-to-average day use in Table 3-4 are from this report. Usage has been converted from U. S. gallons per day to liters per day.

TABLE 3-4. PER CAPITA RESIDENTIAL WATER USE PATTERNS - SAN DIEGO, CALIFORNIA

Study section	Use, L/day(1)		Ratios	
	Average	Maximum	Maximum day to average day	Maximum hour to average day
San Diego				
Rancho Hills	340	595	1.75	5.22
Ruffin Road residential	409	712	1.74	4.40
Muirlands	761	1,476	1.94	6.00

1. Liters per day.

These use data are for public metered water in areas with public sewers. They include irrigation use for beautification such as lawn watering but include no commercial/industrial use.

*Imperial gallons per capita per day.
**A Study of Residential Water Use by F. P. Linaweaver, Jr., John C. Geyer and Jerome B. Wolff - John Hopkins University.

The average annual per capita water use in Bahrain of about 299 liters including leakage and small commercial and industrial uses. While this is higher than for other countries in the Gulf area, it is not unexpectedly so, especially since water rates are low and are not based upon metered use.

Taylor (Reference 1) indicates the following residential use rates based on short term (a few months) measurements:

TABLE 3-5. PER CAPITA WATER USE FROM TAYLOR

Type of dwelling unit	Per capita use L/day	Per capita use Gpd(1)
Houses with gardens	331 to 1,180	73 to 260
Houses without gardens	141 to 363	31 to 80

1. Gallons per day.

Thirty five (35) percent of the premises sampled had a per capita use rate of 141 liters per day which Taylor takes as indicating a basic minimum requirement when water is used sparingly but not necessarily frugally. From this information and the fluctuations in daily production for Manama and Muharraq, Taylor estimates that per capita daily use* may comprise the following:

154 liters system leakage
45 liters wastage inside premises**
204 liters used

403 liters

*In Manama and Muharraq.
**Leaking taps, etc.

In their 1975 study of rural areas, Taylor (Reference 2) presents the data in Table 3-6 on water usage patterns in the rural study area. These data are based on water supplied to the system and, therefore, include system leakage.

Variations in the daily demand pattern for two villages were obtained by Taylor and show for West Rifa'a the peak hourly rate to occur at about 8 a.m. and the minimum at around midnight. The rates of flow occurring at these times are respectively 1.49 and 0.66 times the average daily rate. In Damistan, the peak rate occurred at about 6:30 a.m. and the minimum around 2 a.m. These ratios of flows to average daily rates were 1.93 and 0.22.

In their 1974 report, Taylor indicated that for the combined Manama-Muharraq system, the peak hourly demand occurred at about 8:00 a.m. and was 1.22 times the average daily rate. The minimum flow occurred at 1:30 a.m. and was 0.61 times the average. The ratio of maximum to average day use was indicated to be about 1.14 for Manama and Muharraq.

Watson (Reference 5) has a tabulation of monthly water production figures for 1973 which were furnished by the Water Supply Directorate. See Table 3-7. They show that the ratio of maximum month to average month for 1973 for most systems approaches or exceeds the ratios of maximum to average day presented by Taylor (References 1 and 2). These ratios, as computed by the Water Resources Team, are shown in Table 3-8.

The ratios in Table 3-8 are shown graphically in Figure 3-3 for the study area.

TABLE 3-6. ESTIMATED AVERAGE PER CAPITA WATER USE, 1972 TO 1975

Area and town	Water use, L/capita/day 1972	1973	1974	1975	Peak/average day
Isa Town[2]	563[1]	604	586	-	1.24
Rifa'a Town	462	491	493	-	1.22
Western Division					
Sadad	208[1]	224	245	-	1.38
Karzakkan	94	126	144	-	1.25
Malkiya	177[1]	-	188[1]	-	1.27
Hamala	157[1]	208	236	-	1.34
Zallaq	363[1]	340	348	-	1.29
Jasra	253	336	449	-	1.36
Damistan	-	105	48	-	1.41
Dar Kulaib	155	166	193	-	1.33
Northern Division					
Diraz	219	-	-	-	-
Budaia	262	-	-	-	-
Bani Jamra	156	-	-	-	-
Barbar	154	-	-	-	-
Mankh	416	-	-	-	-
Sar	322	-	-	-	-
Kuraiya	227	-	-	-	-
Magaba	274	-	-	-	-
Jidd Hafs Division					
Abu Saiba[3]	185	-	-	-	-
Qadam[4]	173	-	-	-	-
Qalaa	254	-	-	-	-
Hallat Abdul	338	-	-	-	-
Saleh Magsha	295	-	-	-	-
Karabad	192	-	-	-	-
Sitra Division	-	-	228	-	1.41
Central Division					
Tubli[5]	-	-	-	154	-
Kawara	-	-	-	332	-
Jurdaab	-	-	-	189	-
Sanad	-	-	-	123	-

1. Derived from less than 12 months record.
2. Also serves Salamabad.
3. Also serves Shakhura.
4. Includes Al Hajar and Boguwah.
5. Includes Hujair and Jubailat.

TABLE 3-7. MONTHLY WATER SUPPLY FIGURE FOR MAIN CENTERS (1973), MCM

Month	Manama	Muharraq	Hidd	Al-Khamis	Jiff Hafs and Sanabis	Rifa'a	Isa Town	Sitra Island(1)
January	0.8556	0.2838	0.0392	0.0517	0.0757	0.2046	0.1556	0.0685
February	0.8386	0.2733	0.0368	0.0480	0.0749	0.2273	0.2175	0.0608
March	0.9444	0.2614	0.0455	0.0562	0.0834	0.2500	0.1929	0.0621
April	0.9012	0.3250	0.0466	0.0610	0.0705	0.2409	0.2058	0.0646
May	1.0206	0.3465	0.0518	0.0699	0.1600	0.2045+	0.1907	0.0750
June	1.0154	0.3441	0.0550	0.0674	0.1205	0.2273	0.2025	0.0795
July	1.0720	0.3589	0.0586	0.0720	0.1242	0.2409	0.1792+	0.0845
August	1.5540	0.3710	0.0589	0.0700	0.1284	0.2273	0.2172	0.0894
September	1.0943	0.3549	0.0488	0.0670	0.1131	0.2500	0.2367	0.0854
October	1.0860	0.3571	0.0475	0.0685	0.0748	0.2273	0.2570	0.0940
November	0.9800	0.3034	0.0451	0.0666	0.0527	0.2364	0.2522	0.0819
December	0.9285	0.2905	0.0420	0.0616	0.0786	0.2273	0.2405	0.0740
Total	12.2906	3.8699	0.5758	0.7599	1.1568	2.7638	2.5478	0.9197

1. Does not include the refinery area.

+ - Possibly affected by installation works.

Source: Reference 5, Volume 4, Table 3.2, page A3-3.

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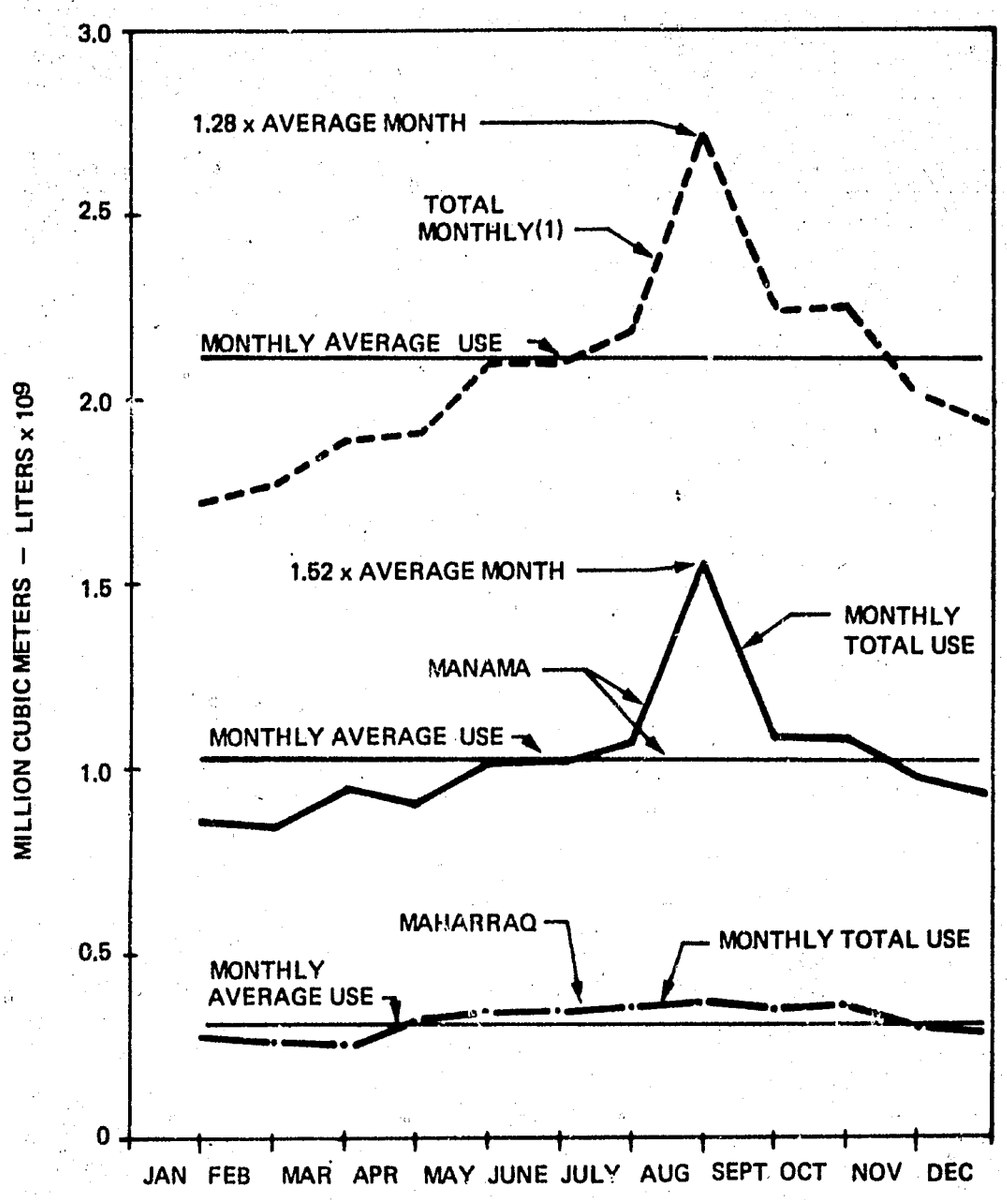
TABLE 3-8. COMPARISON, RATIO OF MAXIMUM MONTH TO AVERAGE MONTH - WATER USE 1973

System	Ratio	Month of maximum use
Manama	1.52	August
Muharraq	1.15	August
Hidd	1.23	August
Al Khamis	1.11	August
Isa Town	1.21	August
Sitra	1.23	October
Rifa'a	1.09	March and September
Jidd Hafs and Sanabis	1.66	May

The foregoing tends to confirm our belief that the present water systems, especially in the major urbanized areas, place restrictions on water use, either because the system will convey no more water at present pressure heads or because insufficient water is available to meet the demand. Most probably, both factors serve to limit maximum day and peak hour use.

We, therefore, believe that water use demand levels derived from historical data in Bahrain, except possibly for some of the smaller systems and Isa Town, may not be representative of the true usage which would occur when system restrictions have been removed.

We recognize that the provision of user storage tanks of a capacity equal to one day's use reduces the peak hour demand. It does nothing, however, to limit the maximum day rate of use and, in fact, because all are equipped with float valves and



1. INCLUDES MANAMA, MAHARRAQ, HIDD AL-KHAMIS, SIDD HAFS AND SANABIS, RIFA'A, ISA TOWN AND SITRA ISLAND EXCEPT REFINERY'. DOES NOT INCLUDE AREAS OUTSIDE THE STUDY AREA.

FIG. 3-3 MONTHLY WATER USE — 1973

overflows, considerable water may be lost when the tanks are full and the system hydraulic gradient above them.

Without financial or physical restraints on water use, we expect that for the urban areas covered in Taylor's 1974 report (Reference 1), average per capita water use after system improvements would be as shown in Table 3-9.

TABLE 3-9. PROJECTED PER CAPITA WATER USES, L/DAY

	1976	% of total	1985	% of total
Domestic uses(1)	227	48	250	42
Ancillary uses(2)	130	27	200	34
Commercial/industrial(3)	50	10	65	11
Subtotal	407	85	515	87
Losses, etc.	70	15	80	13
Total	477	100	595	100

1. Domestic uses, including bathing, washing, sanitary uses, cooking, dishwashing, cleaning house, etc.
2. Ancillary uses, car washing, window washing, irrigation of ornamental plants and small garden plots, beautification of streets and parks.
3. Commercial/industrial uses - stores, laundries, restaurants, hotels and light industry.

Taylor (Reference 2) estimates that the average per capita water demand* in rural areas and small villages** will be about 270 liters per day by 1985. In our opinion, this is a reasonable estimate. However, we would expect that per capita water use in these areas would be about 10 percent higher without metering and

*Including system leakage.
**Excluding Awali, Rifa'a and Isa Town.

METCALF & EDDY

around 11 percent less with metering and the proposed water rates Table 3-10 lists the percapita demands we would anticipate with and without metering.

TABLE 3-10. 1985 PROJECTED AVERAGE DAY PER CAPITA USE IN RURAL AREAS - WITH AND WITHOUT METERS - (L/DAY)

	No meters	Meters	% reduction
Domestic	140	100	28.5
Ancillary uses	100	80	20.0
Commercial/industrial	30	30	-
Subtotal	270	210	22
System losses	30	30	0
Total	300	240	20

With metering, the proposed water rates and better quality water (lower in total dissolved solids), we would expect a reduction in water use in the urban and suburban areas as shown in Table 3-11.

TABLE 3-11. COMPARISON PROBABLE 1985 PER CAPITA WATER USE URBAN AND SUBURBAN AREAS - L/DAY

Area	Water use(1) No meters	Meters	% reduction
Manama, Muharraq, Arad, Hidd and Jidd Hafs	595	405	32
Isa Town	585	350	40
Rifa'a	540	400	26

1. Estimated by M&E.

Per capita water use data from Table 3-11, together with Taylor's projections and per capita water use for the rural areas, shown in Table 3-10, when combined with the projected population levels (per Taylor's Reference 2), yield the water use distribution shown in Table 3-12 for 1985. There are three projections, one based on Taylor's estimates (References 1 and 2) with savings due to installation of meters, the second is our expectation with no effective metering or rate structure and the third, our expectation with savings in water use due to metering and an effective rate structure.

Taylor estimates that the water demand for the State of Bahrain will be about 43 MCM per year in 1985 assuming that there will be a 25 percent reduction in demand trends due to metering and application of new metered rates for water. Should per capita water use be slow in developing or should meter installation lag, it is possible that water use in 1985 could be around 69.6 MCM per year, an increase of about 61 percent over the design average day flow. In our opinion, it is likely to be 47.96 MCM, or about 12 percent, above the design rate.

Taylor has assumed that peaking factors, peak day and hour flows in terms of average day flows would remain the same with reduction in the average day per capita use rates and has used these ratios in projecting future maximum flow rates. Since most of the saving in water demand will be in the form of reduction in leakage within the premises and the distribution system, the savings will have the effect of removing a sizeable portion of

TABLE 3-12. COMPARISON, PROJECTED 1985 WATER USE - WITH AND WITHOUT SAVINGS

Area	Projected(1) 1985 population	Use L/capita/day			1985 average day use, MLD		
		Taylor	No savings(2)	M&E with savings	Taylor	No savings	M&E with savings
Major Urban							
Manama Town	135,250	320	595	405	43.280	80.474	54.776
Muharraq Town	55,540	320	595	405	17.773	33.046	22.494
Arad and Hidd	16,400	320	595	405	5.248	9.758	6.642
Muharraq rural	5,400	320	595	405	1.728	3.213	2.187
Jidd Hafs Town	27,450	320	595	405	8.784	16.333	11.117
Suburban and Rural							
Rural Jidd Hafs	9,070	270	300	240	2.449	2.721	2.177
Northern Division	17,390	270	300	240	4.695	5.217	4.174
Western Division	13,600	270	300	240	3.672	4.080	3.264
Isa Town	30,000	385	585	350	11.550	17.550	10.500
Central Division	10,500	270	300	240	2.835	3.150	2.520
Sitra Town	10,420	270	300	240	2.813	3.126	2.501
Sitra rural	7,290	270	300	240	1.968	2.187	1.750
Rifa'a Town	16,770	490	540	400	8.217	9.056	6.708
Awali	2,000	-	-	-	-	-	-
Rifa'a rural	1,440	490	540	400	0.705	0.778	0.576
Total					115.717 (3) (25.46) (4) (42.24)	190.689 (3) (41.96) (4) (69.60) (5)	131.386 (3) (28.9-) (4) (47.956) (5)

1. Assumes 100 percent served.
2. As per Table 3-11 for major urban use in 1985; for rural, either present use plus 11 percent; Rifa'a and Isa Town or estimated use (Taylor) plus 11 percent.
3. Million imperial gallons per day.
4. Million cubic meters per year.
5. Upper limit per price waterhouse, Reference 3, is 39.27 MCM per year.

the base load which could result in greater peaking ratios. We would expect peaking ratios quite a bit higher than used by Taylor, say something close to those shown in Table 3-13.

TABLE 3-13. PROBABLE PEAKING RATIOS[1]

	Maximum day	Peak hourly
Urban areas[2]	1.4	1.8
Suburban towns[3]	1.6	2.0
Rural areas	1.3	2.0

1. In terms of average annual daily use.
2. Manama, Muharraq, Greater Manama.
3. Isa Town, Sitra and Rifa'a.

Should the peaking ratios, shown in Table 3-13, in fact, occur and should the average day flow rates be in accordance with our estimates, the maximum day flows for the major urban areas in 1985 would be 136.10 MLD or 41± percent greater than the design maximum flow rate. The system, as designed, might require some additional reinforcement to meet flow rates of this level. However, there are no firm bases for either these or Taylor's estimates.

In the absence of strong zoning laws, we believe there is presently little chance of accurately predicting the actual growth pattern for Bahrain. We, therefore, do not believe that adjustments in the proposed rural, urban and suburban water systems are necessary. The proposed systems allow room for reasonable population growth and provide for ample per capita water supply. Should one area develop faster then another,

reinforcements can be made as necessary. Conversely, if growth is slower than expected in an area and water demand lags, planned reinforcements may be delayed.

Industrial. The principal industrial water users are BAPCO, an aluminum smelting plant, and construction sites. Water use in 1975 by these industries totaled 13.3 MCM per year of which 11.2 MCM per year was used by BAPCO, 2.1 MCM per year by the melter plant and 0.2 MCM per year by others.

BAPCO, which accounts for 84 percent of the total industrial use, operates three major pump stations, all of which rely on well water. Their Budaia station consists of two wells which pump an average 13. MCM per year. Pumpage from wells at the BAPCO refinery near Sitra average 4.4 MCM per year and average pumpage from wells at Zallaq is 5.5 MCM per year, part of which is used as a public supply at Awali. Water pumped at the refinery is of poor quality having a total dissolved solids content of over 15,000 ppm and is obtained from an aquifer which occurs beneath the two principal aquifers from which most of Bahrain's water needs are supplied.

The aluminum smelter plant obtains its water from wells tapping poorer quality water in the deeper aquifer. In addition, the plant has a requirement of about 0.3 MCM per year of better quality water which is obtained from the public water supply system.

Groundwater is also abstracted by private users as a source for mostly small capacity demineralization plants. Among

these are the Pepsi Cola Factory which uses an electrodialysis process to produce about 0.02 MCM per year. Both the Hilton Hotel and a newly constructed aggregate plant near Askar process well water using a reverse osmosis procedure. The Hilton plant has a capacity of 0.110 MCM per year, while the aggregate plant has two reportedly large capacity wells which supply a demineralization plant for processing washwater.

Future increases in industrial water use are unknown, but are expected to be relatively small. Anticipated industries, either under construction or proposed, include a dry dock capable of handling oil tankers of up to 430,000 tons, an aluminum extrusion and atomizer plant and other proposed industries on Sitra. Generally, water requirements for these industries is expected to be small. The proposed extrusion plant is estimated to require 0.64 MCM per year of high quality water to be provided from the distillation plant at Sitra. The other proposed industries on Sitra are collectively estimated to require less than 0.3 MCM per year. A small requirement for high quality water is also anticipated for concrete mix and curing. However, a relatively large water requirement of 3.6 MCM per year is anticipated for washing aggregates. Part of this requirement is currently being met at the new aggregate plant near Askar which uses, as its source, well water of reportedly low quality.

CHAPTER 4

GEOHYDROLOGY

General

The water resources of Bahrain are almost exclusively limited to groundwater of variable quality which occupies three principal artesian aquifer systems contained within carbonate rocks of Eocene age. Such water is associated with an extensive groundwater flow network which originates in the mainland portions of Saudi Arabia and extends toward offshore areas where it ultimately discharges into the Arabian Gulf. Hydrologic factors in the aquifer areas contiguous to Bahrain which regulate or modify groundwater flow and its disposition under present conditions of water use are schematically shown in Figure 4-1. The principal intake area to the aquifer system occurs in a broad band of outcrop in Saudi Arabia located over 150 miles west of Bahrain. Recharge within the intake area has, within past times when rainfall was estimated to be greater, sustained groundwater storage at a higher level than in more modern times. As a result, depletion of groundwater storage has been taking place for many years since the total natural discharge from the aquifer exceeds recharge available under existing climatic conditions. Such natural discharge includes evaporative losses or spring flow in areas where groundwater is reaching the land surface as leakage through imperfect confining beds, or where the aquifers are exposed at ground level or to the sea. The rate of storage depletion is also being accelerated as a result of artificial

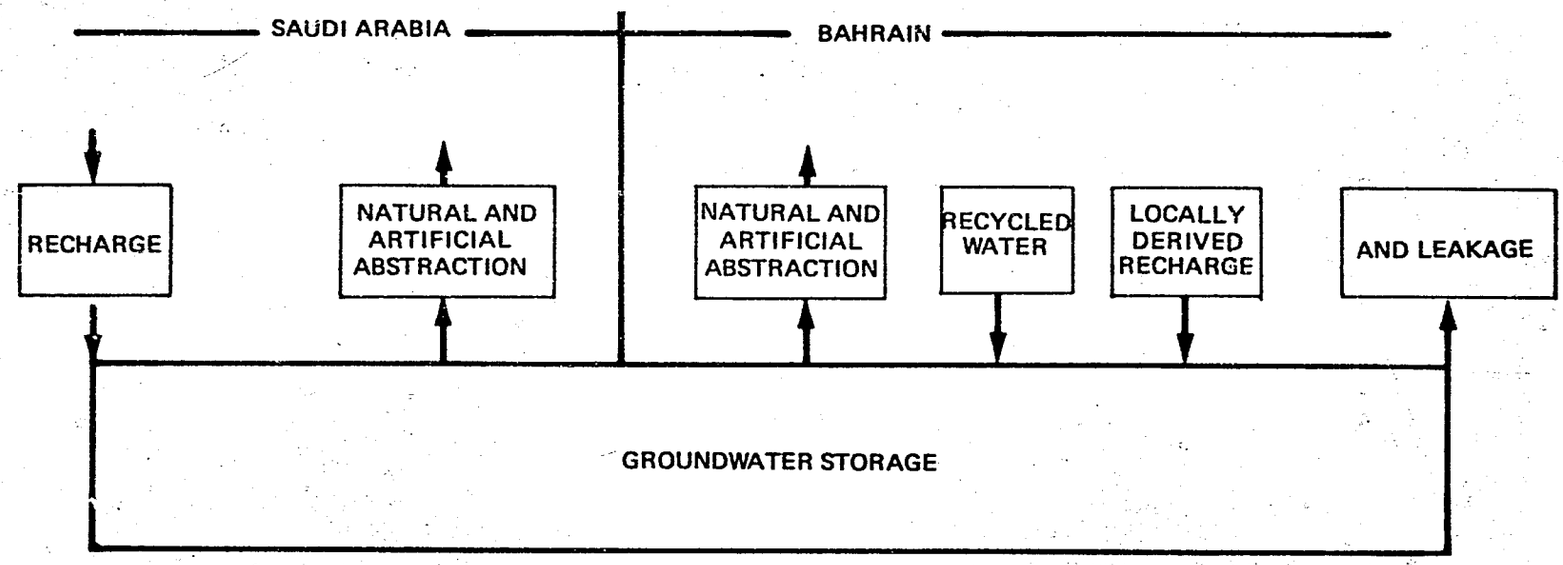


FIG. 4-1 SCHEMATIC DIAGRAM OF AQUIFER SYSTEM

abstraction by wells. A modifying influence on the rate of storage depletion is the recycling of irrigation waters and a possible reduction in natural evaporation and spring flow losses resulting from an overall decline in groundwater levels. Quantification of the various factors which influence groundwater availability is primarily limited to estimated groundwater abstraction rates and the rate of head decline since at least 1940 on Bahrain Island. The mechanics of groundwater flow and interaction of such flow in the three principal aquifers is only known approximately and not in sufficient detail to permit any accurate forecasting of future events.

The following sections briefly summarizes the overall knowledge of the geology and groundwater system as presently understood. To date, the most comprehensive studies on groundwater in Bahrain were prepared by Dr. E. P. Wright (Reference 8) and Italconsult (Reference 7). More recent information is available for interpretation from hydrologic data collected by the Water Resources Board and BAPCO. A recent interpretation of the islands geology is also described in a materials survey of Bahrain (Reference 4).

Geologic Setting

Bahrain consists of a chain of islands made up predominantly of calcareous sedimentary rock. Exposures of Eocene rocks which make up the oldest exposed geologic units are found on Bahrain Island where they contain the principal aquifers. On Bahrain Island, such explosures are associated with a north-south trending

anticlinal structure which strongly influences both topography and land forms.

The predominant land form on Bahrain is a rimrock that encircles the central part of the island along the crest of an anticlinal structure. The rimrock is an erosional feature consisting of rock generally more resistant to weathering than the older exposed core material which, with the exception of Jabal and Dukhan, forms a topographic depression in which drainage is internal. Seaward, the land slopes relatively gently away from the rimrock and becomes flatter along the coast.

Geologically, the dominant rock types include limestone, dolomitic limestones and chalk which are extensively exposed in the interior parts of Bahrain Island while clay, silt, marl and thin limestone layers of varying degrees of cementation, veneered with sandy material, are predominant in the coastal areas of Bahrain Island and extensively cover the islands of Muharraq and Sitra.

The exposed rock units in Bahrain are part of a thick sequence of sedimentary rocks which are extensively distributed throughout the Arabian Gulf area. Of these, the most important in terms of water resources are the Ummer Radhuma, Rus, and Damman formations of Eocene age. These are overlain throughout most of the coastal areas of Bahrain Island by Miocene and Quaternary sediments commonly referred to as the Neogene complex. A stratigraphic summary of rocks of Eocene age and younger and their water-bearing character is given in Table 4-1. Geologic

TABLE 4-1. STRATIGRAPHIC SUMMARY

Age	Formation	Member	Thickness, ft	Description
Recent			0-10±	Sand, gravel, silt - locally source of water supply.
Quaternary to Miocene		Neogene complex	0->200	Principally, clay, marl, shale and sandy limestone. Mostly nonwater bearing.
Eocene	Damman	White limestone	0->200	Locally referred to as Zone A aquifer; equivalent to Alat limestone member in Saudi Arabia.
		Orange marl	0-50±	Predominantly marl; acts as an imperfect confining unit for Zone B aquifer.
		Brown limestone	0-150±	Locally referred to as Zone B aquifer; equivalent to Khobar limestone member in Saudi Arabia.
		Shale-marl	0-50	Predominantly shale and marl; acts as an imperfect confining unit for Zone C aquifer.
	Rus		115-230	Referred to collectively as Zone C aquifer.
Paleocene	Ummer Radhuma		>1,000	

maps showing their distribution on Bahrain are available in several reports (References 7, 8 and 10).

The lower most aquifer within the stratigraphic sequence shown in Table 4-1 are the Ummer Radhuma and Rus formations which collectively make up the Zone C aquifer. On Bahrain, they consist of chalk, limestone, dolomitic limestone, with some evaporite deposits and layers of marls and clays which total over 200 feet in thickness beyond their area of outcrop. Groundwater within the Zone C aquifer is under confinement except in or near areas of outcrop. The water is generally saline on Bahrain island and is used primarily by industries for process water.

Overlying the Rus formation is a predominantly shale-marl sequence which forms the basal member of the Damman formation. This member attains a maximum thickness of 50 feet beyond its outcrop area and forms an imperfect confining unit between the Zone C aquifer and an overlying brown limestone member. This member consists of a porous limestone and dolomitic limestone which averages about 100 feet in thickness beyond its area of outcrop. The limestone member makes up the Zone B aquifer which is the most prolific aquifer in Bahrain and a source of relatively fresh water.

An imperfect confining unit, commonly termed Orange Marl, occurs above the Zone B aquifer. The marl averages about 40 feet in thickness beyond its area of outcrop and separates the Zone B aquifer from an upper water-bearing white limestone member, referred to as the Zone A aquifer. This member consists of

limestone which is partly chalky and partly dolomitized. It ranges in thickness from 0 feet in its area of outcrop to over 200 feet. On Bahrain Island, this member is generally less than 150 feet thick.

In coastal areas and extending seaward, the Eocene rocks, which include the aquifer Zones A, B and C, are capped by a sequence of clay, marl, shale and sandy limestone which in Bahrain range from 0 to over 200 feet in thickness. Generally, the upper part of this sequence consists of a calcareous sandstone. These sediments, when present, act as a confining unit over the older Eocene rocks. The sediments are of questionable age but probably range from Quatenary to Miocene in age. They commonly are referred to as the Neogene complex.

Recent surficial deposits including beach sands, loose surficial deposits of gravel, sand and silt, and sabkah deposits mantle older deposits on the less elevated portions along the coast and within the rimrock area. The sabkah deposits consist of wind-blown material mixed with residual salts derived from the evaporation of shallow groundwater. In addition, Recent limestone and calcareous mud occur in shallow water near shore. The Recent deposits are generally less than 10 feet and commonly rest directly on the older Eocene rocks.

Studies recently carried for the State of Bahrain's Ministry of Work, Power and Water (Reference 4) have resulted in a reinterpretation of the stratigraphy and reclassification of rock units on the Island of Bahrain. The principal changes have

been to divide the principal formations into subunits on the basis of lithologic and mineral makeup. Outcrops formerly associated with older rock units have, in some places, been identified with rocks of more recent age. The overall stratigraphic sequence of rock units, however, remains similar to those identified in earlier studies.

The occurrence and distribution of the various rock units is controlled by a major north-south trending anticlinal structure. The flanks of the anticline have a relatively gentle dip of 2 degrees to 5 degrees. The anticline represents localized deformation of a sedimentary sequence of rocks ranging from Permian to Eocene times. Their main area of outcrop is over 150 miles west of Bahrain on the Arabian Peninsula. Structures associated with the major antilcine include subsidiary folds and minor faults having displacement of not more than 50 feet. The subsidiary structures are believed to be primarily associated with collapse features caused by subsurface leaching of evaporite beds and have probably enhanced localized hydraulic interconnections between aquifers by vertical fractures and displacement of confining beds.

Soils derived from the various rock units are described as being mostly sandy in texture and having high infiltration capacities. Typically, sand grains make up over 90 percent of the soil with silty and clay comprising less than 10 percent.* The

*Watson, Reference 5.

soils are mostly derived from Recent deposits. Elsewhere, in areas of shallow or outcropping limestone deposits, which are extensive on Bahrain Island, the soils are either absent or poorly developed and have little potential for agricultural development. Gypsum is also commonly found in soils other than on agricultural lands where the soils are relatively free of gypsum due to repeated leaching by irrigation water. A hardpan is typically present in unirrigated soils as a result of cementation by evaporite deposits which form within the capillary fringe of soils which contain a shallow water table. Soil maps of Bahrain are available in several reports (References 21 and 4), the former covers the northwestern and western areas of Bahrain Island, while the latter includes all of Bahrain Island and adjoining islands.

Aquifer Descriptions

As described in the previous section, the three principal aquifers in Bahrain are referred to as Zones A, B and C, each of which is associated with laterally extensive carbonate rocks of Eocene age. The aquifers are part of a major confined groundwater flow system which originates on the Arabian Peninsula and extends easterly into the Arabian Gulf. In Bahrain, the aquifers occur at the surface as a result of regional updoming of sediments. The updoming is evident from a major anticlinal structure which forms the core of Bahrain Island. Hydraulically, the aquifers respond as a confined system except in or near areas of

outcrop where water table conditions exist. Of the three aquifers, only Zone C extends throughout Bahrain, whereas Zones A and B are missing along the eroded crest of the anticline. The aquifers become progressively deeper away from their outcrop area down dips along the flanks of the anticline.

The aquifers are to some degree hydraulically interconnected by either direct leakage through the relatively impermeable confining units or by localized fracturing associated with collapse features. Studies in the coastal portions of Saudi Arabia suggest a more complete interconnection between Zone A and B aquifers than in Bahrain.* Evidence for interconnection between the three aquifers on Bahrain is available from geochemical studies by Wright (Reference 8) and from records of wells which are open to two or more aquifers. Generally, the degree of interconnection is not well understood but is estimated to vary considerable from place to place. Direct interconnection with the sea exists in the outcrop areas of the Zone A and B aquifers along the east cost of Bahrain Island. Generally, the aquifers are more effectively separated from the sea in coastal areas by relatively thick, impermeable sediments of the Neogene complex. The occurrence of freshwater springs which discharge from Neogene sediments along the northeast coast, however, suggest that some degree of hydraulic interconnection also exists with the deeper aquifers.

*Italconsult.

The hydraulic properties of each aquifer have been investigated by others (References 7 and 8). Results of such investigations are summarized in Table 4-2 which includes aquifer transmissibility and storage coefficient. The wide range in values for transmissibility is probably the result of poor control during aquifer testing procedures. Interference effects during pumping tests by tides and localized pumping by other wells are expected to make the analysis of the test data only approximate. Transmissibility values of 2 to 3 square meters per second for the Alat-Khobar aquifer system as determined from regional pumping effects in coastal Saudi Arabia* (Reference 7) are perhaps more representative of the magnitude of aquifer transmissibility of the Zone A and B aquifer system near or at Bahrain. However, the data is too inconclusive to permit mathematical modeling of the aquifer system without a more complete understanding of the distributed hydraulic properties of aquifers and the degree by which they are interconnected. It is likely that regional structures associated with folding and collapse features significantly influence the hydraulic properties of aquifers and control on groundwater flow as suggested by the lobate extensions of fresher water in the Zones A, B and C aquifers from the mainland area of Saudi Arabia toward Bahrain (Reference 9).

*Italconsult.

TABLE 4-2. SUMMARY OF HYDRAULIC PROPERTIES OF AQUIFERS

Aquifer	Bahrain		Coastal Saudi Arabia	
	Coefficient of transmissibility range, sm/sec[1]	Coefficient of storage range	Coefficient of transmissibility range, sm/sec	Range in coefficient of storage
Zone A			1.6×10^{-3} to 3.6×10^{-3}	1.3×10^{-4} to 5.3×10^{-4}
Zone B	7×10^{-3} to 7×10^{-2}	4.8×10^{-4}	7×10^{-3} to 2.7×10^{-1}	2.1×10^{-5} to 1.3×10^{-6}
Zones A and B	1×10^{-2} to 1×10^{-1}		1.3×10^{-1} to 3	7.8×10^{-3}
Zone C			1.5×10^{-1} to 6.4×10^{-1}	1.5×10^{-2} to 2.5×10^{-5}

1. Square meters per second.

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Hydraulic properties of surficial materials including Recent deposits and sediments of the Neogene complex show low-to-moderate permeabilities. Results of tests conducted in soil borings (References 19 and 20) show a wide range in permeability for the following sediment types:

Sand, fine to coarse	6.4×10^{-5} to 1.7×10^{-2} cm/sec
Sand, fine to medium	5.9×10^{-6} to 1.6×10^{-2} cm/sec
Sandstone	2.0×10^{-3} cm/sec
Silt and silty sand	7.4×10^{-6} to 6.5×10^{-3} cm/sec
Siltstone and mudstone	4.9×10^{-6} to 1.3×10^{-3} cm/sec

On the average, the permeability for sandy materials is estimated to be in the order of 1 to 5×10^{-3} cm (centimeters) per second and where they are of sufficiently saturated thickness may yield small quantities of water to dug wells. Generally, the surficial sandy sediments, which are relatively prevalent in the northern parts of Bahrain, are expected to have a high infiltration capacity. Where they directly overlie carbonate aquifers, they are estimated to contribute significantly to the recharge of the deeper carbonate aquifers by return irrigation waters.

Hydrology

Bahrain's water resources, which are almost exclusively obtained from groundwater, originate primarily from storage in extensively confined aquifers whose principal area of outcrop is located in Saudi Arabia. Based on studies carried out to date, the quantity of groundwater which discharges both naturally and artificially exceeds the available recharge to the aquifer system. Current recharge in the aquifers principal outcrop areas

in Saudi Arabia is estimated to be inadequate to permit any significant sustained groundwater development on Bahrain in the foreseeable future. Rather, the quantities of water available for development will depend on the rate of on-going storage depletion and, more importantly, the rate at which salt water is displacing the depleted freshwater. Such displacement is taking place along an encroaching saline water front in an area of natural discharge. In Bahrain, most of such discharge presently occurs near or along the southeastern and the southwestern coast. Natural discharge of fresh groundwater is expected to result largely from leakage via springs or through overlying confining beds, direct overflow to the sea where aquifers are exposed to the sea, and by soil evaporation in sabkahs. In addition, natural discharge to the sea by leakage through confining units is expected throughout the aquifer area between Bahrain and coastal Saudi Arabia. Large volumes of groundwater are also lost by soil evaporation in the coastal areas of Saudi Arabia. Although unsubstantiated, it is reported by Italconsult (Reference 7) that the total natural discharge by soil evaporation and springs may exceed that being abstracted by wells.

Large quantities of water, estimated to exceed 300 MCM per year, are being abstracted by wells located both on Bahrain and from the contiguous aquifers in the Saudi Arabian mainland. To offset the net aquifer depletion by well withdrawals, approximately 50 percent of the water pumped for irrigation is returned to the groundwater system in Bahrain while minor quantities of

water enter the aquifers in their area of outcrop as infiltrating rainfall or occasional streamflow.

Streamflow on Bahrain occurs infrequently and only in response to relatively high intensity storms of short duration. It is characteristically flashy with a short response time between rainfall and runoff. Because of inadequate drainage, especially in urban areas, temporary flooding will normally occur in low-lying areas or natural depressions. In higher areas, about 10 meters or more above sea level, the opportunity for the infiltration of overland runoff is estimated to be small and limited by the widespread occurrence of naturally compacted desert surfaces (Reference 4). In low-lying areas, infiltration is limited to some extent by a shallow water table developed either on top of underlying and impermeable Neogene sediments or in sandy deposits in which the water table coincides with the pressure head of the underlying carbonate aquifers. It is reported that a very small percentage of the streamflow is used either directly or percolates to the groundwater (Reference 4). Most runoff reaches the sea directly or is lost by evaporation from standing pools of water in depressions. Direct recharge from locally derived precipitation, however, does maintain a shallow freshwater lense, reportedly 3 to about 5 meters thick. The lense is present within the central part of Bahrain Island where it is developed on top of more saline groundwater which saturates the Zone C aquifer and its adjoining outcrop area.

Optimum recharge to the freshwater lense is reported at about 0.8 MCM per year on the average (Reference 7).

Information on naturally occurring discharge from the main aquifers is based on infrequent flow measurements taken of both land and known marine springs. The springs are mostly located in the north and northeastern parts of Bahrain. In 1924, the discharge from the land springs totaled 69.5 MCM per year. By 1952, the flow declined to 41.5 MCM per year while in 1971, it was only 7.2 MCM per year (Reference 7). Additional flow from marine springs during 1953 was reported at 9.6 MCM per year. No other data on marine flow is available. An historical decline in spring flow is evident from extensive irrigation works which were in disuse prior to 1924.* Presently, most springs in Bahrain Island have ceased flowing. The overall decline in spring flow has been accompanied by decline in the groundwater pressure head which for the period of 1941, the earliest time of record, to 1970 ranged between 4 to 9 cm per year. More recently, there is evidence to show that the rate of decline has decreased. Accompanying this overall decline in the pressure head is a steady increase in pumpage by wells which in 1952 amounted to about 61 MCM per year, and by 1971 totaled 126 MCM per year in Bahrain. A corresponding increase in groundwater abstraction is also reported in coastal areas of Saudi Arabia, where 174 MCM per year were pumped by wells in 1949, and 236 MCM per year by

*Italconsult (Reference 7).

1967. The accompanying decline in water level head has resulted in salt water encroachment along the east-central coast in the vicinity of the BAPCO oil refinery and the southeasterly part of Sitra Island.

Information on the distributed pressure head in the Zone A and B aquifers is available in reports by Wright (Reference 8) and Italconsult (Reference 7). These show the pressure gradient to be in a general southeasterly direction with a maximum head of between 3 to 4 meters above sea level, as of 1970-1971, in the extreme northwestern part of Bahrain Island. The pressure head declines to about sea level along each anticlinal flank toward the southern end of the island. Associated with the decrease in pressure head gradient is a gradual increase in groundwater salinity. Available studies suggest that the pressure head normally increased with depth, being highest in the Zone C aquifer and lowest in Zone A aquifer. Differences in the pressure head between the Zone A and B aquifers are reportedly masked by their interconnection via wells. This has resulted in similar water level heads between the two aquifers. Other modifications of the water level head is evidenced by localized groundwater mounds which exist in areas of recharge from return irrigation water. These reportedly are limited primarily to the Zone A aquifer where it occurs at or near land surface.*

*Dr. Wright, personal communication.

Information on the distributed pressure in the Zone C aquifer is limited. Some data is available in the area where the pressure head was found to range mostly from about 4 to 6 meters above sea level; the year when measured is, however, unknown.

Generally, the upper zone of groundwater saturation is typically near ground level throughout most of the coastal areas of Bahrain, Sitra and Muharraq. In places, it represents the water table position in the outcrop areas of the Zone A and B aquifers or, elsewhere, a perched water table developed on top of impervious Neogene sediments. The surficial proximity of the water table throughout the coastal areas also suggests that large volumes of groundwater are lost by either plant use or by soil evaporation. It has been estimated by Italconsult (Reference 7) and others that abandoned date palm groves are consumptively using an estimated 20 to 30 MCM per year of groundwater. A potentially high soil evaporation rate of up to 0.7 meters per year was also determined by Italconsult in sabkah areas in the coastal Saudi Arabia where climatic conditions are similar to those of Bahrain.

Water Level Trends

A review of water level data was made to establish any trends which might indicate any changes from those reported as of 1970. Information on water levels from standard observation wells in Bahrain was provided by BAPCO and the Water Resources Board. Water level readings are presently taken by BAPCO on

only two standard observation wells, No. 27 and 34, located in Budaia and Zallaq, respectively. In addition, the Water Resources Board maintains a network of 15 observation wells in which water level readings are taken at quarterly intervals during the year. The Board's wells are mostly located in the northern portion of Bahrain Island and on the islands of Sitra and Muharraq.

Two typical hydrographs of water level fluctuations are shown in Figure 4-2. The levels are based on average monthly pressure heads for wells which are each completed in the Zone B aquifer. The hydrographs show a leveling off in the rate of water level decline since about the mid-1960's. A similar change in rate is also suggested in water level records for both the Zone A and B aquifers provided by the Water Resources Board. The cause for the declining rate of change in water levels is unknown, although it is suspected that it has resulted primarily from a reduction in total discharge by either an overall reduction in well pumpage, a reduction of uncontrolled on-land spring flow, or a decrease in the aquifer's velocity head which would reduce its depletion rate. Effects of variations in groundwater discharge, whether by artificial withdrawals or by natural losses such as evaporation are apparent in the annual changes in pressure head. The pressure head normally reaches its maximum level during the winter and is at a minimum during the summer. The seasonal decline in head is mainly attributed to increased groundwater withdrawals during the summer months when water use is

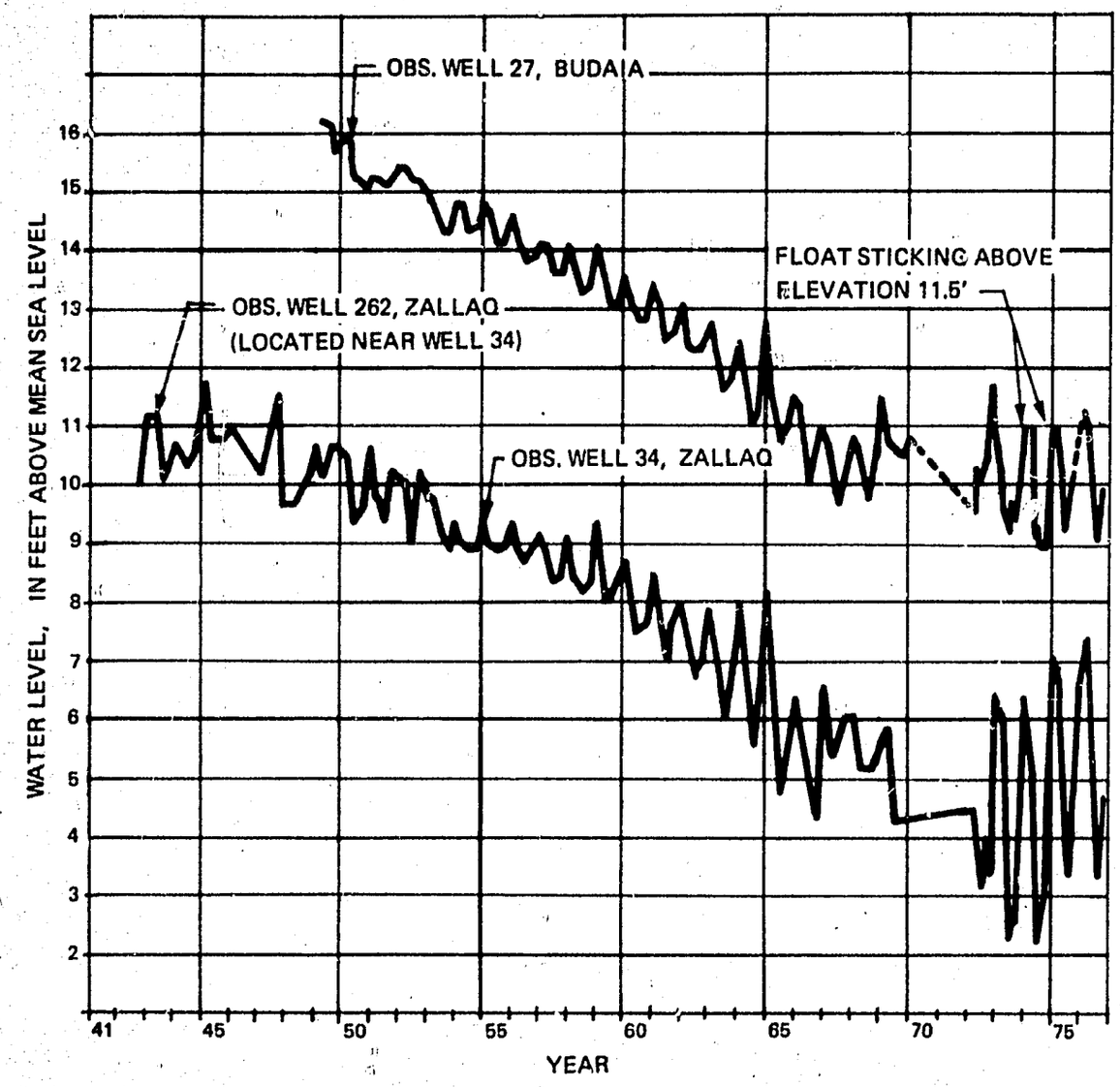

FIG. 4-2 HYDROGRAPHS, ZONE B AQUIFER

reportedly twice that of winter usage.* The total annual range in water level fluctuation, which at the Zallaq well site is as much as 5 feet, would suggest that the rate of artificial extraction does have an effect on pressure head and is probably responsible for a significant portion of the overall decline in water level head observed since 1941. It is, therefore, likely that any lowering of the rate of groundwater abstraction would tend to reduce the projected depletion rate of 4 to 9 cm per annum in water level decline (postulated by Italconsult, Reference 7).

Water Quality

The quality of groundwater in Bahrain ranges widely from less than 1,000 ppm in total dissolved solids to that of sea water. Generally, the groundwater becomes more saline in a southeasterly direction, coincident to the direction of groundwater flow. Of the three principal aquifers, only Zones A and B contain sufficient quantities of better quality water to provide nearly all of Bahrain's present needs. Groundwater in the Zone C aquifer is mostly too saline for economic use.

Maps showing the distributed total dissolved solids or sodium chloride content in the Zone A and B aquifers are available for the years 1965 and 1970/1971 in reports by Wright (Reference 8) and Italconsult (Reference 7), respectively. These show an overall increase in total dissolved solids of less than 4,000 ppm in the northern and western parts of Bahrain Island

*Italconsult (Reference 7).

to over 6,000 ppm along the southeastern coast. An anomalous high in total dissolved solids of up to 12,000 ppm also is found in the north-central part of Bahrain Island just west of Isa Town. Groundwater having a total dissolved solids of 2,000 to 3,500 ppm is generally available along a narrow coastal strip, 3 miles or less in width, which extends from about Zallaq at its southwesterly extreme and follows the coastline north and east to about the northern end of Sitra Island. Elsewhere, groundwater in the Zone A and B aquifers on Muharraq Island contains total dissolved solids of mostly less than 2,500 ppm. Typical quality of groundwater in the Zone A and B aquifers are listed for municipal supply wells in Tables 3-2 and 3-3. These show the groundwater, at best, to be of marginal quality for potability, although agriculture is practiced successfully with irrigation water having a total dissolved solids content of up to 4,000 ppm. Other miscellaneous data on the quality of groundwater in the A and B zones indicates that the boron content ranges from about 2 to 3 ppm and reportedly has reached the limit of tolerance for most crops (Reference 7). Groundwater temperatures are relatively constant at 27 to 28 deg C.

Groundwater in the Zone C aquifer is usually of poorer quality than in the overlying aquifers. Although little data is available, it has been reported (Reference 7) that total dissolved solids in the Zone C groundwater range from about 6,000 to over 15,000 ppm on Bahrain Island. The water also typically contains hydrogen sulfide. The direction of salinity increase is probably

similar to that in the Zone A and B aquifers and, therefore, is expected to become fresher toward the northwest end of Bahrain Island. Locally, water having a total dissolved solids content of less than 2,000 ppm is available from a freshwater lense in the Zone C aquifer in its area of outcrop. Data from wells here suggest that the freshwater lense is relatively thin and of variable distribution. It is expected that even moderate pumping in the freshwater lense will cause upconing of the underlying salt water, and thereby contaminate a well supply. This is suggested in water quality records reported by Italconsult for several wells located in the rimrock area where a rapid rise in the salinity was noted after an indeterminate period of well use. One well showed a rise in sodium chloride from less than 300 ppm to over 2,000 ppm within a one-year period.

Relatively little data on water quality is available for water-bearing materials beneath the Zone C aquifer. Information from a report by Naimi (Reference 9) suggests that the older Wasia and Biyadh formations, which are a source of water supply in Saudi Arabia, are expected to contain over 6,000 ppm in total dissolved solids in their coastal extension toward Bahrain. Additional data from BAPCO* shows groundwater having a minimum total dissolved solids content of about 8,000 to 9,000 ppm to occur in the Yamana formation of Cretaceous age and at considerable depth below the Zone C aquifer. The distributed salinity

*W. Helms, BAPCO, personal communication.

in the Yamana formation is unknown, although water with total dissolved solids exceeding 9,000 ppm is present and could be a constraint to any future groundwater development.

The water quality in materials other than in the principal aquifers includes that of a shallow groundwater system which is developed in an overburden which blankets or caps the underlying aquifers, or forms the water table in the outcrop areas of the Zone A and B aquifers. Available data, primarily from soil investigations (References 4, 6 and 19), indicate a highly variable quality in the shallow groundwater which, in part, is caused by the leaching of salts when irrigating or by residual concentrations of salts resulting from soil evaporation. In some places, dilution by better quality wastewaters from the public supply system and perhaps from system leakage has resulted in improving groundwater quality. However, total dissolved solids exceeding 20,000 ppm are frequently found in the shallow groundwater, particularly in unirrigated areas. It is expected that most of such saline water is found above the Neogene complex where there is little opportunity for dilution by recharge, but a high potential for evaporation because of a shallow water table. It has been reported that the total dissolved solids content of the shallow groundwater in irrigated areas is normally greater than that of the deeper groundwater. As a result, groundwater in the Zone A aquifer in the irrigated areas of northern Bahrain will contain, on the average, higher dissolved solids than in the Zone B aquifer. As a result, the total dissolved solids content

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in the Zone A aquifer in northern Bahrain is reported to range from 6,000 to 8,000 ppm, whereas in the Zone B aquifer, it is usually less than 4,000 ppm.*

Data on surface water quality is limited to only a few samplings of standing water on Bahrain Island. A range in specific conductance of 39,000 to 85,000 micromhos was measured in water which had accumulated in depressions (Reference 4). A specific conductance of 2,600 micromhos was measured in standing water just north of Rifa'a which probably originated from recent runoff.

Water Quality Trends

Salinity measurements of supplies from selected wells and springs in Bahrain have been taken routinely since 1941. Much of this work was done until about 1970 by BAPCO. Since then, the program has been continued by the Water Resources Board.

Since at least 1941, little variation in the salinity of groundwater has been noted other than increases in the Sitra refinery area and variable increases observed near Manama and in the Buri-Ali-Salambad area (Reference 8). Changes in salinity noted at the above localities are attributed primarily to sea water encroachment and upward leakage of poorer quality water into the Zone B aquifer from Zone C. The latter condition is limited to the Buri-Ali-Salambad area where such leakage has resulted in a localized high total dissolved solids content of

*I. Lori, personal communication.

up to 12,000 ppm in the Zone B aquifer. It is also suspected that water from Zone C is reaching the shallower aquifers through imperfectly sealed wells which are open to each aquifer and were subsequently abandoned.

The most significant rise in salinity has taken place in the Sitra refinery area where a sharp increase in total dissolved solids was first noted in 1954 on the east coast of Sitra Island. By 1957, similar increases in salinity occurred at wells and springs within an area south of a line extending from the northern end of Sitra Island to the refinery. By 1970, the total dissolved solid content rose from as little as 3,000 ppm prior to 1957 to over 20,000 ppm by 1967. Data available until the end of 1970 show that the rise was essentially continuous although there are some indications of stabilization in salinity levels since about 1967. Generally, the rise in salinity is attributed to a continuous lowering of the groundwater pressure head with an attendant encroachment of saline water from the south.

It has been demonstrated by Wright (Reference 8) that the rise in salinity in the Sitra refinery area is the result of sea water intrusion rather than intrusion by saline connate or older waters. The position and form of the salt-freshwater interface is, however, not well known. Salinity measurements taken in wells in the Sitra refinery area show a rapid increase within a depth interval of as little as 70 feet, suggesting that the interface may be wedge shaped with its toe located in a northwesterly direction beneath fresher groundwater in the Zone A or

B aquifer. It is estimated, however, that the front of the interface extends some distance east of Sitra Island and north of the new Dry Dock off Muharraq Island where a new well reportedly encountered only saline water in the Zone A and B aquifers.

No studies are available on the rate of sea water encroachment. However, the salinity of a public supply well located on Sitra Island about 1 mile west of the 8,000 ppm salinity contour shown by Italconsult during 1970/1971 has remained essentially unchanged since at least 1970, suggesting that the rate of salt water encroachment is less than 1,000 feet per year.

Significant increases in the salinity of wells or springs have also been noted in the north end of Bahrain Island near Jidd Hafs and Salambad. A comparison of total dissolved solids since 1953 of spring flow in either area showed as much as a four-fold increase in concentration by 1971, indicating an ongoing deterioration of the groundwater in either area. It is likely that the cause for increasing salinities in these areas is partly due to recharge from more saline irrigation waters and from an increase in the leakage rate from the Zone C aquifer as a result of greater declining heads in the Zone A and B aquifers.

Changes in groundwater salinity have also been noted in the Zone C aquifer at the refinery where total dissolved solids have increased from about 15,000 ppm to nearly 20,000 ppm since about 1974. The source of saline water is not known but assumed to be a mixture of residual saline groundwater which occupies the Zone C aquifer.

Water Resources Inventory

An inventory of the water resources on Bahrain is limited to both measured and estimated groundwater discharge, the components and quantities of which are listed in Table 4-3 for those years shown. Determinations of total discharge for any given year, however, are not consistent since discharge by marine springs and consumptive use by date palms on abandoned agricultural lands are unreported for most years. In addition, other estimated significant groundwater losses via soil evaporation in sabkah areas and natural discharge other than spring flow have not been identified. As a result, reliable estimates of the total actual groundwater discharge are not available. Also, the quantities shown are expected to be approximate since well pumpage, which makes up most of the total discharge, is largely based on estimates of unmetered agricultural water use.

Additional items for inventorying the water resources are only approximately understood. Little or no data is available on present recharge to the aquifer and net changes in groundwater storage, particularly in the aquifers' main intake area in Saudi Arabia. Data on abstraction from the contiguous aquifers in Saudi Arabia suggest that they presently make up over 50 percent of a total of about 400 to 450 MCM per year pumped. Centers of large withdrawals in Saudi Arabia are located on the coast and include Ras Tanura, Qatif, Damman and Al Khobar. The large abstraction rates in coastal Saudi Arabia can be a significant

factor in determining the quantities of groundwater available for future use in Bahrain.

TABLE 4-3. WATER RESOURCES INVENTORY, BAHRAIN

	In MCM/yr					
Year	Marine springs	Land springs	Well pumpage	Consumptive use(1)	Totals	Source
1924	u.n.	69.5	u.n.	u.n.	u.n.	Wright, Ref. 5
1952	9.6	41.5	60.6	u.n.	111.7	Wright, Ref. 5
1966	u.n.	u.n.	159(2)	u.n.	159	Wright, Ref. 5
1971	u.n.	7.2	126.2	22	155.4	Italconsult ref.
1972	u.n.	u.n.	u.n.	34	u.n.	
1973	u.n.	u.n.	140.7(2)	20	160.7	Watson ref.
1976	u.n.	u.n.	199(2)	u.n.	199	Min. of WPW

1. For abandoned agricultural lands.
2. Include land spring flow.

A review of Table 4-3 shows an overall reduction in spring flow which to some extent has been offset by increased well pumpage. This is partly indicated by the more pronounced cyclical pattern in annual water level changes evident with the progression of time (see Figure 4-2). Such changes are expected to be more closely associated with increasingly greater, but regulated, pumpage by wells as opposed to a declining, but unregulated, spring flow.

Nearly all of the spring flow and well pumpage on Bahrain is from the Zone A and B aquifers. The Zone C aquifer provides

a poorer quality which is used by industries, either directly or after demineralization. Reportedly, many wells are completed, in both the Zone A and B aquifers, although present government policy is to require well completion in either the Zone A or Zone B aquifer. Most wells are of 6-inch diameters, although 10-inch diameter wells are being proposed for municipal sources of supply. Wells completed in Zone B normally penetrate only 30 feet into the aquifer, whereas in Zone A, they are open to the aquifer's entire thickness.

About 98 to 99 percent of the total known groundwater discharge is estimated to be from the Zone A and B aquifers. On Muharraq Island, almost all of the discharge by wells is from Zone A. Over 2.5 MCM per year is withdrawn for industrial use by wells from the Zone C aquifer. Other wells which tap the Zone C aquifer include those used for fire protection by BAPCO, two wells which supply water for washing aggregate at a new plant near Askar, and a number of probably small-yielding wells used for watering stock in the south-central part of Bahrain Island.

Although reportedly there is no clear evidence of any substantial increase in groundwater withdrawals since at least prior to 1973, information on groundwa er pressure heads suggest the opposite. Since the mid-60's, pressure heads have on the average become stable, probably as a result of a decrease in the total discharge, which is not apparent in the data given in Table 4-3. Possible reasons for the discrepancy may be a reduction in unaccounted-for discharge by marine springs, by natural

diffusion with sea water along the salt-freshwater interface, and perhaps by a decline in soil evaporation as a result of lowering water levels. The opportunity for soil evaporation and transpiration by abandoned date palms and unirrigated areas is limited to mostly coastal locations where the water table is near the land's surface. Estimates on the quantity transpired by abandoned date palms range from 20 to 34 MCM per year. No quantities are available on soil evaporation.

Sources of recharge to the groundwater system in Bahrain are primarily from return irrigation water, in-line leakage from the municipal distribution system, and wastewater return via land disposal systems. Much of this water is groundwater originally pumped from the Zone A and B aquifers. In-line leakage may now include new water obtained from the municipal distillation plant which presently supplies 2.5 mgd. It has been reported that about one-half of the irrigation water used returns to the water table. What proportion of the return water reaches the main aquifers as opposed to the shallow-perched groundwater body which in places overlies the main groundwater body, is unknown. In-line leakage from the municipal distribution system is reportedly high and may amount to over 25 percent of the system's flow (Reference 5). Data on wastewater return is unavailable. The amount of such waters reaching the main aquifers is expected to be minor, however.

Future Availability

Studies to date indicate that the groundwater resources in Bahrain are being naturally depleted by the slow drainage of the main aquifer system. The rate of natural depletion is unknown, but is to some extent accentuated by artificial withdrawals from wells on Bahrain and in Saudi Arabia. Actual pumpage from the aquifer ranges now from about 400 to 450 MCM per year. In Bahrain, efforts are currently underway which will result in a lesser dependence on groundwater as a source of future supply. The need for alternate supply sources is imposed by a lack of suitable quality groundwater for potable use and a progressive encroachment of salt water into the main aquifers. Present indications are, however, that the availability of usable groundwater under existing rates of abstraction should extend for some period beyond the year 2000 as postulated in prior studies (Reference 7). Efforts by the Government of Bahrain to decrease abstraction rates through conservation practices should result in further extending the period during which usable groundwater remains available, and thereby becoming less dependent on costlier distilled water or imported water from sources beyond the Bahrain land mass. The extent to which groundwater remains available, however, will depend on Saudi's policy on groundwater abstraction and conservation practices which are expected to have an impact on groundwater conditions in Bahrain.

The present policy in Bahrain is to meet future municipal requirements by blending groundwater with distilled water to

achieve a total dissolved solids content between 700 to 1,000 ppm. Although groundwater of similar quality is not available in any significant quantities, it is anticipated that by continued conservation measures, the blending ratio can be maintained at the present low level for the foreseeable future, thereby maintaining a lower overall cost in public water supply production. A municipal water use of 56 MCM per year is projected to the year 1985. Of this amount, about 10 MCM per year will be groundwater while the balance is distillate water. In relation to a present municipal usage of about 20 MCM per year, the net reduction in municipal groundwater production will amount to 10 MCM per year. A significant reduction in agricultural usage amounting to about 25 percent of the present level of about 130 to 170 MCM per year is anticipated by more efficient irrigation practices. In addition, 52 MCM per year of municipal wastewater will become available for irrigation of both cropped areas and parklands by the year 2008. Since no major increase in total irrigated areas is anticipated, a net reduction in groundwater withdrawals of at least 80 MCM per year should be realized. Industrial usage is expected to increase from 13 to 15 MCM per year. Since it is the government's policy to encourage low water-consuming industries and to meet such needs by encouraging either demineralization or direct use of water from the deeper and more saline Zone C aquifer, the net draft from the Zone A and B aquifers is expected to remain minimal. It should be pointed out, however, that the effects of pumping the Zone C

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aquifer on overlying aquifers is unknown. Should such effects prove detrimental to the shallower aquifers, other sources of saline water with a total dissolved solids content of 15,000 ppm might be available in water-bearing zones which underlie the Zone C aquifer. These might include the Wasia, Biyadh and Yamama formations. It has also been suggested that the freshwater discharge from marine springs be captured directly. Assuming that the reported total marine flow measured at nearly 10 MCM per year in 1952 has not declined, which is unlikely, the quantity would still be too small to make such a scheme feasible or economical.

Water which will become available for irrigation from municipal sewage is anticipated to have a total dissolved solids content of less than 2,500 ppm as a result of infiltration into the sewage system of more saline groundwater (Reference 12). It is cautioned that because of exceptionally high total dissolved solids which frequently exceed 20,000 mg/L in the shallow groundwater that precautionary steps be taken to minimize infiltration into sewers.

Other possible sources of supply for irrigation include excess drainage in areas having a high water table. Since such water can be expected to have a higher total dissolved solids content as a result of salt buildup in the root zone, considerations might be given to the collection and blending of such waters with less saline wastewater.

Management

A program to manage the water resources of Bahrain should be based on a policy of water conservation with its objective to reduce the net draft on the usable groundwater supply. Such a supply will have a continued importance in the development of Bahrain. It is believed that by conservation practices, the usable life of the available groundwater can be extended.

Present and proposed conservation practices are estimated to result in an overall reduction of about 90 MCM per year in the rate of groundwater abstraction within the next 20 to 30 years. Of this quantity, about 80 MCM per year will be saved by more efficient use of irrigation water and by the use of municipal wastewater for irrigation. An additional 10 MCM per year will be saved as a result of using distillate water for a public supply. Other savings are expected in agriculture by the use of drip irrigation and plastic lining of ditches which are presently under study at the Governments Agricultural Experimental Station. It is also likely that areas proposed for future agricultural use will be operated more productively and efficiently by the government than under existing agricultural practices. Presently, farming on Bahrain is carried out on relatively small plots mostly by tenant farmers using antiquated procedures.

Efforts to regulate water use are being carried out in Bahrain by the Water Resources Board of the Directorate of Commerce and Agricultural. The Board's functions include:

1. Approval on applications for constructing new water wells, the approval for which is based on a proven water need.
2. Carrying out routine measurements of water levels and water quality in selected wells and maintaining a record on newly constructed wells.
3. Responsible for the construction of all new wells.
4. Responsible for sealing and plugging off abandoned wells.

The Board is presently carrying out a short-term groundwater investigation under the direction of Dr. Wright of the British Institute of Geological Sciences. The objectives of this study include an assessment of the current groundwater situation and recent trends in changes of the groundwater pressure head, water quality, and water usage as well as evaluating alternative sources of supply. Recommendations also are to be made on types of future studies required and on water development options. The investigations also recognize the need for a joint groundwater program between the governments of Bahrain and Saudi Arabia.

The Board and the Saudi Arabian Ministry of Agriculture is carrying out a program to construct observation wells in areas off the coast of Bahrain for a more regional understanding of the impact on area-wide groundwater levels and quality in relation to major pumping centers in and near Bahrain Island and along the coastal areas of Saudi Arabia.

Among present policies on water use, the Board is restricting the use of the Zone A aquifer for agricultural and the Zone B aquifer, which generally contains a better quality water, for domestic supplies. Also being considered as a matter of policy are the metering of all well supplies and increasing the areas devoted to the landscaping of publicly owned lands. There is also an awareness of a shortage of trained personnel to effectively carry out the policies and functions of the Water Resources Board whose activities are principally devoted to the construction of wells.

Although proposed by other studies, there has been no attempt to evaluate the feasibility for artificial recharge using municipal wastewaters or infrequent storm runoff. Presently, the proposed usage of wastewater for irrigation and a public beautification program is expected to fully utilize all of the available sewage until at least the year 2008. Storm runoff is not expected to greatly add to the total water resource because of the low rainfall. A study to evaluate any potential savings in costs for large-scale demineralization of groundwater as opposed to sea water having a higher salt content should be undertaken. Other considerations on groundwater conservation include the possibly adverse affects on groundwater quality of harbor dredging. A review of harbor borings in the Mina Sulman, Muharraq, and Dry Dock areas show a relatively thick sequence of mostly unconsolidated to weakly cemented sand and silts to depths of 35 meters or greater. Generally, the borings suggest that in

these areas, the underlying Zone A aquifer is separated from the harbor bottom by relatively impermeable sediments of the Neogene complex. Dredging operations carried out in the Mina Sulman and Dry Dock areas typically extend 11 to 15 meters below the harbor bottom and are not expected to adversely affect groundwater conditions there. However, considerations should be given to carrying out studies prior to dredging operations which recognize the possible need to curtail or to minimize such operations in areas where an opportunity exists for exposing freshwater aquifers to the sea.

CHAPTER 5

WASTEWATER SYSTEMS

General

Manama and Muharraq are presently served by what Watson (Reference 5) has described as fairly extensive, but totally inadequate drainage systems. These systems carry septic tank effluent, surface and subsurface drainage. The slopes are too flat to carry raw sewage. Drain cross sections vary from narrow deep, to wide shallow, channels together with sections of ogee or circular concrete pipe. The channels are generally covered with precast-concrete slabs, many in poor condition. The drains are surcharged in many areas and blockages with area flooding are common. These drains discharge wastewater without treatment to the Gulf through a number of outfalls, most of which do not extend to deep water.

With the exception of Isa Town which has a combined sewerage system with an outfall to Khor Lupin, most of the rural areas and small villages have septic tanks and soakaways (leaching pits). The Isa Town system is a relatively modern sewerage system which utilizes mostly asbestos-cement bituminous-coated sewer pipe made with sulphate-resistant cement and some PVC flexible-joint sewer pipe which the contractor substituted for the asbestos-cement pipe due to difficulty with deliveries.

Bahrain and the World Health Organization have sponsored a detailed study, Master Plan and Preliminary Design for a

Sewerage Project covering the urbanized areas of Muharraq, Manama Town and Greater Manama.

This study was completed in October 1975 and has been accepted by the Ministry of Works, Power and Water and the World Health Organization. IBRD (The International Bank for Reconstruction and Development) has accepted the report with reservations. That is, they prefer, on a capitol basis, one of the alternative solutions to that recommended.

Presently, the sewerage project status is as follows:

1. J. D. and D. M. Watson have been engaged as consultants to design the proposed facilities and provide construction inspection services,
2. Subsurface investigations for the treatment works and the primary interceptors is complete,
3. Pipe for the sewers has been ordered and delivery is expected in December 1976 or January 1977,
4. The pipe storage compound is under construction,
5. The treatment plant site landfill contract has been awarded, and
6. Civil works contract documents have been received by the Ministry.

Sewage Flows and Quality

In studies carried out at Isa Town and Awali, Watson assumed that the present flows and per capita-pollution loading would be most representative of present and future conditions in a modern Bahrain township with proper sanitation. Data from

these studies on water use and present sewage flows and pollution loads are shown in Tables 5-1,* 5-2* and 5-3.* Watson considers this to be a relatively weak wastewater more suited to biological filtration (trickling filters) and oxidation ponds as treatment processes. The trickling filters would be followed by micro-strainers and chlorination.

TABLE 5-1. ISA TOWN WATER SUPPLY AND RESULTANT SEWAGE DISCHARGE (PER CAPITA PER DAY)

Category	Water, L	(gal.)	Sewage, L	(gal.)
Total consumption or discharge	482	(106)	280	(62)
Water distribution wastage	50(1)	(11)	NIL	
Garden use	151(1)	(33)	NIL	
Commercial, industrial, construction	1	(0)	NIL	
Domestic use	230	(51)	230	(51)
Domestic abuse	50	(11)	50	(11)
Infiltration	-	-	Less than 1	(0)

1. Estimated.

*Tables 5-1, 5-2 and 5-3, Watson Volume 1 (Reference 4).

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TABLE 5-2. PRESENT ESTIMATED SEWAGE STRENGTHS FOR BAHRAIN

Sewage analysis (related to flow)	Isa Town	Awali Town	Manama/Muharraq outfalls(3)	Police training college(4)
No. of samples	8	4	6	3
BOD, mg/L	58	46	66	100
SS, mg/L	81	60	62	144
Ammonia nitrogen, mg/L	18	14	19	40
Cl, mg/L	2,150(1)	1,550(2)	2,000	1,550
Flow, L/day	250	310(5)	220	202

1. Water supply contains approximately 2,200 mg/L Cl.
2. Water supply contains approximately 1,370 mg/L Cl.
3. Average of six spot samples taken during daytime period from three outfalls.
4. Average of three spot samples early morning-midday.
5. Estimated from water supply figures.

Source: Reference 5.

The total effluent flows as projected by Watson are shown in Table 5-4.* These projected flows, together with anticipated BOD (biochemical oxygen demand) loads are also shown graphically in Figure 5-1.

Watson, based on studies at Isa Town and Awali, estimates that sewage flows will comprise about 16.5 percent infiltrated groundwater (227 liters per capita per day wastewater and 45 liters per capita per day infiltrated groundwater). Total dissolved solids loads of shallow groundwater in the study areas vary from as low as 3,000 to over 50,000 mg/L (milligrams per liter).

*Table 5-4 from Watson (Reference 5).

TABLE 5-3. ESTIMATED PRESENT PER CAPITA POLLUTION LOADS FOR ISA AND AWALI TOWNS AND OTHER LOCATIONS

Sewage strength and per capita pollution load	Isa Town	Awali Town	Doha	Dubai	Beirut	Singapore	England
No. of samples	8	4	-	10 (May 1974 average)	9 (spot samples)	-	-
BOD, mg/L	58	46	316	443	400	200	-
gpd(1)	14.4	14.2	15.5	40.3	54.4	45.4	51.3
SS, mg/L	81	60	303	480	350	220	-
gpd	20.1	18.6	14.9	43.6	47.6	50.0	85.3
Ammonia nitrogen, mg/L	18	14	39.8	46	-	44	-
gpd	4.5	4.3	2.0	4.2	-	10.0	3.6
Flow, L/day	250(2)	310(3)	49	91	136	227	-
Sources			Pencol May '74	Govt. of Dubai Operational Contract, J. D. and D. M. Watson	Beirut Reg. Main Drainage Prelim. Study, J. D. and D. M. Watson, November 1963	Govt. of Singapore Kim Chuan results, 1973	WPRL Study Wat. Poll. Control, 196,2,67

1. Grams per day.
2. Estimated from pump hours-run meters.
3. Estimated from water supply figures.

Source: Reference 5

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TABLE 5-4. PREDICTED SEWAGE QUANTITIES[1]

Area	1978		1988		1992		2008	
	Ml/day	Mgd	Ml/day	Mgd	Ml/day	Mgd	Ml/day	Mgd
Manama and Greater Manama	39.14	8.61	56.30	12.38	64.36	14.16	108.20	23.80
Muharraq Town	13.57	2.99	19.53	4.30	22.30	4.91	37.51	8.25
Hidd	1.90	0.42	2.72	0.60	3.16	0.70	5.63	1.24
Isa Town	4.90	1.08	7.48	1.65	8.57	1.89	14.52	3.19
Total	59.51	13.10	86.03	18.93	98.39	21.66	165.86	36.48

1. Average daily flows inclusive of infiltration based on uniform per capita rates of 227 + 45 L/day.

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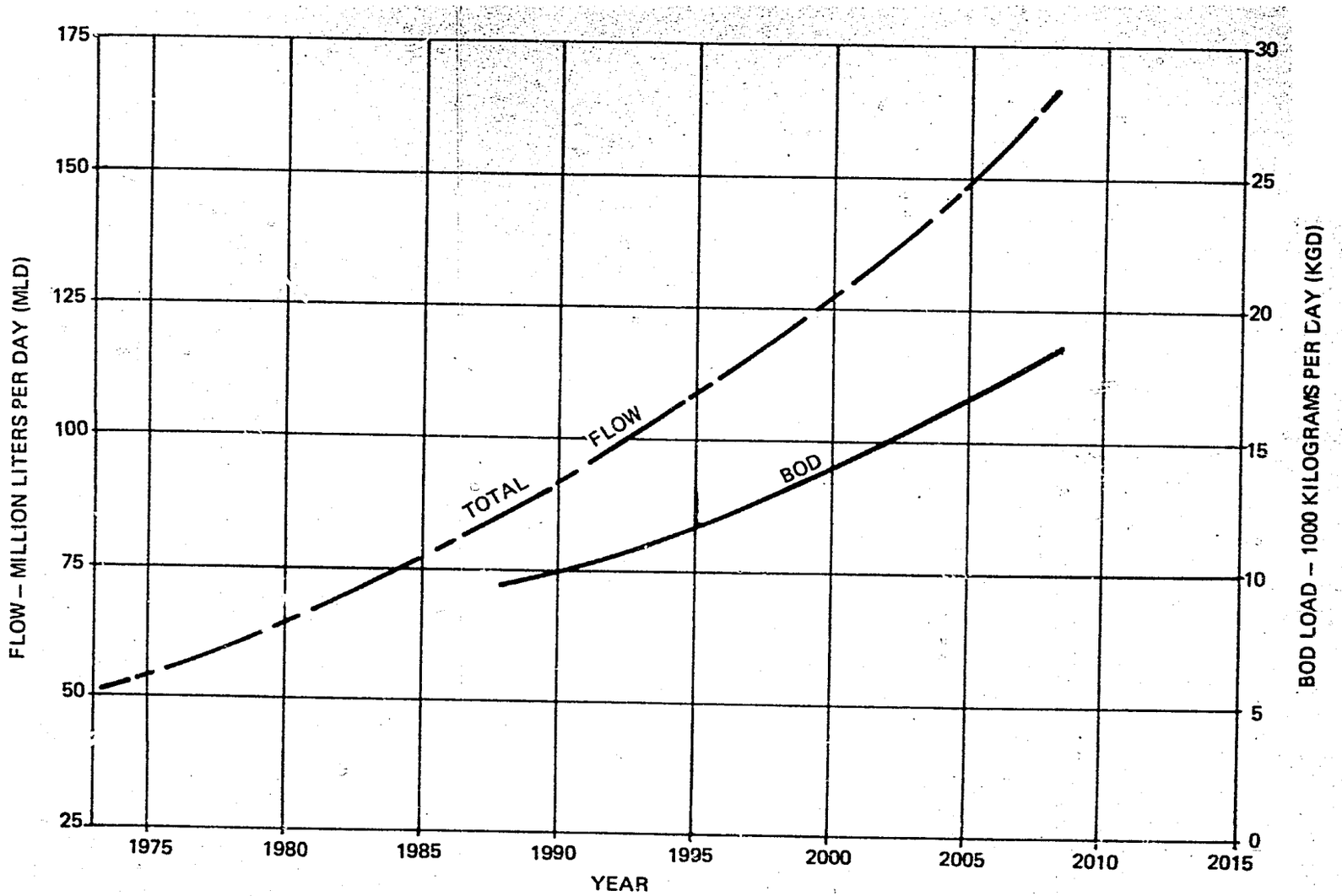

1. MANAMA, GREATER MANAMA, MAHARRAQ TOWN, HIDD AND ISA TOWN

FIG. 5-1 BAHRAIN SEWERAGE SYSTEM – PROJECTED SEWAGE FLOW AND B.O.D.(1)

Figure 5-2 shows the effect of various rates of infiltration of shallow groundwater on the quality of sewage or reclaimed water. This figure indicates that the quality of reclaimed water is quite sensitive to the rate of infiltration of saline shallow groundwater and, therefore, extreme care in design and construction of the collection system is recommended. Sewer manholes and sewer pipe joints are most likely to be sources of groundwater infiltration. If reasonable care is taken during construction, joint leaks can be largely eliminated. Manholes are generally constructed from concrete, either precast or cast-in-place, or are concrete block or brick masonry structures. Most manholes will project from below the groundwater table through the capillary zone to the surface and, therefore, will be subjected to salt weathering. Based on observation of manholes in the existing Manama drains, we would expect that within 10 years of completion of the system, manhole salt weathering and increased infiltration could be sufficient to cause significant increases in total dissolved solids of the reclaimed water.

To avoid such a situation, we recommend that fiber glass reinforced-plastic manhole cores complete with bottom liners and wall penetrations with bells designed for rubber O-ring gasketed pipe joints. These cores could be prefabricated complete with fiber glass reinforced-plastic ladders. The core would then be placed to proper elevation and either concrete-block masonry or concrete surrounds placed around the outside to provide added

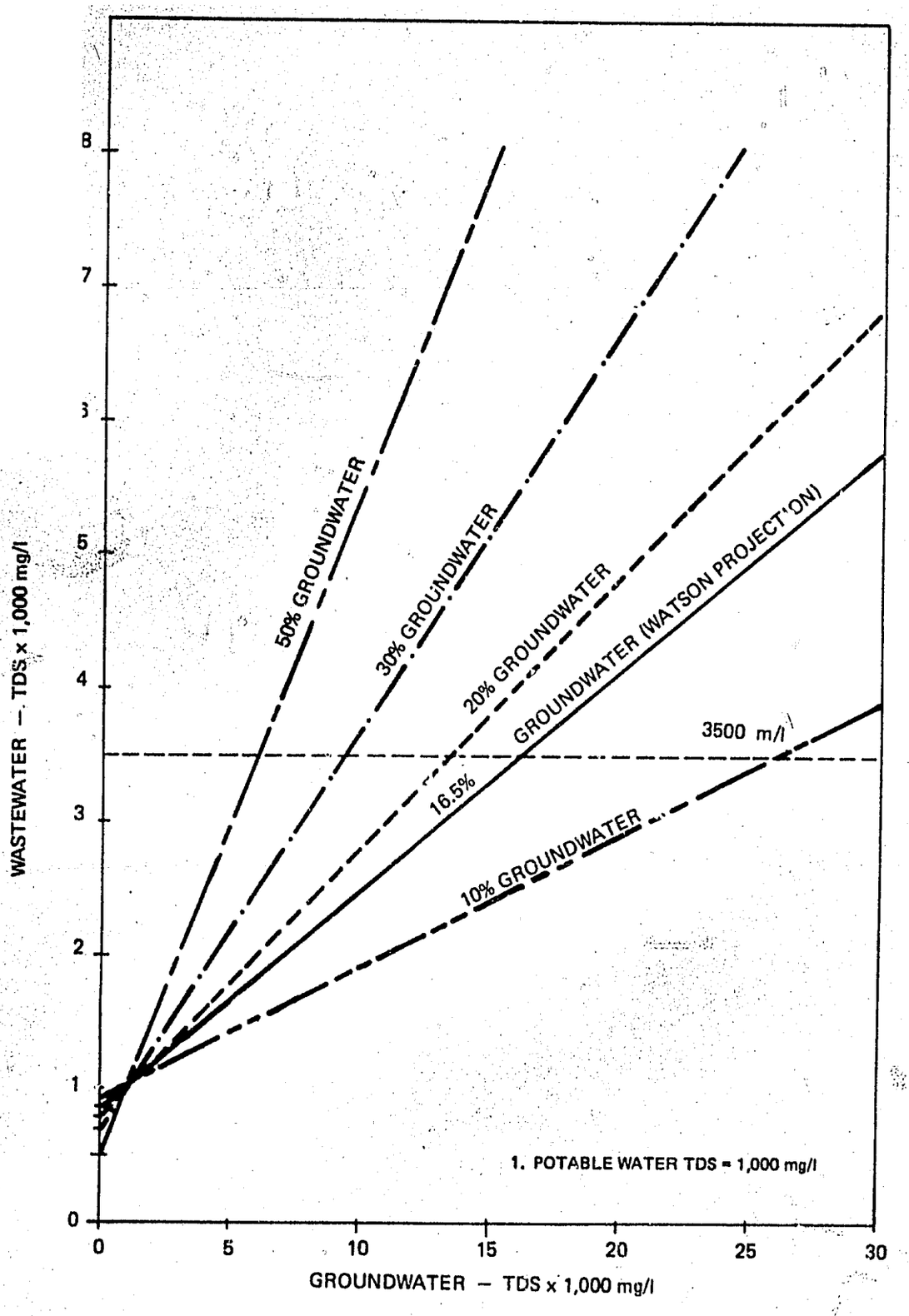

FIG. 5-2 EFFECT OF GROUNDWATER INFILTRATION ON TOTAL DISSOLVED SOLIDS OF WASTEWATER

strength and protect the fiber glass core from damage during backfilling operations.

Availability of Reclaimed Wastewater

Watson has projected for the proposed service area* total wastewater (sewage) volumes, including infiltration (at 16.5 percent), of 31.4 MCM per year or 86 million liters per day in 2008 (see Table 5-4). Reclaimed water allowing for losses in treatment (including leakage, evaporation, etc.) has been projected by McGowan (Reference 12) to be about 3.5 MCM per year in 1978, 27.2 MCM per year in 1988 and 52.3 MCM per year in 2008. Figure 5-3 shows projected reclaimed wastewater annual flows and connected population. Based on the present status of the sewerage project, these projections are, in our opinion, reasonable.

Public Health Concerns

Watson (Reference 5) and McGowan (Reference 12) have considered the public health aspects of reclaimed water use for irrigation. In their respective reports, they have recommended that sewage treatment comprise primary settling and biological filtration (trickling filters) followed by microstrainers and chlorination. In addition, Watson has recommended adoption of bacteriological standards for the reclaimed water which are consistent with the most sensitive planned use or possible inadvertent accidental use.

*Manama and Greater Manama, Muharraq Town, Hidd and Isa Town.

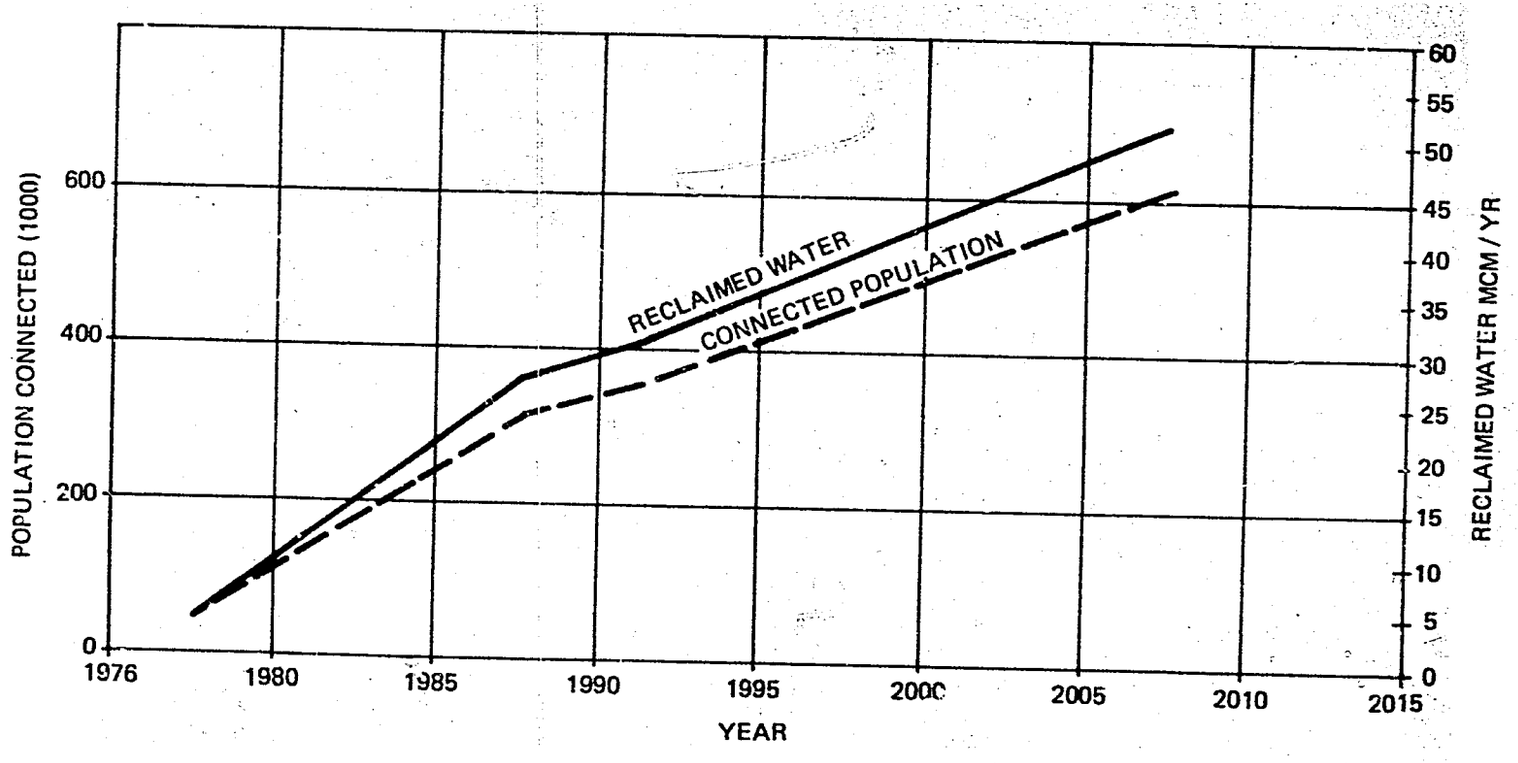

FIG. 5-3 ESTIMATED CONNECTED POPULATION AND RECLAIMED WATER FLOW

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Generally, these reports recommend that adoption of standards based on WHO requirements and the more conservative requirements of the State of California, the Republic of South Africa and the Federal Public of Germany. These standards are summarized in Table 7 of the McGowan Report (Reference 12).

In our opinion, reclaimed water treatment and quality control are extremely important factors in reuse of wastewaters since there is always the possibility of improper or inadvertent use of the reclaimed water. We, therefore, agree with Watson and McGowan and recommend conservative standards apply to reclaimed water treatment regardless of the planned use.

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CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Our principle conclusions and recommendations are summarized in this section. They are primarily concerned with available water resources, water requirements and the need for water conservation.

Conclusions

1. It is generally recognized in Bahrain that there is a need for an overall policy to manage its water resources. The present management policy is rightly directed toward establishing methods by which groundwater abstraction can be reduced through conservation measures.
2. Based on a review of available studies and data, there is every indication that the availability of usable groundwater can be extended by conservation practices beyond a time originally predicted (about the year 2000) in the Italconsult study.
3. An apparent reduction in the rate of groundwater depletion is evident since about the mid-1960's. The cause for the apparent reduction is not fully understood but may be the result of a net decline in total groundwater discharge.
4. An overall review of the literature and data on groundwater indicates that a more careful evaluation and interpretation of the data base as well as

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additional information is needed to adequately describe the hydraulic parameters of an extensive groundwater system which extends from Saudi Arabia to Bahrain. The overall lack of adequate data precludes any meaningful understanding of this system as required for predicting future events which could have a limiting effect on the groundwater resources or as needed for the proper management of a finite water resource.

5. More immediate programs are needed to establish the rate of saline water encroachment and the disposition and extent of the salt-freshwater interface. Existing information is inadequate to describe the dynamics of this interface in relation to changes in pressure head and avenues by which saline waters are migrating. The lack of adequate data on groundwater conditions between Saudi Arabia and Bahrain is, in part, being resolved by the construction of observation wells in areas offshore from Bahrain. Data obtained from these wells, however, are not expected to have a direct application to the present problem of salt water encroachment as it effects more immediate groundwater users.

6. Information on existing and past groundwater abstraction is believed to be unreliable or incomplete, particularly in relation to total groundwater discharge.

A particular need exists for accurately establishing the quantities and rates of groundwater abstraction for irrigation which accounts for at least 80 percent of total groundwater use.

7. The present policies and objectives on water conservation, use and management are not fully integrated under any one single authority. The divergent requirements, objectives and priorities of industrial, agricultural, domestic and municipal use will require a coordinated plan which recognizes both social and economic needs as yet not clearly established. Such a plan will provide management objectives by which priorities and allocation for different types of water usage can be implemented or planned for.

8. There have been a number of valuable studies regarding the groundwater resources and the use and conservation of these resources. Many of these reports' recommendations have been carried out, are underway or are in the planning stage.

9. The major water use is for agriculture. This is largely a very poorly controlled use with the only real restraint the capacity of existing wells or the depth of wells and number of wells allowed by the Water Resources Board.

10. Irrigation practices are still generally wasteful of water since from 30 to 40 percent more is used than

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is necessary for plant use and salt leaching. It has been estimated that the present irrigation use of about 166 MCM per year could be reduced to from 100 to 120 MCM per year without reduction in yield or land in cultivation.

11. Correction of the wasteful use of water in agriculture is presently being attempted by the Agricultural Directorate through demonstration plots and publicity. This is a slow and not always successful process.

12. Per capita domestic and municipal use appears to be quite high but should be reduced with metering and higher water rates.

13. Recycling of wastewater as irrigation water for agricultural use, and for plantings on roadsides, in parks and/or recreational lands is planned in connection with a new sewerage system for the urban areas.

14. There are three bodies concerned with groundwater extraction: water distribution, water production and water treatment.

15. Without a stepped system of water rates, based on metered water use, wasteful water use by domestic, commercial and industrial users will not be reduced.

16. Collection, treatment and reuse of wastewater (sewage) is an important adjunct to any water conservation plan proposed.

17. Many of the farmers, most wasteful of water, are tenant farmers who are least able, financially to adopt water-conserving irrigation methods and have little incentive to do so.

Recommendations

Policies and Planning

1. A policy should be formulated which details the Government's long-range economic and social objectives as well as development priorities. Such policies should be capable of being equated into terms of future water requirements as they relate to both quantity and quality.
2. Considerations should be given for a more definitive plan of land use and zoning. The need for such a plan is of special importance should the government expand resort developments, allocate open-space land for both recreation and agriculture, and promote certain types of industrial or commercial developments which are based on the availability of specified natural resources. A land-use plan should also be based on assessing residential expansion from the major population centers and the economic impact of completing the causeway which will link Bahrain with Saudi Arabia.

Management and Conservation

1. In view of Bahrain's limited groundwater supply and the need to conserve this resource, it is proposed that a central water authority be established which would be empowered to establish the right of water allocation in keeping with the government's policy to encourage economic growth and to provide for the welfare of its people. The authority should also be involved in national policies which affect the nation's water resources. In addition, the authority should carry out the following functions:

   a. Set water use allocations consistent with national policies and planning for individual industries, agricultural users, and private household use, whether from public or private sources.

   b. Meter all water use including use from private wells and/or use of reclaimed wastewater.

   c. Establish water usage rates based on metered use, for potable water, reclaimed wastewater, and groundwater (from private or public wells) for agricultural, industrial or household use. The rate structures should make allowance for the quality of water supplied. The minimum charge for potable water would allow for sufficient quantity to supply water requirements consistent with maintenance of good health for each family

at a subsidized rate. The charge rate for usage beyond this level would be designed to recover the remaining cost of potable water production. Usage rates for reclaimed water and groundwater would be similarly structured with the individual user's allocation at the lower rate and usage above this level at sufficiently high rates to discourage wasteful use.

d. Approve proposed water supply wells and carry out all those functions presently under the control of the Water Resources Board.

e. Operate and maintain a national public water supply and wastewater reclamation system.

f. Carry out hydrologic studies to update and forecast future impacts on the groundwater resources and to recognize the need for alternative water supplies.

g. Set water conservation policies and establish and define conservation practices.

2. Conservation policies under present consideration which should be implemented immediately include:

a. Metering of all wells including domestic, agricultural and industrial wells both private and public.

b. Encourage farmers to produce crops having a higher yield, greater monetary return or higher economic benefit to the national economy.

c. Promote improved irrigation practices by levying monetary penalities on excess or wasteful irrigation and other uses.

3. Other conservation approaches which should be evaluated include:

a. Setting policies on harbor dredging activities which could adversely affect groundwater availability.

b. Setting guidelines on depth of land stripping for aggregates. Maximum allowable depths of excavation should be established for areas containing usable groundwater and be designated by levels to which excavation can take place without increasing the potential for soil evaporation.

c. Determine the feasibility for recycling industrial wastewaters for processing or other beneficial uses.

Hydrologic Studies

1. Considerably greater detailing of the aquifer system is required before a meaningful program to manage the groundwater resources can be established and time projections on availability of groundwater can be made. Such detailing should require a full-time

effort by a staff of trained hydrologists for at least a two to four-year period.

2. The proposed study program should be undertaken in cooperation with the Saudi Arabian government who share the same aquifer system.

3. The prime objective of the study program would be to model the aquifer system in sufficient detail to permit forecasting the impacts by use and conservation, and such related practices which affect the available groundwater resources both in terms of quantity and quality.

4. Because of a lack of trained hydrologists in Bahrain, it is recommended that the staffing be provided by other countries who maintain government agencies specializing in groundwater hydrology.

5. Any proposed study of Bahrain's groundwater resources should include a training program and relate to specific technical tasks which may include:

   a. Assembly and retrieval of data in readily usable form.

   b. A thorough review of available reports and studies and their reevaluation on the basis of new and additional information on file at both BAPCO, the Water Resources Board and other governmental and private agencies.

c. Accurately establish hydraulic parameters which govern flow in an interconnected groundwater system.

d. Evaluate the potential for supplying groundwater from deeper water-bearing zones.

e. Recommend and carry out additional and applicable programs to establish the necessary data base required to evaluate the impact of groundwater abstraction on aquifer depletion rates, the rate and dynamics of salt water encroachment, and such man-made activities which affect groundwater, either beneficially or adversely.

f. Design and prepare an appropriate hydrologic model which is capable of simulating actual groundwater flow conditions in that portion of the aquifer system which contributes directly to the groundwater resources in Bahrain.

g. Considerations should be given to augmenting Bahrain's groundwater resources by artificial means which utilize storm runoff and wastewaters. Use of wastewaters for recharge should be made only when strict standards of treatment and disinfection of the wastewater are applied.

h. The effects of either existing or proposed dredging and other major projects involving earth

should be studied in relation to their impact on groundwater.

i. Studies should be carried out to more accurately evaluate the benefits of existing or any proposed conservation practices.

j. Evaluate alternate approaches in groundwater development. Such approaches might include the use of skimming tunnels and infiltration galleries particularly in areas where groundwater is susceptible to contamination by deeper or nearby saline waters.

CHAPTER 7

POSSIBLE USAID ASSISTANCE

We suggested that the two areas in which AID-sponsored advisors might be most beneficial to the Government of Bahrain are in the establishment and management of a National Water Authority and in further investigation of the groundwater aquifer system. The following types of advisors are recommended:

1. An advisor to assist in establishing and developing or building the suggested Water Authority. He should be an individual who has been Manager or Deputy Manager of a Major Water Authority during its formative years, preferably one which included water supply for irrigation as well as potable water supply. He need not be an Engineer, but should understand engineering reports and studies and have sufficient background in economics and water systems so that he can aid in evaluating the recommendations in a series of reports prepared over the past few years and arrive at the most cost-effective total solution to such questions as: Should there be a centralized desalination plant on Sitra in conjunction with the proposed power plant expansion there or is it more economical to go to a separate desalting plant nearer the center of demand? Perhaps a retired or retiring Manager or Chief Engineer from one of our Southwestern Authorities or Irrigation Districts would be a good candidate.

2. There is a need for further investigation of the groundwater aquifer system which supplies Bahrain so that aquifer response to conservation measures may be determined and a better understanding of the aquifer attained. The study should develop enough information to allow better prediction of future declines in yield and quality of water with increases or decreases in use, both in Bahrain and Saudi Arabia. This would be a long-term project. Perhaps such a program could be an outgrowth of the present cooperative effort (between Bahrain and Saudi Arabia) to install additional observation wells.

This is the type of project for which an organization such as the U. S. Geological Survey (with support from the participating countries) would be very well qualified.

The project team should like to express their gratitude for the opportunity to visit and work in Bahrain and for the courtesies and aid willingly extended by the Embassy and by the Bahrain officers and individuals listed in the Introduction.

Respectfully submitted,

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