Technological Aspects of Water Resources Management *

John D. Keenan †

1 Introduction

The purpose of this paper is to discuss the technology available for resolving water problems in the Jordan and Euphrates drainage basins. In each of these watersheds, the discharge is strongly seasonally dependent. In addition, both the flow and the water quality decrease downstream as a result of evaporation losses, infiltration, and nonconsumptive uses. Because of these quality and quantity issues, long-term economic growth depends upon aggressive water resources management. Superimposed upon these quantity and quality limits is an agricultural system which requires a significant and continuing hydrological and energy investment for its sustenance.

Water resources technologies are aimed at controlling the quantity and quality of water. In the regulation of water quantity, the objective is to match the supply of water with the demand for it. Thus, these technologies may seek to control either demand (*e. g.*, conservation, drip irrigation techniques, etc.) or supply (cloud seeding, storage reservoirs, supply systems, etc.). On the quality side, the technologies of interest are designed either to alter the nature of the water (*e. g.*, desalination) or to change the nature of its use (development of salt-resistant crops, wastewater reuse). Included in this paper are a review of the technologies used to improve

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†Professor, Civil Engineering Systems, and Associate Dean, Undergraduate Engineering Education, University of Pennsylvania, Philadelphia, PA 19104-6391

water quality; a discussion of the use and the limitations of technology in the context of the Jordan and Euphrates; and, a few examples of the application of technology in the study area.

2 Euphrates

The headwaters of the Euphrates River provide a water which is of reputedly high quality. Data are not available to quantify this, although van Aart [1] states that irrigation waters used in the lower part of the Euphrates average 300–500 ppm salinity, and that the river water in the south may reach 600 ppm. Cressey [30] reports that the salinity of the Euphrates averages about 250 to 445 ppm. However, the use of the water for irrigation purposes upstream attests to its quality. In the estuary region located south of Basra, the salinity levels are naturally much higher. This is especially true at high tide in the autumn when the flow is lowest. During such periods, the salinity is typically over 5000 ppm [1].

Talling [80] presents groundwater data for the basin at stations located at Musaiyib on the Euphrates and at El-Zubeir on the Shatt al-Arab. These data indicate very high concentrations of dissolved ions, especially sodium, magnesium, chloride, and sulfate. The salt content of the upper groundwater ranges from 7000 ppm in the central part of the Lower Mesopotamian Plain to 30,000 ppm in the south [1]. Talling also presents data showing the salinity of the river increasing from 160 to 525 ppm over the seasonal cycle as measured at Samawa, about 220 km above Qurna. Other data presented by Talling show electroconductivity increasing from 575 mmho/cm at Qaim to over 900 micromho/cm at and below Samawa. Edaphic factors in the lower basin contribute naturally to a reduction in water quality as the river moves downstream. In this regard, it is important to note that the flooding of the Abu Dibis depression by the Iraqis in the 1950s resulted in a degraded water because of the rapid evaporation rate and the high salt content in the soils of the depression.

The lower part of the Euphrates is naturally prone to the problems of salinization. This results from a combination of poor drainage, centuries of irrigation, and natural soil factors.

As noted in the section below, the three riparian states have extensive plans for further developing the waters of the Euphrates. These plans are expected to mature and be implemented over the next twenty years. The intended results of the plans are increased irrigation, population growth, and an expanded industrial base. An unintended result will be the certain degradation of the quality of the water in the river's lower reaches. This will undoubtedly render the water progressively less fit for use by the Iraqis. It is not unreasonable to expect that the lower part of the Euphrates will experience a degree of reduction in water quality proportional to that observed in the River Jordan in recent decades.

2.1 Current water use in the Euphrates Basin

Turkey makes use of the upper reaches of the Euphrates primarily for the generation of electricity via hydroelectric stations. In the future, this is expected to change as there are in existence Turkish plans for making greater use of the stream, particularly for irrigation purposes.

The waters of the Euphrates and its major tributary, the Khabur, are used primarily for agricultural purposes in Syria. The Syrian economy has grown substantially during the past forty years, and much of this growth has been attributed to increased agriculture. According to Beaumont [20], water from the Euphrates for irrigation purposes amounted to 3000 Mcm per year in the late 1960s. The implementation of the Tabqa irrigation projects over the next two decades will accentuate this trend. It is estimated that the Tabqa dam will provide irrigation water for over 600,000 ha, and that further development of the Khabur will bring another 400,000 ha under irrigation. As of 1984, only 60,000 ha had been reclaimed [11]. Additionally, Syria plans to develop this area as an industrial center.

Data are not readily available to document Iraq's use of the Euphrates. Bari [18] states that little agriculture is supported in the al-Jazira region in Iraq, in spite of the potential fertility of the soil. The bulk of Iraqi agriculture is based in central and southern Iraq in the region around Baghdad and south of it. Barley, rice and dates are the staple foods. Beaumont [20] indicates that the water withdrawn by Iraq rose from 27.3 percent of mean flow in 1940–1949 to 45.1 percent in 1960–1969. Most of this increase of approximately 65 percent (in twenty years) is attributable to expanded agricultural irrigation. Gischler [44] indicates that 48 percent of the cultivated land is under irrigation and that 80 percent of the irrigated land is affected by salinity.

Water demands in the basin will undoubtedly continue to grow. The population growth in the three riparian states has averaged around 3 percent per year [20]. The increasing population will produce a proportional demand for electricity, agricultural production, and industrial production, all of which in turn will place a strain on the water resources of the region. For example, the Ministry of Planning for Iraq expects the amount of surface water extracted in 1995 from surface sources for potable and industrial uses to be seven times the amount used in 1975 (increasing from 1553 to 10,425 Mcm per year). Whether accurate or not, the key point is the anticipated stress placed on the water sources of the region in the near future.

The use of the Euphrates system by the Syrians and Turks has serious international consequences. Of particular concern is the downstream riparian, Iraq. Continued use of the Euphrates for irrigation will lead to degraded water quality in the Euphrates which will adversely affect the use of the water in Iraq. The other ramification is that increased use upstream by Turkey and Syria will reduce the flow in the river because the major use of the water is for irrigation which, of course, is a consumptive use. Additionally, the irrigation water which is returned will be of degraded quality and will further aggravate the water quality problem. The role of the Tigris-Euphrates link in Iraqi water supply is not yet fully developed.

Indeed, the three riparians have held discussions regarding the use of the Euphrates. Such discussions have been kept secret, and the negotiations have been linked to other watersheds (the Orontes) and to other issues. Although the data are not available, it is apparent that the riparians have had great difficulty reaching an accord with respect to allocations of the flow of the Euphrates. In view of the competing plans for the further development of the Euphrates River mentioned above, it is apparent that a pact among the users will be required to prevent disagreements over the next twenty years.

2.2 Large-scale constructed facilities on the Euphrates

The three riparians, Turkey, Syria and Iraq have all formulated plans and implemented projects over the years to achieve flood control on the Euphrates and to use its waters for the generation of hydroelectricity and large-scale irrigation. Little effort has been made to coordinate the planning of the three entities, and no formal agreement has been reached regarding the allocation of the water to riparians.

The Hindiya dam was completed in 1913. This barrage is located in Iraq, and it represents the earliest of the modern developments on the Euphrates. The purpose of the Hindiya was to divert water to reconstructed irrigation canals, including the Al Hillah irrigation channel. In the 1950s, a second dam was built at ar-Ramadi. This project was designed for flood control and it permitted flood waters to be impounded in Lake Habbaniyah and the Abu Dibis depression. The soils of the depression proved saline and this resulted in a degradation of water quality and the scrapping of the irrigation plan. A third dam was planned for al-Haditha, further upstream above ar-Ramadi and Hindiya. It was scheduled for completion in 1982, but the Iran-Iraq war caused drastic cutbacks in Iraq's development spending. The dam was dedicated in 1985. It is intended to damp seasonal fluctuations in flow and, in the future, to probably provide irrigation water.

As noted in the discussion of the Orontes, Syria has achieved a considerable growth in irrigated land over the past three decades. According to Beaumont *et al.* [20], reserves of cultivable rain-fed lands have almost been depleted. Given the experience of economic growth in Syria, and its anticipated continuation, an expansion of the amount of irrigated land is a necessity. During the immediate post-World War II era, this was achieved in the Orontes. Further expansion of irrigation requires more complete use of the Euphrates and the Khabur. Costly irrigation systems will be required for both rivers because each flows in a narrow deep channel. Plans for the Khabur include the construction of additional dams downstream from Tel Mahafy at Saab, Skouhar and At-Taaf to irrigate a predicted 120,000 ha. On the Euphrates, an earthen dam has been constructed at Tabqa (ath-Thawrah). The dam was completed in 1973. The lake behind this dam stores approximately 40,000 Mcm which is used to irrigate the Raqqa plateau above the east bank of the river, and the district of Resafe on the west. The planned amount of irrigated land was to be about 550,000 ha.

Turkey has plans to make extensive use of the waters of the Euphrates River for hydroelectric generation and for irrigation. The first interest shown by Turkey in the Euphrates was as a hydroelectric source. The Keban dam, completed in 1973, was designed to produce electricity and to attenuate the seasonal peaks in the flow regime of the river. The dam is 200 m high and forms a lake 115 km long behind it. The power plant has an installed capacity of 620 MW. The Keban is designed to provide a minimum discharge of 450 cu m/s, and to almost completely prevent discharges greater than 1000 cu m/s. The lower Euphrates project anticipates the irrigation of about 80,000 ha from groundwater in that river basin.

Turkey also has plans for three additional dams below the Keban. These should be advancing towards completion, although the final date is unknown. Recent evidence indicates that the construction schedule has been accelerated. The dam at Ataturk (Karababa) is intended to supply irrigation water for 300,000 ha in the Urfa, Harran, and Lower Mardin plains, and to an additional 400,000 ha in the Siverek-Hilvan, Upper Mardin and Nusaybin-Cizre areas. (This dam is located furthest downstream, the others, the Karakaya and the Golkoy, being designed for hydropower.)

The start-up date for the Turkish irrigation works was reported to be 1983, with a planned construction period of about two decades. When completed, it is projected that the irrigation system will require between 17.5 and 34 percent of the total flow of the Euphrates River at Keban. This will result in a significant reduction in the river's flow which will not be compensated by the seasonal flow regulation of the dams.

Given the proposed development schemes of each of the three users of the Euphrates, it is apparent that in the near future, the waters of the river will be completely utilized. In fact, successful completion of all the planned projects may lead to a very small surplus (or even a small deficit) of water in average flow years, and severe shortages in drought periods [20]. The anticipated completion dates of these projects are subject to conjecture and some doubt; however, in the absence of improved efficiency and increased conservation, it is reasonable to assume water shortages in the basin by the end of the present century.

Additional water resource projects will link the Euphrates with Lake Tharthar, north of Baghdad. This is especially interesting because it could be used to provide a connection between the Tigris and the Euphrates in Iraq. The Samara barrage on the Tigris, constructed in 1955–56, is capable of diverting 9000 cu m/s towards the Wadi Tharthar, a natural depression of storage capacity 72,840 Mcm. The Tharthar Canal is 65 km long. The Tharthar-Euphrates canal, providing a link to the Euphrates is the next phase. According to Khadduri [57], the plan is to store enough water in the Tharthar lake in order to divert it to the Euphrates for irrigation as well as to provide water for the Tigris in seasons when its water availability is too low. The Tharthar and other water supplies are expected to provide water for irrigation where rainfall is scarce and irregular. The effect of soluble salts in the Tharthar from the soil on water quality is not yet defined. This may result in water quality sufficiently degraded to prevent use of the water.

3 Jordan

The headwaters of the Jordan are generally of high quality. The three tributaries of the Upper Jordan, the Dan, Hasbani and Baniyas, have a salinity of about 20 ppm which is clearly sufficient to satisfy most uses. The salinity of the Yarmuk River is also reasonably low, being reported as 100 ppm. The salinity of the lower portion of the Jordan River System becomes progressively greater below the entry of the Upper Jordan into Lake Tiberias.

A number of natural sources render Lake Tiberias water saline to the extent of about 350 ppm [43] which is too high for some sensitive crops, most notably the citrus fruits which are economically important in this region. Much of the salt results from the inflow of salty subterranean springs. (Considerable efforts have been devoted to reducing the salinity of Lake Tiberias. Current levels in the upper portion of Lake Tiberias are about 240 ppm which is still marginal for superior irrigation water.) As the Jordan proceeds down into the Rift Valley towards the Dead Sea it becomes saltier, reaching several thousand parts per million by the Allenby Bridge near Jericho. Ultimately, the salinity of the Jordan River System reaches 25 percent (250,000 ppm) in the Dead Sea, a level approximately seven times that of the ocean. Naturally, this is too high to support plant or animal life, although certain minerals, especially bromines and potash can be extracted by (solar) evaporative processes.

The development of the Jordan has accentuated the salinity of the Lower Jordan. The salinity in the lower reaches of the river has increased in recent years [66] as a result of the diversion of the low salinity headwaters both to the National Water Carrier and to the East Ghor Canal.

Although the greatest water quality concern in this region is salinity and its impact on the agricultural fitness of the water, there is some recent concern with other water quality issues. The first of these is domestic pollution of the Upper Jordan which may eventually threaten the National Water Carrier. Additionally, there has been a heightened concern with eutrophication in Lake Tiberias, although evidence indicates that conditions there are not representative of lakes undergoing typical cultural eutrophication [74].

3.1 Patterns of water use in the Jordan Basin

The primary users of the waters of the Jordan are Israel and Jordan. Between them, the Jordan River System has been extensively exploited and this river accounts for about one-half of their water demand. The other riparian states are Lebanon and Syria. Lebanese use of the Jordan at present is minor in comparison to that of the others. The extent to which Syria uses the waters of the Jordan, *i. e.*, the Yarmuk, is not presently known.

3.1.1 Israel

The current estimate for the total annual demand for water by Israel is about 1750 Mcm, approximately 80 percent of which is used for irrigation, 15 percent for domestic use, and 5 percent for industrial use. Approximately 43 percent of the cultivated land is irrigated. This amounts to 185,000 ha (1.85 million dunams). Present estimates indicate that Israel presently uses as much as 95 percent of the total renewable water resource available to it although Galnoor [42] states that the total stock of sustainable water yield in Israel is only 1500–1600 Mcm per year. This represents an extremely high degree of utilization of water resources. This is true in spite of the fact that per capita consumption (537 cu m per year; 86 cu m per year for domestic purposes only) is not out of line compared to other industrialized nations (although it is high compared to its neighbors).

The role of the West Bank in the water economy of Israel is worth comment. It is estimated that one-third of Israel's water requirement originates in rainfall over the western slopes of the West Bank and is drawn from the same aquifer system that supplies the West Bank.

3.1.2 Jordan

Data are generally not available for water consumption by Jordan. The history of irrigation in Jordan has been limited, and the estimates are that only 4.6 percent of the cultivated land was irrigated in 1972 (compared to 41.1 percent for Israel and 7.6 percent for Syria) [68]. Gischler [44] gives these figures as 7.2 percent and 9.8 percent for Jordan and Syria, respectively. The Jordan Valley has 36,000 ha of cultivable land of which 24,000 were irrigated in 1979 [58]. Eighty percent of the irrigation water of the Jordan Valley is provided by the East Ghor Canal and the Yarmuk is the main source. It is clear that the population of Jordan (and with it, water consumption) has been rising at a rapid rate. Total annual consumption was 555 Mcm for 1980 of which 465 Mcm were for agriculture, 30 Mcm for industrial users, and 60 Mcm for domestic use. The estimates for the year 2000 are for a total annual demand in Jordan for 1009 Mcm.

The Jordan River is extensively developed by both Jordan and Israel. For all practical purposes, the available quantity of high quality water is presently extracted, leaving only poor quality highly saline waters in the main stem of the River Jordan. The potential for conflict here is great because the available water is being used and both societies are expanding with an increasing thirst. It may very well be that the pressure created by this complete exploitation of the Jordan will spill over into a nearby system (*e. g.*, the Litani) as the principal riparian users of the Jordan seek other sources.

3.2 Large-scale constructed facilities associated with the Jordan Basin

3.2.1 Jordan

The development plan undertaken by the Jordanians originally involved cooperative efforts with the Syrians. The Jordanian Great Yarmuk Project was undertaken at the same time as the Israeli's National Water Carrier [43].

The first stage of the Great Yarmuk Project was a headwater irrigation program designed to provide controlled winter irrigation and expanded summer irrigation in the El-Muzeirib region of Syria. Initially, the plan called for two canals to run parallel to the Jordan and carry low salinity waters through the East and West Banks for irrigation and other uses. These efforts were called the East Ghor Canal and the West Ghor Canal. The West Ghor Canal was never started because of the 1967 war and the subsequent occupation of the West Bank. The Upper East Ghor Canal phase was completed in 1962 [72]; by 1979, it had reached a length of 100 km, and a further expansion has been planned to bring it adjacent to the Dead Sea.

The Maqarin Dam phase of the Great Yarmuk Project involved the planned construction of a dam at Maqarin on the Jordan-Syria border. Two dams were eventually proposed for the Yarmuk River. The Maqarin Dam was to be located approximately 35 km east of the confluence of the Yarmuk River and the Jordan. The Mukheiba Dam was to be located about 10 km east of the Yarmuk-Jordan confluence. Work on these two dams was delayed because of Israeli land gains in the 1967 war, and work on the Mukheiba Dam, which lies below the occupied Golan Heights, was never resumed. Israel and Jordan were thought to have reached an agreement mediated by Philip Habib regarding the Maqarin Dam, but work has not been resumed. The Maqarin Dam will be 125 m high, store 150 Mcm, and irrigate 15,000 ha. The King Talal Dam, completed in 1977, lies across the Zarqa River. It has storage volume of 52 Mcm and a generating capacity of 5 MW.

The Kufrein-Hesban Project, located in the southern part of the Jordan Valley, consists of a diversion dam on the Wadi Hesban, the Kufrein Dam, a pipeline between Wadis Hesban and Kufrein, and a sprinkler irrigation system. The purpose of the pipeline is to carry Hesban flows in excess of local needs to the Kufrein reservoir.

3.2.2 National Water Carrier

For Israel, the implementation of water works following the non-ratification of the Johnston Plan took the form of the construction of the National Water Carrier, an extensive conduit system designed to transport water from the water-rich (at least 1000 mm precipitation/yr) north to the potentially fertile but arid (30–200 mm/yr) out-of-basin regions of the Negev Desert. The Carrier, completed in 1964, lies entirely within Israel's pre-1967 boundaries and diverts water from the Jordan from the northern edge of Lake

Tiberias primarily to coastal areas along the coast and to the Negev.

The Yarqon-Negev part of the National Water Carrier system, completed in 1955, is fed by wells east of Tel Aviv and provides 270 Mcm for that city and for irrigating the Lachish area. Another portion of the system is used to collect water from northern Galilean creeks which was formerly discharged to the Mediterranean and to irrigate portions of the Esdraelon Valley. A third part of the system drained marshy areas (Huleh Valley) in an effort to improve the flow of the Upper Jordan. These three parts of the overall system were completed early and are often not considered to be part of the National Water Carrier proper.

The Carrier consists of a series of pumps, canals, and tunnels used to convey water taken from Eshed Kinrot on Lake Tiberias (210 m below sea level) to as far as 200 km to the south [51]. The average water flow is 320 Mcm per year and the maximum elevation difference is 360 m. Water from Eshed Kinrot is pumped to the Eshkol Reservoir at elevation 145 m above sea level. From the Eshkol Reservoir, a pressurized system conveys water to the Zohar Reservoir. The connection between the two reservoirs consists of 85 km of a 2.7 m diameter prestressed concrete pipe which splits to form two 60 km lines, the Western Yarqon Line (1.8 m) and the Eastern Yarqon Line (1.7 m). From the Zohar Reservoir, a 1.7 m line carries water further south to the Negev.

As an adjunct to the Carrier, work has been undertaken to reduce the saline inputs to Lake Tiberias in an effort to reduce the salinity in that lake which serves as a reservoir for the National Water Carrier [43]. Projections are that the salinity of Lake Tiberias will eventually be reduced to about 130 ppm.

Other Israeli development has included drainage and canalization work in the Huleh Valley to control runoff and flooding in the area. A program of irrigation has been undertaken in the Golan Heights, which by 1980 involved the use of 22 Mcm per year for the irrigation of 6500 ha. This water came from developing local resources and by drawing water from Lake Tiberias.

4 Key Technologies

In much of the Middle East, the available supplies of high quality fresh water are almost completely utilized. The pressures of expanding water demand are inevitably leading managers to consider using water of progressively poorer quality. Assuming for the moment that this water is to substitute for cleaner (sweeter or less polluted) water, then it is apparent that its quality must be improved to the level of those standards appropriate for a particular use. In the Middle East, the most readily available alternatives are saline and brackish waters as well as various waste waters. In the paragraphs below, technologies for desalination and waste water renovation are reviewed.

4.1 Regional Constraints on Technological Options

The design and operation of water resources systems in the Middle East is certainly not an easy task. As noted above, the quantity of available water is limited by the semi-arid to hyperarid climate of the region. The combined effects of evaporation, soil chemistry, and nonconsumptive use of water contribute to degraded water quality throughout most of the downstream reaches of the rivers under study.

Problems of water use in the Middle East are aggravated by the tradition of agriculture in conditions under which modern agriculture may be pursued only through application of massive energy and water subsidies. This is not unique to the Middle East; but in this region, and particularly in Israel, the energy subsidy to the agricultural sector is excessively high, in large part because of the great expense of bringing sufficient irrigation water to the most productive soils. Fully one-fifth of the energy resources currently consumed in Israel is used for pumping water, and 80 percent of the water is used for agriculture. The historical and ideological commitment to agricultural self-sufficiency is a major determinant of the pattern of water utilization in the Middle East. In economic terms, considerations of security, ideology, and politics are used to rationalize the provision of water at costs that exceed its marginal value [38].

5 Desalination Techniques

Desalination is one possible solution for some of the water needs of the Middle East, since most countries of this region have coastal or other saline water supplies available. As an example, Israeli water planners have forecasted an increase in water demand of at least 700 Mcm/yr by the end of the century [22]. This additional demand will have to come from alternative supplies since virtually all fresh water is currently used. Reductions in the cost of desalination make it less forbidding than it once was. Other countries face a similar situation. Approximately two-thirds of the global installed desalination capacity is found in the Middle East, much of it in the Arabian peninsula, and the total installed desalination capacity in the study area is at least 50 Mcm/yr.

The desalination technologies are used to reduce the concentration of total dissolved solids (TDS). Fresh water typically possesses less than approximately 1000 mg TDS/L. Most published drinking water standards include a prescribed maximum of 500 mg TDS/L, and certain industrial applications, most notably boiler feed water, require no more than about 5 mg TDS/L. Seawater is typically on the order of 33,000 mg/L, with deviations depending on local rates of dilution and evaporation. Brackish water is usually defined in an intermediate position, at approximately 1000 to 3000 mg TDS/L; brine refers to waters which are more saline than seawater.

In the following discussion, the various desalination methods have been organized on the basis of their principal mode of operation. These include technologies based on distillation, membranes, and ion exchange. In theory, methods based on freezing are applicable to the desalination of water; however, there have been no commercial operations based, and, as a result, freezing is not included in the following discussion [4,26].

5.1 Distillation Methods

Distillation plants all operate on the principle that vapors boiled off or evaporated from saline water are salt free and that purified water can be produced by condensing these vapors. The distillation technologies are energy intensive because of the need to drive the change of state.

5.1.1 Multi-stage flash distillation

Since its first commercial application in 1960, multi-stage flash distillation (MSF) has grown in use until today it is both the most common evaporative process and the one with the greatest total worldwide operating capacity (6.76 Mcm/day [63]). MSF is applicable to even the saltiest seawater, and can yield a final product with as low as 25–50 ppm TDS. In general, MSF achieves cost effectiveness only when used to process more than approximately 1000 cu m per day [23].

5.1.2 Multi-effect distillation

Multi-effect distillation (MED) is an evaporative process which was exploited commercially very early [23,39,82]. It then became less popular, but, in recent years, has been developed into a highly efficient technology with further potential. The MED process is usually used for seawater and yields a high purity product of about 20 ppm TDS. In MED, evaporation occurs on a heat exchange surface made either of horizontal or vertical tubes. Hence, the two process variants are termed horizontal tube evaporation (HTE) and vertical tube evaporation (VTE), respectively.

5.1.3 Vapor compression

Vapor compression (VC) is a third evaporation process. It is very different from the two processes discussed above, because it is a single stage compact system [27,32,52]. This is a relatively new technology still undergoing development. VC is a highly efficient process, most likely the least energy consumptive of all the evaporative processes. It is used only in smaller operations, as it is economically favored at nominal capacities of less than 3800 cu m per day. The operating temperatures of this process are quite low, 55 to 70° C, with higher efficiencies obtained at the higher temperatures. Thus, the primary energy is not heat, but the electrical energy to operate the compressor. The low operating temperature also minimizes scaling and corrosion. Pretreatment for scale prevention usually consists solely of polyphosphate addition.

5.2 Membrane Processes

The distinguishing feature of the membrane processes is that saline water at ambient temperatures is forced through a barrier which allows the passage of water molecules, but prevents the passage of dissolved materials. Thus, two fractions accumulate, one lower (the product water) and the other higher (the reject brine) in TDS than the feed water.

It is often convenient to categorize the membrane processes in terms of the potential gradient which provides the driving force through the membrane. This may be pressure as in reverse osmosis (RO), or ultrafiltration (UF). (UF does not separate low molecular weight organics or salt from water. Hence, the UF process is of limited value in the solution of the pressing water problems of the study area and will not be considered further in this paper.) On the other hand, the process may be non-pressure driven as in electrodialysis (ED) or transport-depletion (to date, only used at the laboratory scale). The reader is referred to the works of Applegate [12] and Belfort [21] for relatively recent reviews of membrane technology.

5.2.1 Reverse osmosis

The first commercial application of RO was in the late 1960s, when it was used to desalt brackish water. The initial testing and development for seawater desalination began in the mid-1970s. Today, it is the second most widely used desalination process, behind only MSF in global installed capacity. An excellent monograph on the theory and practice of reverse osmosis has been edited by Bakish [17].

The scale of installed RO systems has steadily increased over the years. The early conventional wisdom that RO was suited only for small plants has been replaced by the understanding that the process is competitive in large scale operations as well. An example is the Malta seawater RO facility at Ghar Lapsi which, at an installed capacity of 20,000 cu m/day, is the world's largest RO facility [8].

5.2.2 Electrodialysis

Electrodialysis (ED) was developed in the early 1950s, and has been applied primarily to brackish waters [54,55]. The ED process consists of alternating anion and cation exchange membranes with the feed water flowing between them. Direct current voltage is applied so that the anions and cations pass through the anion and cation exchange membranes, respectively. This demineralizes one stream and concentrates another. Membrane fouling is a recurrent problem which can only be solved by stopping the process and flushing the membranes with cleaning chemicals.

5.2.3 Electrodialysis reversal

Electrodialysis reversal (EDR) works on the same principles as ED except that the direction of the DC field is periodically reversed [53,54,55]. When the reversal occurs, automatic valves interchange the concentrated and dilute streams. The process is thus self-cleaning because the films and scale are carried away with the waste when the flow is reversed. Virtually all electrodialysis equipment installed since the mid-1970s has used polarity reversal. The process has been used successfully to desalt brackish water up to 4000 mg TDS/L with water recovery up to 93 percent. The energy consumption is quite low, typically 3 to 5 kWh/gal brackish water (2850 to 4750 kJ/L), including pumping. Electrodialysis processes have also entered the market for seawater desalination. The world-wide installed capacity of EDR technology has reached approximately 330,000 cu m/day [81]. Many of these installations are relatively small and most are institutional or industrial.

5.3 Ion exchange

Ion exchange occurs when ions in solution are exchanged for other ions on a solid surface [19]. Water to be desalinated is passed through a bed of ion exchange material (almost always synthetic organic resins). In desalination applications, both an anionic and a cationic resin would generally be used. Once the exchangeable ions on the resin have been exchanged, the resin must be regenerated. The reactions used in ion exchange are reversible, and, therefore, contacting the spent resin with a high concentration of the ion originally on it can shift the equilibrium point and regenerate the ion exchange resin.

5.4 Hybrid Systems

A variety of combinations of processes are possible to meet the particular constraints of an individual situation. Increasing attention is being paid to hybrids of RO and distillation. The various advantages of RO/MSF have been discussed by Awerbuch [15]. Very high recoveries have been shown to be possible using a hybrid system incorporating reverse osmosis and vapor compression distillation [34]. The actual process train included pellet softening for the removal of calcium, reverse osmosis operating at 90 percent recovery, followed by distillation of the RO brine using vapor compression. The RO/VC combination is believed to be a promising one for remote areas or for small communities [7]. Kamal *et al.* [52] concluded that this process may be the way for distillation to compete with membrane processes in single purpose (*i. e.*, water only) seawater desalination.

Systems have been developed which combine reverse osmosis and ion exchange for a more efficient desalination process. One example is to first treat seawater by RO producing a brackish permeate of 1600 ppm. The water then passes through a thermally regenerated exchange system. The resin is regenerated with the heat of the seawater upstream of the RO unit [19]. The product is pH adjusted and combined with brackish permeate to yield a final product of 500 mg salinity/L. A similar system was used for treating ground water that had high concentrations of silica, sulfate, alkalinity, and hardness. The ground water was processed by ion exchange followed by reverse osmosis. After pH adjustment and appropriate blending, the product contained 400 to 500 mg TDS/L. Process efficiency was such that 91 percent recovery of groundwater was possible [29].

5.5 Comparison of Desalination Technologies

The type of desalination technique appropriate for a given situation depends in large part on the raw water TDS and the desired product TDS. As a general rule, the distillation based processes can be used to achieve very high purity water (less than 50 or so mg TDS/L), whereas the membrane based processes can achieve TDS levels in the range of several hundred mg/L. Other factors of comparison include environmental impacts, energy requirements, and costs which are discussed next.

5.5.1 Environmental Effects of Desalination

The major impacts of desalination are related to the water intake and discharge. These must both be carefully managed in order to minimize or eliminate harmful environmental effects [25,28,85].

Discharge involves both physical and chemical effects. Physical effects include temperature and flow changes from the discharge. The temperature may rise appreciably downstream from thermal process plants. It is well known that a change in the temperature may produce a wide range of biological, chemical, and physical changes.

The chemical effects include increased concentrations of brine, chlorine or other biocide residuals, and various descaling chemicals [85]. The total dissolved solids can also increase to 1.3 to 2.0 times the original level. Heavy metals, especially copper which is well known for its toxicity, are also potential hazards. The quantities of heavy metals actually discharged vary as a function of corrosion and the materials of construction. Heavy metals and other toxicants may accumulate by transfer through the food web.

Sludge disposal is also a possible problem with large scale desalination plants. Slurries containing the lime used for pretreatment and other chemicals are frequently transported to evaporation ponds. These ponds must be lined with an impervious material to prevent percolation into the groundwater. Once the sludge is dried it should be covered to prevent air dispersal.

5.5.2 Energy Considerations

Energy requirements for distillation processes are substantial due to the change of state of the water. The energy may be supplied by the combustion of fossil fuels. This is especially attractive in areas where the cost of such fuels is relatively low as it is in much of the Middle East. Alternatively, desalination may be combined with the generation of electricity in such a way that lower temperature, *i. e.*, partly expanded, steam is used to drive the distillation process. Other possibilities include nuclear, solar and geothermal sources.

Dual purpose facilities. Dual purpose plants are those installations which combine power generation and water desalination [14,79]. Most distillation type facilities are operated this way because the evaporative processes require low pressure steam. Some low pressure steam is thus diverted from the production of electricity to the production of water. The incremental cost to produce the high pressure steam needed to generate electricity is more than offset by the value of the electricity.

Dual purpose plants can also utilize membrane desalination. It has recently been suggested that RO can function in a dual purpose electricity/water production facility [24]. In such an application, the full potential of the steam would be directed to the generation of electricity a fraction of which would then be diverted to run the RO plant.

Solar Energy. Solar energy sounds like it ought to go very well with desalination since there is an abundance of it in the arid areas which could use desalination. However, it is rarely cheaper to use "free" solar energy than to use fossil fuel [26,67,78]. The principal problem in any system designed to use solar energy is collecting it because of its diffuse nature. Solar powered desalination may be the most economic method of providing desalted water to remote arid regions [3]. Solar powered RO is another promising possibility for small scale and remote locations [2].

Collectors are the most costly part of solar desalination. In commercial desalination plants, either flat or concentrating collectors may be used. The flat collectors have an efficiency of 28 to 48 percent. Concentrating collectors use mirrors or lenses to reflect or transfer the solar energy to a heat absorber. Some of these collectors track the sun during the day, giving them efficiencies of up to 70 percent. The types of desalination plants used with such collectors are MED (both HTE and VTE) and MSF, although some work has been done with solar driven reverse osmosis.

Solar ponds provide another method for collecting solar energy [77,78]. Solar ponds are shallow artificial black-bottomed ponds or lakes. The heat is kept at the bottom by a density gradient and temperatures over 90° C can be obtained. Energy from solar ponds can be used directly or combined with fossil fuel to operate low temperature MED plants. Under the conditions prevalent in Israel, between 20 and 25 percent of the incoming solar radiation can be collected from the bottom of a solar pond. This amounts to 400 to 500 million kWh (thermal) per yr-sq km, and is approximately equivalent to 50,000 tons of fossil fuel [77], depending on the energy conversion efficiency.

Geothermal. Geothermal energy represents an energy source which could be used to drive distillation processes. Certain geological formations have been found in Israel which contain water saturated with salt at temperatures of at least 100° C [59]. These formations were uncovered using exploratory wells drilled at Ashdod. The specific formations were the limestones and dolomites of the Zohar and Shderot formations of the Upper Jurassic. The Zarqa Main hot springs on the east side of the Dead Sea in Jordan may constitute a geothermal energy source worth further study.

5.5.3 Comparative energy requirements

Regardless of the particular desalination process selected, there are a number of crucial operating cost factors, including the energy required, either for the change of state of water or for overcoming the osmotic pressure gradient. The energy requirements reported by a variety of authors have been summarized recently by Keenan [56], see Table 1. In summary, the

Table 1: Energy Requirements for Various Desalination Methods. The energy units are MJ/cu m of product.

Process	Energy	Reference
Seawater RO	21-36	[5,24,48,84,31]
Brackish RO	4-8	[3,46]
Seawater EDR	32-48	[10]
Brackish EDR	3-14	[10,70]
Seawater MSF	46-60	[5,31,24]
Seawater VC	45-68	[33]
Seawater MED	33-37	[6]

available data support the contention that one of the principal advantages of RO relative to the distillation processes, especially MSF, is the reduced energy requirement.

5.5.4 Post-treatment Requirements

Desalted water, whether derived from membrane or from distillation technologies tends to be aggressive, *i. e.*, corrosive in nature. Consequently, both distillates and permeates require a certain amount of post-treatment, especially for corrosion control and to improve the potability of the product water. A variety of different treatment methods are available [64], but most typically, small amounts of alkali, such as lime, are added to the product to stabilize it, *i. e.*, to render the product less corrosive.

5.5.5 Comparative Costs

The decade of the 1980's has seen a shift in the prevailing wisdom regarding the economics of desalination. In the early 1980's, the economic situation was such that membrane processes were favored over distillation for the treatment of brackish waters, and for seawater desalination for small scale operations and at sites where energy costs were high. The data which have become available since that time indicate that today, even for large scale seawater applications, the membrane based technologies have become competitive. The major reason is a reduction in the costs associated with RO due to operation at higher pressures, increased energy recovery, and decreased chemical and membrane replacement costs. The relative price of energy remains a critical criterion for the difference between the two competing processes. A summary of recent cost data is presented in Table 2 [56].

Table 2: Cost comparison of distillation with RO desalination. The costs are in units of 1st Quarter 1991 U. S. dollars per cu m of product.

RO Cost	Distillation Cost	Reference
1.50-2.82	1.90-4.15	[35]
1.21-1.54	1.25-1.80	[61]
1.34-1.96	1.40-2.13	[16]
1.24-1.87	1.85-3.07	[5]
1.44	2.55	[31]
1.31-1.36	1.36-1.82	[62]

An example is the Malta seawater RO facility at Ghar Lapsi which, at an installed capacity of 20,000 cu m/day, is the world's largest RO facility [8]. The cost of water from this facility is $1.08 per cu m produced [9].

In almost every case, desalinated water costs less when produced in a dual purpose plant as opposed to single purpose plant. Economically, the decision of a single vs. dual purpose plant depends on the difference in investment for the high pressure steam generator used in a dual purpose plant versus that for the low pressure steam generator in the single purpose plant. The economics also depend on the investment required for the back pressure turbogenerator for the dual purpose installation and on the income from electricity sales. The distillation plant does not respond very quickly to changes in the load so it is best to operate the system at full capacity, sending both the water and the electricity to a large-scale distribution network.Thus, it is most economical to have steady year-round water and power demands; otherwise, pumping and storage of the desalted water is necessary. In the Middle East, the electric power station in the large dual purpose plants is almost always fossil fuel-fired.

The cost data suggest that RO is generally the most cost-effective process for the desalination of brackish waters. EDR also tends to be most economical in situations where the feed water is relatively low in dissolved salts since the energy requirements are roughly proportional to the TDS concentration. For the other processes, energy, and, therefore, total operating costs, are much more independent of the salt concentration. Fraivillig [41] prepared a detailed comparison of RO versus EDR for 1 MGD (3785 cu m/d) plants producing a 500 mg TDS/L product. Feed water concentrations varied over the range of 1000 to 5000 mg TDS/L. The results are presented in Table 3.

Table 3: Cost comparison of EDR with RO desalination. The costs are in units of 1st Quarter 1991 U. S. dollars per cu m of product.

TDS mg/L	RO Cost	EDR Cost	Reference
1000	1.25	1.56	[41]
5000	2.25	4.88	[41]

Among the distillation processes, there is increasing support for the contention that MSF is not the least expensive. Greig and Wearmouth [47] concluded that mechanical vapor compression is the cheapest, followed by thermal vapor compression. Leitner [61] states that MED, either in the vertical or horizontal configuration, produces the lowest cost water among the distillation technologies.

In summary, the technological state-of-the-art and the current economic situation clearly favor the use of reverse osmosis for most situations in which the desalination of either seawater or brackish water is needed. Furthermore, RO is competitive in all situations including large-scale and dual purpose facilities. The principal reason for this has been a significant reduction in the operating costs of RO installations, most notably energy, membrane replacement, and chemicals.

5.6 Regional Desalination Use

Countries in the Middle East are heavily involved in desalination research and development. A low temperature vapor compression process was developed by Israel Desalination Engineering, as was the horizontal aluminum tube multi-effect process. In addition, the Joint U. S.-Israel Desalination Project Authority, Ltd., has built low temperature multi-effect plants in the U. S. Virgin Islands and Ashdod, Israel. The world's largest MED was started up in March 1983, at Ashdod, Israel [71], and the results of the first year's operating experience have been summarized by Fisher *et al.* [40]. In their analysis of the MED plant at Ashdod, Fisher *et al.* [40] showed that the total specific energy consumption for the first year of operation was 8.2–9.4 kWh/ton (32.5–37.3 MJ/cu m). They estimated that in an optimally designed dual purpose plant (combined with a 550 MW turbine), the energy requirement could be lowered to 5.7 kWh/cu m (20.5 MJ/cu m).

In the case of a plant in the town of Eilat, on the Red Sea, experience has been gained with a hybrid process combining ion exchange and reverse osmosis [83]. A pre-existing RO plant was used to desalt brackish water containing 6000 ppm TDS at 50 percent recovery, leaving a 12,000 ppm TDS reject brine. It was found that process efficiency could be improved by pretreating the reject brine with ion exchange and recycling it through the RO plant. The ion exchange resin is regenerated using seawater. Reuse of the reject lowered the cost by \$0.17 to \$0.30 per cubic meter compared to the cost to desalt new seawater with reverse osmosis.

Recent large scale work, also at Eilat, with low pressure desalting of brackish water has been reported by Glueckstern *et al.* [46]. This plant produces over 3000 cu m/d from brackish water at 6000–6500 mg TDS/L. The plant achieves 65 percent recovery and operates at 195 psi (1344 kPa). During a full year of operation, permeate TDS was always less than 300 mg/L, and the power consumption was approximately 1 kWh/cu m of product (3.6 MJ/cu m).

The increasing role of reverse osmosis in the study area is perhaps best viewed from the perspective of the Mekerot Water Company [45]. The plan for Israel is to increase the 1984 desalting capacity of 3 or 4 Mcm/yr to as much as 100 Mcm/yr by the year 2000 [22]. This increase is to be achieved through the installation of reverse osmosis plants at Eilat, Ein Boqeq, Nitzana, Mashabei Sade, and Nahal Taninum. The feed water will largely (93 percent) be brackish water in the TDS range of 2400–6000 mg/L, with the balance coming from seawater. It is also stated by Glueckstern [45] that the longer term technological water fix for Israel will be predominately RO.

6 Reclamation and Conservation Technologies

In this final section, the potential for increasing water availability via the reclamation of stormwater and wastewater is explored. The terms reclamation and renovation here refer to those technologies used to render spent waters fit for some other purpose.

6.1 Stormwater Renovation

The use of stormwater for a variety of purposes has had a long and obvious history ranging from rain barrels through runoff agriculture. An unfortunate artifact of modern life is that the quality of rainfall is rapidly degraded during runoff processes. The most important mechanism by which stormwater becomes contaminated is entrainment of suspended particles. (In urban areas, stormwater may become mixed with domestic wastewater. The mixture is termed combined sewage.) Typical contaminants are suspended solids and associated absorbed materials including metals, pesticides, fertilizers, pathogens, etc. Thus, depending upon its history, stormwater may have a quality level almost as degraded as wastewater.

Stormwater treatment technologies are almost always directed to the removal of suspended solids. Thus, sedimentation and (to a lesser extent) filtration processes are most commonly encountered. Holding basins are widely used in stormwater treatment systems. These may be designed in either of two ways. First, with a lining to prevent percolation, holding basins may be used solely for solids separation with the clarified water overflowing the basin. An alternative design is used to promote groundwater recharge in which case the basin is not lined and the water is allowed to infiltrate into the ground. Solids removal occurs by filtration of the water through the soil medium. In either case, the intercepted stormwater may be readily used for agricultural purposes, either directly or indirectly.

6.2 Wastewater Reclamation

Wastewater reclamation can be an important method of supplementing available water supplies. The potential role increases dramatically in a water-scarce region such as the study area. The two principal purposes served by wastewater reclamation are water supply augmentation and water pollution control. If the wastewater is applied to the land, then the application of nutrients and groundwater recharge are additional purposes. Historically, the most important and earliest method of wastewater reclamation has been land treatment and disposal directly to agricultural land.

In general, the wastewater constituents of concern in reuse applications are suspended solids, organic matter (*i. e.*, BOD), and pathogenic microorganisms. In particular situations, especially where industrial wastewaters are involved, the presence of toxic organics, heavy metals, etc., may be issues. Suspended solids removal is typically achieved in sedimentation processes, although filtration may be cost-effective in certain situations. Organics removal may be accomplished by biological treatment, and occasionally by chemical coagulation. In Middle East applications, stabilization ponds are the most frequently encountered biological treatment units. Disinfection involves suspended solids removal and chlorination (or ozonation).

There are a number of filtration procedures by which particulate materials may be removed from water and wastewater. Filtration through a bed of sand is probably the earliest, and still the most popular, method of water filtration. For water and wastewater treatment purposes, slow and rapid sand filters are available. Dual and multiple media filters have some applicability in wastewater treatment. Ultrafiltration is a relatively new technology for filtering water and wastewater. The major applications have been in the industrial sector where there is an economic incentive to recover valuable materials and recycle the water. The experience with ultrafiltration is largely confined to the United States, Europe, and Japan.

6.3 Use of reclaimed wastewater

The reuse of wastewater effluent is a notion which is not readily accepted by all peoples. For a variety of reasons, some people may reject the use of effluent for different purposes. In the Muslim countries, the use of effluent is still limited. On the other hand, in Israel, the reuse of wastewater is a part of the national water policy [76].

Reclaimed wastewater can theoretically be used for any purpose to which water can be applied. The major constraint is that the water must be treated to the degree which is appropriate for that use. In some cases, economics will prevent the use of reclaimed water for certain purposes. However, for other purposes, notably irrigation and some industrial applications, wastewater effluent is a technically acceptable alternative.

The principal use of reclaimed wastewater in the study area is associated with Israeli efforts. In this case, the major uses are in the agricultural and industrial sectors. In fact, industrial reuse of water is legally enforced in Israel. Other options for reuse include aquaculture, recreational impoundments, some restricted municipal use, and groundwater recharge [75]. Restricted municipal use refers to street cleaning, watering golf courses, and other non-contact purposes. There are too many lingering public health questions regarding the survivability of viruses and the presence of trace contaminants to recommend the use of reclaimed wastewater for unrestricted municipal uses.

6.3.1 Health effects.

There are many potential problems that need to be confronted in order to reuse wastewater safely. Problems may arise from food crop contamination, ground or surface water pollution, or from pathogen-laden aerosols. Pathogens of concern include various bacteria (bacterial dysentery, cholera, and the typhoid fever), viruses, protozoa, and helminth worms. It is essential that the technology used for wastewater reclamation be appropriate for the purpose to which the water will be put, and, in general, this should include the capabilities to remove and/or destroy pathogenic organisms. In the study area, the principal use of reclaimed wastewater is for irrigation.

Following their exhaustive review of the literature, Kowal *et al.* [60] make the following recommendations regarding the use of wastewater effluent in irrigation applications. First, raw domestic wastewater should never be used for irrigation. Second, the appropriate level of pretreatment is much less than the secondary treatment ordinarily required by U. S. regulatory groups. Their recommendations assume properly-designed sedimentation as the appropriate level of pretreatment; however, installations with greater public access or with shorter rest periods, would require greater degrees of pretreatment. The risk of aerosols indicates that public access should be prevented within 100 to 200 m of a spray source. For human food, they recommend a one month rest period for aerial crops; subsurface and low-growing crops should not be grown for six months following the last wastewater application. These waiting periods do not apply for the production of animal feed crops.

The Israelis have also developed guidelines for wastewater reuse in agricultural applications. These regulations establish buffer zones of 300 m between spray irrigated fields and residential areas when low quality effluent is used [76]. Under current regulations, effluent may be used for unrestricted irrigation of all edible crops if the effluent has been well-treated with coliform levels approaching those of drinking water. Oxidation pond treatment is required for all cases of wastewater irrigation. The minimum adequate treatment is considered to be one to two days detention in an anaerobic pond followed by three to seven days detention in aerobic-facultative ponds.

6.3.2 Salinity Issues

Salinity is a major concern in all arid and semi-arid regions. The study area is no exception. It has been estimated that 20 to 30 percent of all the land in Iraq's traditionally irrigated area in the Fertile Crescent between the Tigris and Euphrates Rivers has been abandoned due to salinity. The pattern is one of over watering in conjunction with inadequate drainage leading to waterlogging and secondary salinization.

The omnipresence of the salinity threat in the study area requires that any irrigation system must supply proper drainage and adequate amounts of leaching water to be viable. The application of such techniques can be used to reclaim land that has been salinized either through waterlogging or through inadequate leaching.

Irrigation can also lead to increasing salinity in surface waters. It has been estimated that one-third of the salt load of the Colorado River is due to irrigation [73]. Irrigation leads to increased salinity because of the relatively higher TDS content of the irrigation return water which is due to evaporation, dissolution of salts in the soil, and occasionally displacement of highly saline groundwater.

The relative abundance of saline or brackish water in the study area has led to consideration of ways to use water that is generally too saline for agriculture. Irrigation with brackish waters should prompt special concern for leaching requirements [73]. It is reported that the Saudi Arabians commonly use brackish water with over 2000 ppm TDS to irrigate sugar beets, cotton, spinach, and date palms [69].

Drip irrigation is extremely useful in efforts to irrigate with salty water. Because the drip system applies water slowly, but consistently, the soil salinity does not vary as much as it does with more cyclical irrigation techniques. This permits the plants to adapt to the soil conditions and also reduces the maximum stress to which they are exposed. Forest plantations have been grown in Ethiopia using irrigation water of salinity 10 ppt by combining drip techniques with deep sandy soils [13].

6.3.3 Wastewater Irrigation

The reuse of wastewater effluents as irrigation water offers a means of augmenting the water supply of an area. As noted elsewhere, there are often a variety of reasons why a given people will not reuse wastewater effluents. One the other hand, this approach allows water planners to align water use with water quality constraints. That is, high quality water is saved for high quality uses, and progressively lower quality uses receive lower quality water.

There are a number of disadvantages associated with the use of reclaimed wastewater for irrigation purposes [65]. The production of wastewater is more or less constant over the course of a year, but the demand for irrigation water is seasonal. This necessitates the use of storage mechanisms or the disposal of effluent during the non-growing season. Treated effluent may contain sufficient small particles to plug spray nozzles and clog the pores of soil. Certain effluents may contain substances harmful to the crops (chloride, sodium, boron, organic acids, phenols) or to the animals and people consuming the crops (heavy metals, pathogens). Under some conditions, the use of wastewater may produce nuisance conditions (odors, insects).

6.4 Regional Reclamation Examples

The Dan Region Project is the largest, most advanced, and most controversial wastewater reuse scheme in Israel. In fact, this effort is the second largest wastewater reuse system in the world. It serves the Tel Aviv metropolitan area, the largest in Israel, including Tel Aviv-Yafo, Ramat Gan, Bnei Beraq, Givatayim, Petah Tiqwa, Rishon-Le-Zion, Holon, and Bat Yam. The purposes of the project are to stop pollution of the Tel Aviv shore line due to wastewater discharge into the Mediterranean Sea, and to recycle water to supplement Israel's limited natural water resources, primarily for agricultural and industrial uses [37,49].

Stage I of the Dan Region Project went into complete operation in January, 1977. In Stage I, 25-30 Mcm/yr of wastewater from the southern communities of the region undergo treatment consisting of recirculated oxidation ponds, lime precipitation, and polishing ponds [36]. The effluent is recharged to the groundwater by intermittent application over fine dune sand recharge basins. The water is reclaimed with recovery wells, chlorinated, and distributed in the national distribution network.

Stage II of the Dan Region Project is scheduled for completion in the late 1980s. This facility will have an average treatment capacity of 50 Mcm/yr with provisions for expansion to 160 Mcm/yr after the year 2000. Raw wastewater from an anticipated population of 1.3 million will be collected and treated using a modified, low-rate activated sludge process, without primary clarification. The process will be operated as a single sludge system achieving nitrification, denitrification, and high removals of carbonaceous BOD and phosphorus [37]. This second stage will connect with a dual supply system operating in the south of the country. High quality reclaimed wastewater for non-potable uses, mainly irrigation, will come from one system. The other will provide municipal drinking water from groundwater wells and a different distribution main [49,76].

A key element of the wastewater reclamation and reuse program in the Dan Region is the discharge of the treatment effluent to basins from which it recharges the local groundwater. The treated effluent is spread over leveled sand dunes about 4 km east of the Mediterranean. The recharge site lies above the central part of the coastal aquifer (Pleistocene) near Rishon-Le-Zion. The aquifer is comprised largely of calcareous sandstone, and is divided into subaquifers by silt and clay layers [50]. The recharge facilities consist of four basins with a total area of 29 ha.

In the early years of the project, the treated effluent was diluted in the high quality groundwater already present in the aquifer, and the pumping operation withdrew primarily the pre-existing groundwater. As one would expect, that groundwater is being gradually replaced by the reclaimed wastewater. By mid-1979, the plume of recharged effluent had migrated 600 m from the recharge site, but was still approximately 150 m from the nearest recovery well. This was two years after start-up. The significance is that long-term plans for utilizing the recharged water must account for the time when the recovery wells are primarily pumping the reclaimed wastewater.

7 Summary

The design and operation of water resources systems in the Middle East is certainly not an easy task. As noted above, the quantity of available water is limited by the semi-arid to hyperarid climate of the region. The combined effects of evaporation, soil chemistry, and nonconsumptive use of water contribute to degraded water quality throughout most of the downstream reaches of the rivers under study. Problems of water use in the Middle East are aggravated by the tradition of agriculture in conditions under which modern agriculture may be pursued only through application of massive energy and water subsidies.

On the technology side, two alternatives of major importance are the desalination of saline waters and the reclamation of stormwater and wastewater. With respect to desalination, it is recognized that the economic situation has changed over the last decade such that the membrane processes are now sufficiently competitive that they should be considered as alternatives in all projects. Examples of desalination and reclamation applications are presented in the text.

References

[1] R. Van Aart. Drainage and land reclamation in the Lower Mesopotamian Plain. *Nature and Resources*, 10(2):11–17, 1974.

[2] A. F. Abdul-Fattah. Selection of solar desalination system for supply of water in remote arid zones. *Desalination*, 60:165–190, 1986.

[3] A. F. Abdul-Fattah. Supply of desalted water to remote arid zones. *Desalination*, 60:151–164, 1986.

[4] D. Achboren and M. Waldman. Water for life: Israel's R & D for water renovation and sweet water production. *Desalination*, 30:213–21, 1979.

[5] A. M. R. Al-Marafie and M. A. Darwish. Water production in Kuwait—its management and economics. *Desalination*, 71:45–55, 1989.

[6] K. al Saddiq. The al-Rahad project sets new production records. *Al-Ayyam*, page 5, 1983. [JPRS 83536 NE/SA 2758 5/24/83, Khartoum, 02/21/83].

[7] S. E. Aly. Combined RO/VC desalination system. *Desalination*, 58:85–97, 1986.

[8] W. T. Andrews. The Malta seawater RO facility—update on the first two years operation. *Desalination*, 60:145–150, 1986.

[9] W. T. Andrews and R. A. Bergman. The Malta seawater RO facility. *Desalination*, 60:135–144, 1986.

[10] Anon. Government's ambitious agricultural plans detailed. *Arab World Weekly*, pages 3–6, 1979. [JPRS 74819 NE/NA 2061 12/26/79, Beirut, 11/17/79].

[11] Anon. Syria—attempting to tame the Euphrates. *MEED*, pages 55–56, 1984. [03/24/84].

[12] L. E. Applegate. Membrane separation processes. *Chemical Engineering*, pages 64–89, 1984. [June 11].

[13] A. Arar and D. L. Huss. Some interrelationships between water management, livestock, rangeland and crop production in the arid and semi-arid areas. In Margaret R. Biswas and Asit Biswas, editors, *Alternative Strategies for Desert Development and Management, Vol 2—Agriculture*, pages 287–310. Pergamon Press, Elmsford, NY, 1982.

[14] F. S. Aschner. *Dual Purpose Plants*, chapter 5, pages 1983–2056. Academic Press, New York, 1980.

[15] L. Awerbuch. Hybrid desalting systems—a new alternative. *Desalination*, 64:51–63, 1987.

[16] T. A. Babbagh and A. Al-Saqabi. The increasing demand for desalination. *Desalination*, 73:3–26, 1989.

[17] R. Bakish, editor. *Theory and Practice of Reverse Osmosis*. International Desalination Association, 1985. Monograph No. 1.

[18] Z. Bari. Syrian-Iraqi dispute over the Euphrates water. *International Studies*, 16(2):227–44, 1977. [New Delhi, Apr 77].

[19] D. Barnes and F. Wilson. Chemical removal—ion exchange. In *Chemistry and Unit Operations in Water Treatment*, pages 234–37, London, 1983. Applied Science Publishers.

[20] P. Beaumont. The Euphrates River—an international problem of water resources development. *Environment Conservation*, 5(1):35–43, 1978.

[21] G. Belfort, editor. *Synthetic Membrane Processes—Fundamentals and Water Applications*. Academic Press, Inc., Orlando, Florida, 1984.

[22] M. Ben Meir. Water resources of Israel and the need for desalination. *Desalination*, 40:15–18, 1982.

[23] J. D. Birkett. Worldwide outlook for the desalination industry through 1990. *Impact*, pages 1–15, 1983. [Arthur D. Little Decision Resources, Cambridge, MA, Apr 83].

[24] D. C. Brandt. Seawater reverse osmosis—an economic alternative to distillation. *Desalination*, 52:177–186, 1985.

[25] D. L. Brining, W. C. Lester, W. N. Jessee, and D. A. O'Leary. Development of environmental standards for combined desalination/power generating stations in the Arabian Gulf region. *Desalination*, 39:255–60, 1981.

[26] R. A. Brosh. Trends in the application of solar energy to water desalination. *Desalination*, 40:95–102, 1982.

[27] Dr. W. Bulang. Desalination by vapor compression. *Desalination*, 38:85–97, 1981.

[28] F. T. Carlson and E. G. Environmental impacts of desalination in the United States. In *International Congress on Desalination and Water Reuse*, pages 1–12, Washington, D. C., 1979. Office of Water Research and Tech, Dept. of Interior.

[29] Dudley W. Coillet and J. E. Cruver. Conjunctive use of reserve osmosis and thermally regenerated ion exchange. *Desalination*, 23:575–86, 1977.

[30] G. B. Cressey. Shatt al-Arab basin—geological review. *Middle East Journal*, 12:448–460, 1958.

[31] M. A. Darwish and M. Abdel-Jawal. Technical and economical comparison between large capacity multi stage flash and reverse osmosis desalting plants. *Desalination*, 72:367–379, 1989.

[32] M. A. Darwish, S. E. Aly, and K. A. Fathalak. Comparative study between conventional and vapor compression multi-effect desalination systems. *Desalination*, 49:153–67, 1984.

[33] M. A. Darwish, M. Abdel Jawal, and G. S. Aly. Comparison between small capacity mechanical vapor compression (MVC) and reverse osmosis (RO) desalting plants. *Desalination*, 78:313–326, 1990.

[34] P. J. de Moel, R. F. M. de Gier, and G. Onderdelinden. Design of the $50,000\,\mathrm{m}^3/\mathrm{d}$ treatment plants for Qasim S. A. desalination of brackish water at 99% recovery. *Desalination*, 55:343–356, 1985.

[35] B. Ericsson and B. Hallmans. A comparative study of the economics of RO and MSF in the Middle East. *Desalination*, 55:441–459, 1985.

[36] E. Idelovitch *et al.* Dan region project in Israel—from laboratory experiments to full-scale wastewater reuse. *Proceedings from Water Reuse Symposium*, 2:808–29, 1979.

[37] D. J. Farchill. The Dan region wastewater project—stage II—an advanced single stage biological wastewater treatment and renovation system. 1979. [Washington, D. C.].

[38] S. Feldman. Chapter 6—Water reclamation and the water economy in Israel—a case study. In Roger E. and Jeanne X. Kasperson, editors, *Water Re-use and the Cities*, pages 101–19, Hanover, NH, 1977. Clark University Press.

[39] U. Fisher. One year of operation of Israel desalination engineering's multi-effect distillation U. S. Virgin Islands. *Desalination*, 44:73–84, 1983.

[40] U. Fisher, A. Aviram, and A. Gendel. Ashdod multi-effect low temperature desalination plant—report on year of operation. *Desalination*, 55:13–32, 1985.

[41] J. B. Fraivillig. *Reverse Osmosis/Electrodialysis Reversal Comparison.* Permasep Products, The DuPont Company. E-56161. Undated.

[42] I. Galnoor. Water policymaking in israel. *Policy Analysis*, pages 339–365, 1978.

[43] M. A. Garbell. The Jordan Valley Plan. *Scientific American*, 212:3, 1985.

[44] C. Gischler. Surface water. In *Water Resources in the Arab Middle East and North Africa*, pages 2–35, England, 1979. Menas Press Ltd.

[45] P. Glueckstern. Current and long term considerations for the application of reverse osmosis technology in Israel. *Desalination*, 58:69–75, 1986.

[46] P. Glueckstern, Y. Kantor, S. Kremen, and M. Wilf. Desalination of high salinity brackish water by low pressure reverse osmosis. *Desalination*, 58:55–67, 1986.

[47] H. W. Grieg and J. W. Wearmouth. An economic comparison of 2x1000 cu m/day desalination plants. *Desalination*, 64:17–50, 1987.

[48] W. Heyden. Seawater desalination by reverse osmosis. *Desalination*, 52:187–99, 1985.

[49] E. Idelovitch. Wastewater reuse by biological chemical treatment and groundwater recharge. *Water Pollution Control Federation Journal*, pages 2723–40, 1978.

[50] E. Idelovitch, R. Terkeltoub, and M. Michail. The role of groundwater recharge in wastewater reuse—Israel's Dan region project. *American Water Works Association Project*, pages 391–404, 1980.

[51] E. Kally. Extension of Israel's national water systems as a function of artificial rainfall prospects. *Water Resources Research*, 10(5):917–20, 1974.

[52] I. Kamal, D. K. Emmermann, and G. F. Tusel. RO, MSF and VTE/VC desalination: A comparative evaluation. *Desalination*, 33:229–239, 1980.

[53] W. E. Katz. The electrodialysis reversal (EDR) process. *Desalination*, 28:31–40, 1979.

[54] W. E. Katz. Desalination by ED and EDR state-of-the-art in 1981. *Desalination*, 42:129–39, 1982.

[55] W. E. Katz and R. Eliassen. Saline water conversion. In *Water Quality and Treatment—A Handbook of Public Water Supplies*, pages 587–624, New York, NY, 1971. McGraw-Hill Book Company.

[56] John D. Keenan. Augmenting water supplies with desalination. The Chemical Marketing & Resources Association, 1991. Annual meeting, May 8, 1991. Philadelphia, Pennsylvania.

[57] M. Khadduri. Social and economic development—irrigation. In *Socialist Iraq—A Study in Iraqi Politics Since 1968*, pages 134–36, Washington, D. C., 1978. Middle East Institute.

[58] R. G. Khouri. *The Jordan Valley—Life and Society Below Sea Level.* Longman, London, 1981.

[59] L. Koifman. Geothermal resources in Israel. *Desalination*, 40:133–34, 1983.

[60] N. E. Kowal, H. R. Pahren, and E. W. Akin. Microbiological health effects associated with the use of municipal waste water for irrigation. In *Municipal Waste Water in Agriculture*, pages 271–342, New York, NY, 1981. Academic Press.

[61] G. F. Leitner. Economic feasibility of the reverse osmosis process for seawater desalination. *Desalination*, 63:135–142, 1987.

[62] G. F. Leitner. Costs of seawater desalination in real terms, 1979 through 1989, and projections for 1999. *Desalination*, 76:201–213, 1989.

[63] L. Liberti, R. Passino, M. Santori, and G. Boari. Technical and economic trends of sea water desalting in the '90s. *Desalination*, 55:503–514, 1985.

[64] H. Ludwig and M. Hetschel. Treatment of distillates and permeates from seawater desalination plants. *Desalination*, 58:135–154, 1986.

[65] J. Noy and A. Feinmesser. The use of wastewater for agricultural irrigation. In Hillel I. Shuval, editor, *Water Renovation and Reuse*, pages 73–91, New York, 1977. Academic Press.

[66] R. Nyrop, editor. *Jordan—A Country Study.* American University, Washington, D.C., 1980.

[67] A. Ophir and N. Nadav. Solar energy as a source for production of power and desalinated water. *Desalination*, 40:103–24, 1982.

[68] D. J. Percious. An apparent multidisciplinary methodology for water resources planning and decision making. Volume 3. In Margaret R. Biswas and Asit K. Biswas, editors, *Alternative Strategies for Desert Development and Management*, pages 516–32, New York, 1977. Pergamon.

[69] Sandra Postel. Conserving water—the untapped alternative. *World Watch Paper*, 67:1–66, 1985.

[70] E. R. Reahl. Reclaiming reverse osmosis blowdown with electrodialysis reversal. *Desalination*, 78:77–89, 1990.

[71] S. A. Reed. *General Technology Report. Joint United States-Israel Desalination Project.* Oak Ridge National Laboratory. ORNL/TM-9198, 1984.

[72] J. R. Rydewski and H. A.-H. Rashid. Optimization of water resources for irrigation in East Jordan. *Water Resources Bulletin*, 17(3):367–72, 1981.

[73] J. Van Schilfgaarde and J. D. Rhoades. Coping with salinity. In Ernest Englebert and Ann Foley Scheuring, editors, *Water Scarcity*, pages 157–179, Berkeley, 1984. University of California Press.

[74] Collette Serruya. Water quality problems of Lake Kinneret. In H.I. Shuval, editor, *Water Quality Management Under Conditions of Scarcity: Israel as a Case Study*, pages 167–87, New York, 1980. Academic Press.

[75] H. I. Shuval. Health consideration in water renovation and reuse. In H. I. Shuval, editor, *Water Renovation and Reuse*, pages 33–69, New York, 1977. Academic Press.

[76] H. I. Shuval. Quality management aspects of wastewater reuse in Israel. In H.I. Shuval, editor, *Water Quality Management Under Conditions of Scarcity: Israel as a Case Study*, pages 211–44, New York, 1980. Academic Press.

[77] H. Z. Tabor. Solar ponds as heat source for low temperature multi-effect distillation plants. *Desalination*, 1(3):289–302, 1975.

[78] H. Z. Tabor. Using solar energy to desalinate water. *Impact of Science on Society*, 28:339–48, 1978.

[79] S. K. Tadros. The efficient production of electricity and water in co-generation systems. *Desalination*, 38:99–108, 1981.

[80] J. F. Talling. Water characteristics. In *Euphrates and Tigris—Mesopotamian Ecology and Destiny*, pages 63–80, The Hague, 1980.

[81] H. C. Valcour. Recent applications of EDR. *Proceedings of the Second World Congress on Desalination and Water Re-Use*, 1:163–183, 1985.

[82] A. W. Veenman. A review of new developments in desalination by distillation processes. *Desalination*, 27:21–39, 1978.

[83] M. Wilf, M. Konstantin, and A. Chencinsky. Evaluation of an ion exchange system regenerated with seawater for the increase of product recovery of reverse osmosis brackish water plant. *Desalination*, 34:189–97, 1980.

[84] H. Winters. Two seawater reverse osmosis plants operating at high pressure and 50% conversion. *Desalination*, 65:189–195, 1987.

[85] H. Winters, I. R. Isquith, and R. Bakish. Influence of desalination effluents on marine ecosystems. *Desalination*, 30:403–10, 1979.