Jordan's Water Resources and Their Future Potential

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Introduction

Although water is the most abundant natural resource, Jordan seems to be among the least blessed areas of the world with respect to its availability. This natural scarcity is aggravated by alarming population growth rates, growing degradation of the available resources and increasing demand due to higher standards of living, industrialization and irrigation.

Jordan at present is using or over-using all of its annual renewable freshwater resources. Rationing of domestic consumption, reducing allocations to agriculture, and damage to vulnerable groundwater resources are becoming more common.

This fragile situation is greatly aggravated by the fact that a good portion of Jordan's water resources flows as international water in the Yarmouk and Jordan rivers, and to groundwater resources divided between neighbouring countries.

Exacerbating water scarcity and regional water sharing are political hostilities and the various intentions and interests of the different countries.

These conference proceedings discuss the above issues to clarify the present situation and to offer recommendations for future actions concerning the scarce, precious water resources of Jordan.

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Jordan's water resources and the expected domestic demand by the years 2000 and 2010, detailed according to area

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Introduction

Jordan is an arid to semi-arid country located east of the Jordan River, with a land area of 90,000 km^2 and variable topographic features. A mountainous range runs from north to south. To the east, the ground slopes gently to form the eastern deserts; to the west, the ground slopes steeply towards the Jordan Rift Valley, which extends from Lake Tiberias in the north (at a ground elevation of -220 m) to the Red Sea at Aqaba. About 120 km south of Lake Tiberias lies the Dead Sea, with a water level of approximately -405 m. The southern ghors and Wadi Araba, south of the Dead Sea, form the southern part of the Rift Valley. To the south of the Wadi Araba region lies a 25-km coastline forming the northern shores of the Red Sea.

Due to the variable topographic features of Jordan, rainfall distribution varies considerably with location. Annual rainfall intensities range from 600 mm in the northwest to less than 200 mm in the eastern and southern deserts, which form about 91% of the surface area (Fig. 1). Jordan's average rainfall amounts to about 8,425 MCM/year, varying between 6,235 and 10,630 MCM/year. Approximately 92.2% of the rainfall evaporates, while the rest flows in

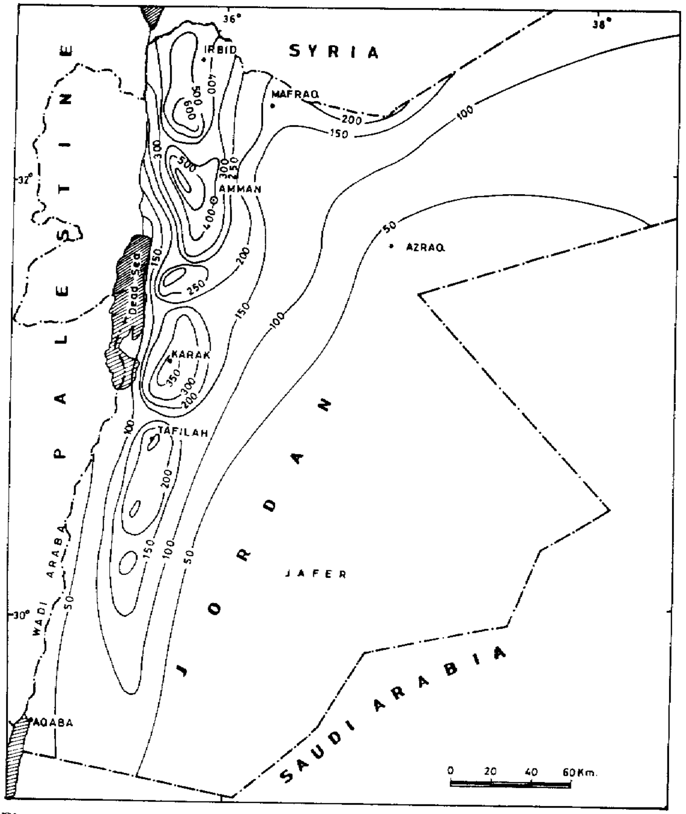


Figure 1. Rainfall distribution in Jordan - mm/year (50-year average).

rivers and wadis as flood flows and recharges to groundwater. Groundwater recharge amounts to approximately 5.4% of the total rainfall volume, while surface water accounts for approximately 2.4%. Jordan's natural water resources are completely dependent on rainfall and evaporation rates; it is clear from the above figures that these resources are scarce and unevenly distributed.

Maximum summer temperatures average 32°C for the highlands and 38°C for the Jordan Valley and the eastern deserts. Maximum winter temperatures average 14-17°C in the highlands and desert areas, and 21°C in the Jordan Valley. Minimum temperatures in winter average 1-4°C in the highlands and desert areas, with occasional snowfall in the highlands, while it rarely falls below 8°C in the Jordan Valley.

Jordan's population is approximately 3.573 million (1991) and is growing rapidly, at 3.6% a year; 91% currently live in northwest Jordan, with 57% in the Amman-Zarka area alone. Settlement patterns are heavily influenced by water availability. Administratively, Jordan is divided into eight governorates: Amman, Irbid, Zarka, Balqa, Mafraq, Karak, Ma'an and Tafileh. Each of these is subdivided into districts, subdistricts and *nahias*.

The uneven natural distribution of water resources resulted in the formation of three categories pertaining to water availability and use:

- Areas where available local water resources are meeting demand.
- Areas where available local water resources exceed demand.
- Areas where available local water resources are not sufficient to meet demand, necessitating the conveyance of water from distances in excess of 100 km, and accordingly requiring heavy capital expenditure for transportation of the water to consumption centers.

Jordan shares some of its most important water resources with neighbouring countries. The country is greatly dependent upon these shared resources -- for both present and future demand -- as they form a large percentage of that which is currently exploited. One of the most important shared water resources is the Jordan River system, where water allocation to riparians forms one of the most difficult regional issues. Various water surveys and plans for this system have been undertaken by various governments and agencies since the beginning of this century; failure to develop a unified approach to managing these water resources, however, has encouraged unilateral development by the various riparians.

Other important shared water resources are the groundwater resources of north Jordan (Azraq, Yarmouk and Amman-Zarka basins), where a large percentage of the natural recharge occurs in Syrian territory. Additional Syrian development of groundwater in these basins would endanger current Jordanian development and greatly reduce the safe yield available to Jordan.

Water resources

In water resources evaluation, a distinction is usually made between surface and groundwater.

Surface water

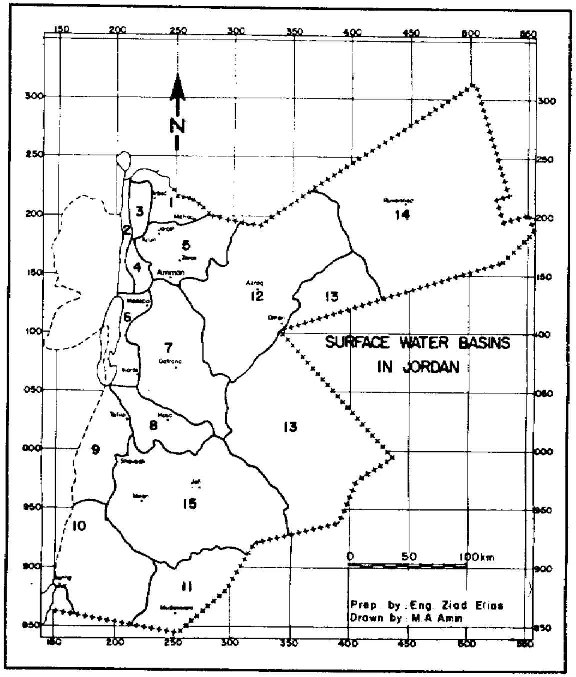
Surface water is that which flows permanently in rivers as flood flows, and from springs. Permanent river, wadi and spring flows vary monthly and are determined by the quantity and duration of rainfall, also contributing somewhat to the groundwater supply. Jordan's surface water is distributed unevenly in 15 basins (Fig. 2); Table 1 lists the distribution of water among them (permanent and flood flows).

The Yarmouk Basin accounts for 40% of the total surface water in Jordan. This includes water contributed from the Syrian part of the Yarmouk Basin. Since this water forms the major tributary of the King Abdullah Canal, it is considered the backbone of development in the Jordan Valley. Other major basins include Zarka, Jordan River side wadis, Mujib, Dead Sea, Hasa, and Wadi Araba.

Jordan's past economic development plans reveal that surface water resources have been extensively developed by the government, with priority given to the construction of dams and irrigation projects in the Jordan Valley, to maximize utilization of this resource before its drainage to the Dead Sea.

Groundwater

Groundwater is considered the major water resource in many areas of Jordan, and the only water resource in some others. It is comprised of both



1. Yarmouk
2. Jordan Valley
3. North Rift Side Wadis
4. South Rift Side Wadis
5. Zarka
6. Dead Sea Rift Side
7. Mujib
8. Hasa
9. Wadi Araba North
10. Wadi Arab South and Wadi Yutum
11. Disi and Southern Desert
12. Azraq
13. Sarhan
14. Hammad
15. Jafer

Figure 2. Surface water basins in Jordan.

Table 1
Distribution of surface water among basins

Basin	Basin	Base flow MCM/year	Flood flow MCM/year	Spring flow MCM/year	Total flow MCM/year
1. Yarmouk at Adasiya	AD	130.00	155.00	21.40	285.00
2. Ghor-Jordan Valley	AB1	0.00	2.40	19.30	21.70
3. N. Jordan River side wadis	A1	36.07	13.91	48.63	49.98
Inter-catchments	AB2	5.10	4.54	18.60	
Wadi al-Arab	AE	1.15	5.00	0.34	
Wadi Ziglab	AF	7.63	0.23	0.05	
Wadi Jurum	AG	10.27	0.20	10.27	
Wadi Yabis	AH	2.62	1.63	4.57	
Wadi Kufranjeh	AJ	5.88	1.00	12.70	
Wadi Rajib	AK	3.42	1.31	2.10	
4. S. Jordan River side wadis	A2	24.76	5.58	28.90	30.34
Inter-catchments	AB3	1.40	2.13	0.00	
Wadi Shu'aib	AM	5.60	1.80	9.10	
Wadi Kafrain	AN	13.44	1.35	12.30	
Wadi Hisban	AP	4.32	0.30	7.50	
5. Zarka River	AL	33.51	25.67	38.91	59.18
6. Dead Sea	C	53.95	7.20	57.60	61.15
Inter-catchments	CA	29.88	1.03	29.30	
Zarka Ma'in	CC	17.74	3.00	17.00	
Karak	CE	6.33	3.17	11.30	
7. Mujib	CD	38.10	45.54	16.00	83.64
8. Hasa	CF	27.40	9.04	3.90	36.44
9. N. Wadi Araba	D	8.99	2.57	15.63	18.20
Inter-catchments	DA	0.80	0.19	3.10	
Feifa	DB	4.31	0.26	7.43	
Khanzera	DC	1.44	0.42	2.32	
Thahel	DD	0.00	0.23	0.03	
Fidan	DE	1.64	0.38	1.70	
Boweirda	DF	0.80	0.16	0.08	
Musa	DG	0.00	0.70	0.88	
Hawor	DH	0.00	0.23	0.09	
10. S. Wadi Araba	E	0.00	3.16	2.44	5.60
Inter-catchments	EA	0.00	0.80	1.84	
Abu Barqa	EB	0.00	0.37	0.60	
Roukaia	EC	0.00	0.19	0.00	
Wadi Yutum	ED	0.00	1.80	0.00	
11. Southern desert	K+ED12	0.00	2.15	0.05	2.20
12. Azraq	F	0.00	26.80	0.60	27.40
13. Sarhan	J	0.00	10.00	0.00	10.00
14. Hammad	H	0.00	13.00	0.00	13.00
15. Jafer	G	0.00	10.00	1.92	11.29
Total		352.78	332.02	255.28	715.12

renewable and nonrenewable resources. Jordan's groundwater is distributed among 12 basins, as shown in Table 2 and illustrated in Figure 3. Some renewable groundwater resources are presently exploited at maximum capacity -- in some cases beyond safe yield -- and are approaching the red-line limit of exploitation.

Renewable groundwater resources. This refers to the water which percolates to aquifers through cracks in rock formations; annual rainfall on the recharge area of the aquifer determines its quantity. Water abstraction from an aquifer has a direct or indirect effect on the natural discharge from that aquifer, whether permanent or spring flow. Many studies and estimates have been completed on groundwater resources in Jordan, and it can be concluded that the safe yield of renewable groundwater resources is 275 MCM/year.

Nonrenewable groundwater resources. This water is stored in ancient aquifers deep inside the earth, and is found under renewable groundwater aquifers; its volume depends on the thickness and storage capacity of the ground layer in which it is found, and on the horizontal layout of that layer.

Table 2
Distribution of groundwater among basins

Basin area or well field	Safe yield MCM/year
A. Renewable groundwater resources	
1. Amman - Zarka	87.50
2. Azraq	24.00
3. Yarmouk	40.00
4. Jordan River side wadis	15.00
5. Jordan River Valley	21.00
6. Dead Sea	57.00
7. North Wadi Araba	3.50
8. South Wadi Araba	5.50
9.a. Jafer	9.00
11. Sarhan	5.00
12. Hammad	8.00
Total renewable	275.50
B. Nonrenewable groundwater resources	
9.b. Jafer	18.00
10. Mudawwara and southern desert *	125.00
Total nonrenewable	143.00
Total	418.50

* Depending on the time horizon of exploitation of the Disi aquifer.

The main nonrenewable groundwater resource presently exploited in Jordan is the Disi (sandstone fossil) aquifer in the south of Jordan. Studies have concluded that the safe yield of this aquifer is 125 MCM/year for 50 years. Its water quality is generally less than 500 ppm. Other nonrenewable groundwater resources are found in the Jafer Basin in Shidiya, with an annual safe yield of 18 MCM.

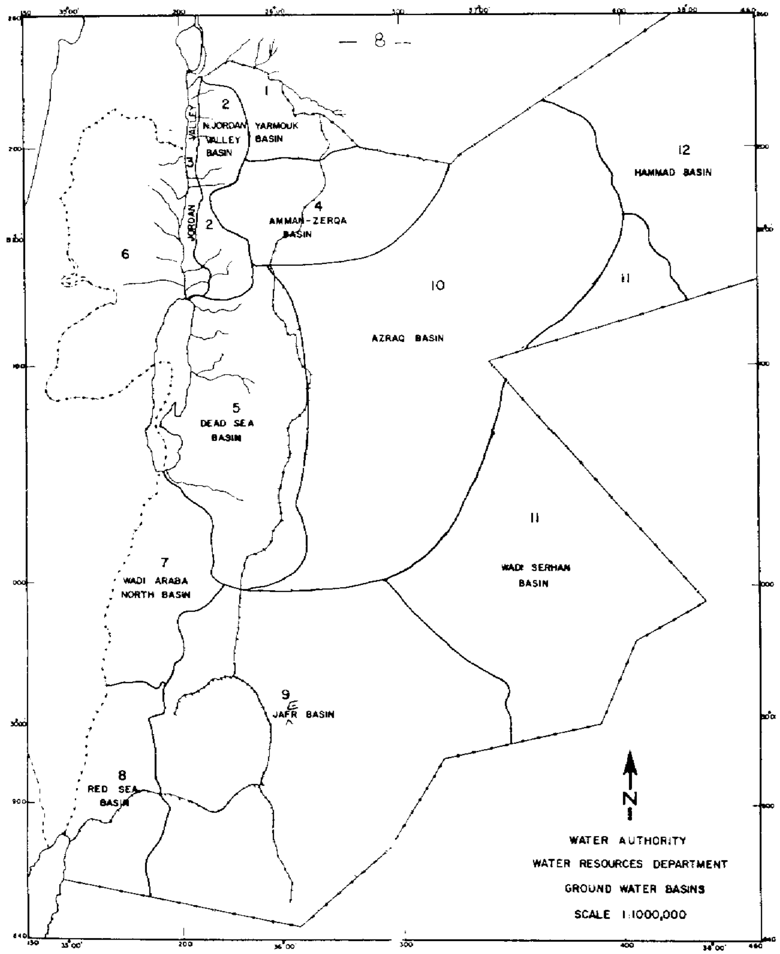


Figure 3. Groundwater basins in Jordan.

Water resources use in Jordan

Water is scarce in Jordan, and competition between consumers is intense -- especially with the annual growth in municipal, industrial and irrigation demand. Because water resources are limited, an efficient management system is needed.

Groundwater production in 1990 for all purposes amounted to 520 MCM, distributed as follows:

- 150 MCM for municipal purposes.
- 329 MCM for irrigation purposes.
- 35 MCM for industrial purposes.
- 6 MCM for livestock purposes.

Surface water consumption in 1990 for all purposes amounted to 360 MCM, distributed as follows:

- 322 MCM for irrigation purposes.
- 30 MCM for municipal purposes.
- 8 MCM for industrial purposes.

Existing groundwater production levels far exceed the potential renewable and nonrenewable resources. Mining of nonrenewable groundwater was estimated at 190 MCM in 1990. This high extraction rate is affecting the quality and quantity of the available groundwater. Over-extraction has degraded water quality and reduced exploitable quantities, resulting in the abandonment of many municipal and irrigation water well fields (such as in the area of Dhuleil).

Municipal water supply

Historically, Jordan's settlement patterns have been influenced heavily by the availability of accessible surface water; such is the case in the cities of Amman, Salt, Karak, Jerash and Tafileh. Water conveyance to consumption centers was once primitive; at present, however, 96% of the population is served by piped networks.

Present municipal water resources

Local spring water was once considered the main municipal water supply source in governorates. The mismatch between Jordan's available water resources and the high population concentration in some areas necessitated the conveyance of water from distant sources to the consumers. The limited and widely scattered sources necessitated the construction of expensive water-conveyance facilities between 1962 and 1987 (Table 3).

Table 3
Municipal water projects

Project	Capacity MCM/year	Conveyor length km	Total cost MJD
W. al-Arab/Irbid	20	36	14
Swaqa/Qastal/Amman	15	72	12
Azraq/Amman	14	102	14.5
Deir Allah/Amman	45	36	55
Sultani/Karak	3.5	36	3.5
Shoubak/Tafileh	1.5	68	4.5
Disi/Aqaba	17	92	10
Za'tari/Dhuleil/Khaw	30	35	1.65
Za'tari/Mafraq	30	45	1.5
Sumia/Mafraq	4	7	0.5

Municipal water resources in 1990 relied heavily on groundwater (150 MCM), forming 80% of the total water supplied; on some spring flows (20 MCM); and on surface water abstracted from King Abdullah Canal (8 MCM), which is considered to be an unreliable source, due to the fact that only excess water after irrigation can be utilized for municipal purposes. The total water supply for municipal purposes and small industries in 1990 totalled 179 MCM. Local sources within the governorates accounted for 80 MCM (45%), while transfers between governorates totalled 99 MCM (55%).

Municipal water supply, 1986 - 1990

Municipal water is that which is used for domestic and commercial purposes, local farm irrigation and small industries, and is supplied from the municipal network. It also includes the water losses from leakages in the municipal distribution system.

Municipal water use was made more systematic with the creation of the Water Authority in 1985. Prior to that, many agencies and municipalities were responsible for the production and distribution of municipal water. Little data on the actual production levels prior to 1986 is available.

Table 4 shows the water quantities supplied for municipal and small industrial uses in the various governorates for the period 1986-1990; the supplied quantities are those measured at the source of production and supplied to the municipal network system. Figure 4 illustrates the growth in municipal water supply and the total shortages between 1986 and 1990.

Municipal water supply to Amman Governorate. The population in Amman Governorate increased from 1.16 million in 1986 to 1.444 million in

Table 4
Total water supply (MCM) per governorate (1986 - 1990)

Year	1986		1987		1988		1989		1990	
Governorate	Supply	Shortages	Supply	Shortages	Supply	Shortages	Supply	Shortages	Supply	Shortages
Amman	59.40	3.00	68.20	2.16	74.60	4.50	73.10	4.32	75.18	12.88
Zarka	11.90	1.00	12.60	1.50	14.70	2.00	17.10	3.00	21.77	3.50
Irbid	23.20	1.00	27.80	1.00	30.00	2.52	30.20	0.00	30.07	8.76
Mafraq	14.00	0.00	11.60	0.00	13.40	0.00	13.30	0.00	15.14	0.00
Balqa	8.20	1.70	9.10	1.70	10.30	1.70	13.10	1.70	12.54	4.82
Karak	3.90	0.00	4.80	0.00	5.00	0.00	5.60	0.00	5.89	0.00
Tafileh	1.70	0.00	1.80	0.00	2.00	0.00	2.30	0.00	2.18	0.00
Ma'an	12.40	0.00	14.50	0.00	14.70	0.00	15.40	0.00	15.88	0.00
Total	134.70	6.70	150.40	6.36	164.70	10.72	170.10	9.02	178.65	29.96
Total Supply + Shortages	141.40		156.76		175.42		179.12		208.61	

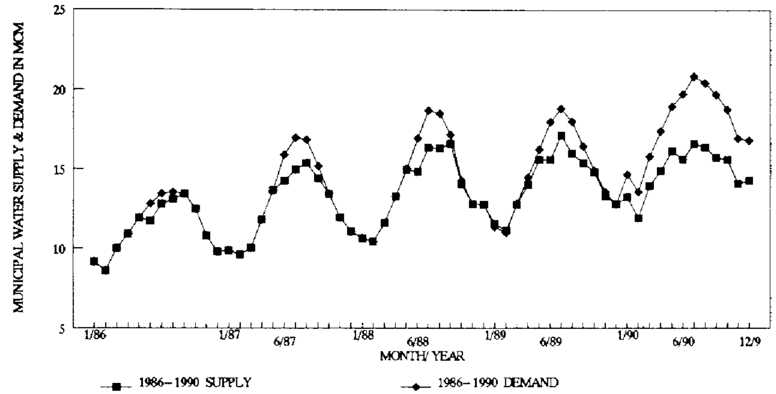


Figure 4. Municipal water supply & demand, 1986-1990.

1990. Municipal water supply to this area rose from 59.4 MCM in 1986 to 75.2 MCM in 1990, with a five-year increase of about 27% (15.8 MCM). Water in Amman is primarily used for domestic and commercial purposes, with the exception of that used for some small industries and minor local farm irrigation. The water supply rates varied from 140 litres per capita per day (L/C/D) in 1986 to 143 L/C/D in 1990.

Starting in 1988, municipal water rationing was implemented in the Amman area. Supply shortages rose from 3 MCM in 1986 to 13 MCM in 1990, an increase of 10 MCM over a five-year period. Some of the shortages in 1990 were due to the influx of returnees to Jordan as a result of the Gulf war. Table 5 shows Amman's municipal water supply and the shortages encountered from 1986 to 1990.

Municipal water supply to Zarka Governorate. The population in Zarka Governorate increased from 0.405 million in 1986 to 0.5309 million in 1990. Municipal water supply to the area rose from 12 MCM in 1986 to 22 MCM in 1990, a five-year increase of about 83% (10 MCM). Water supplied to Zarka is primarily used for domestic and commercial purposes, with the exception of that used for some small industries and minor local farm irrigation. The water supply rates varied from 80 L/C/D in 1986 to 112 L/C/D in 1990. This increase was due mainly to industrial growth (and consequently, the need for a greater water supply) in the Zarka area.

Starting in 1988, water rationing was implemented in Zarka. Supply shortages there rose from an estimated 1 MCM in 1986 to 3.5 MCM in 1990, an increase of 2.5 MCM for that five-year period. Some of the shortages encountered in 1990 were due to the influx of returnees to Jordan as a result of the Gulf war. Table 6 shows Zarka's municipal water supply and the shortages encountered from 1986 to 1990.

Table 5
Monthly water supply in Amman Governorate
MCM/month 1986-1990

Month	1986	1987	1988	1989	1990
January	4.03	4.62	5.11	5.03	6.16
February	3.66	4.21	5.10	4.65	5.32
March	4.03	4.63	5.48	5.32	6.15
April	4.64	5.33	6.23	6.07	6.29
May	5.37	6.16	7.02	6.70	6.85
June	5.70	6.55	7.03	6.52	6.34
July	5.80	6.66	7.29	6.96	6.71
August	6.15	7.06	7.38	6.97	6.73
September	5.79	6.65	6.89	6.58	6.41
October	5.20	5.98	5.71	6.50	6.46
November	4.65	5.33	5.44	6.09	5.69
December	4.40	5.05	5.91	5.71	6.05
Total annual production	59.42	68.22	74.58	73.09	75.18
Average monthly production	4.95	5.69	6.22	6.09	6.26
Maximum monthly production	6.15	7.06	7.38	6.97	6.85
Estimated annual shortages	3.00	2.16	4.50	4.32	12.88
Estimated annual demand	62.42	70.38	79.08	77.41	88.06

Table 6
Monthly water supply in Zarka Governorate
MCM/month 1986-1990

Month	1986	1987	1988	1989	1990
January	0.78	0.82	0.94	1.24	1.54
February	0.85	0.90	0.88	1.21	1.18
March	0.77	0.82	0.97	1.14	1.62
April	0.93	0.99	1.18	1.26	1.81
May	1.02	1.07	1.09	1.61	2.01
June	0.99	1.05	1.06	1.65	1.97
July	1.16	1.23	1.52	1.78	2.08
August	1.15	1.21	1.53	1.67	2.02
September	1.14	1.21	1.53	1.51	1.97
October	1.15	1.22	1.45	1.49	1.96
November	0.99	1.05	1.29	1.31	1.81
December	0.94	0.99	1.26	1.28	1.79
Total annual production	11.88	12.50	14.70	17.15	21.76
Average monthly production	0.99	1.05	1.22	1.43	1.81
Maximum monthly production	1.16	1.23	1.53	1.78	2.08
Estimated annual shortages	1.00	1.50	2.00	3.00	3.50
Estimated annual demand	12.88	14.00	16.70	20.15	25.26

Municipal water supply to Irbid Governorate. The population in Irbid Governorate increased from 0.68 million in 1986 to 0.815 million in 1990. Municipal water supply to the area rose from 23 MCM in 1986 to 30 MCM in 1990, a five-year increase of about 30% (7 MCM). Water supplied to Irbid is primarily used for domestic and commercial purposes, with the exception of that used for some small industries and minor local farm irrigation. The water supply rates varied from 93 L/C/D in 1986 to 101 L/C/D in 1990, due mainly to the growth in water connections from 1987 to 1990.

Starting in 1988, water rationing was implemented in Irbid. Supply shortages in Irbid rose from an estimated 1 MCM in 1986 to 8.8 MCM in 1990, an increase of 7.8 MCM over a five-year period. Some of the shortages in 1990 were due to the influx of returnees to Jordan as a result of the Gulf war. Table 7 shows Irbid's municipal water supply and the shortages encountered from 1986 to 1990.

Municipal water supply to Mafraq Governorate. The population in Mafraq Governorate increased from 0.0986 million in 1986 to 0.1272 million in 1990. Municipal water supply to the area rose from 13.96 MCM in 1986 to 15.14 MCM in 1990, a five-year increase of about 8.5% (1.2 MCM). Water supplied to Mafraq is primarily used for irrigation and domestic purposes. The water supply rates varied from 388 L/C/D in 1986 to 326 L/C/D in 1990. There was the expected increase in domestic use; the drop in L/C/D was due mainly

Table 7
Monthly water supply in Irbid Governorate
MCM/month 1986-1990

Month	1986	1987	1988	1989	1990
January	1.46	1.75	2.02	2.10	2.12
February	1.34	1.61	1.84	2.10	1.98
March	1.47	1.76	2.14	2.39	2.26
April	1.72	2.06	2.38	2.52	2.45
May	2.12	2.54	2.69	2.73	2.73
June	2.14	2.57	2.66	2.66	2.79
July	2.29	2.75	2.83	2.88	2.82
August	2.29	2.74	2.86	2.71	2.69
September	2.20	2.64	3.65	2.95	2.60
October	2.23	2.68	2.50	2.59	2.63
November	1.99	2.39	2.33	2.26	2.58
December	1.91	2.30	2.12	2.28	2.42
Total annual production	23.16	27.79	30.03	30.18	30.07
Average monthly production	1.93	2.32	2.50	2.51	2.51
Maximum monthly production	2.29	2.75	3.65	2.95	2.82
Estimated annual shortages	1.00	1.00	2.52	0.00	8.76
Estimated annual demand	24.16	28.79	32.55	30.18	38.83

to the decrease in water from the municipal system used for irrigation purposes. No supply shortages were encountered in this governorate. Table 8 shows Mafraq's municipal water supply from 1986 to 1990.

Table 8
Monthly water supply in Mafraq Governorate
MCM/month 1986-1990

Month	1986	1987	1988	1989	1990
January	0.81	0.67	0.50	0.88	0.98
February	0.82	0.68	0.70	0.92	1.16
March	0.88	0.74	0.79	1.16	1.41
April	1.34	1.11	0.98	1.11	1.50
May	1.52	1.26	1.13	1.14	1.35
June	1.55	1.29	1.31	1.30	1.31
July	1.47	1.22	1.55	1.33	1.40
August	1.42	1.18	1.32	1.04	1.32
September	1.29	1.07	1.45	1.06	1.26
October	1.14	0.95	1.37	1.23	1.32
November	1.04	0.86	1.19	1.08	1.09
December	0.69	0.58	1.10	1.02	1.06
Total annual production	13.96	11.64	13.39	13.27	15.14
Average monthly production	1.16	0.97	1.12	1.11	1.26
Maximum monthly production	1.55	1.29	1.55	1.33	1.50
Estimated annual shortages	0.00	0.00	0.00	0.00	0.00
Estimated annual demand	13.96	11.64	13.39	13.27	15.14

Municipal water supply to Balqa Governorate. The population in Balqa Governorate increased from 0.1938 million in 1986 to 0.2353 million in 1990. Municipal water supply to the area rose from 8.23 MCM in 1986 to 12.542 MCM in 1990, a five-year increase of about 52% (4.3 MCM). Water supplied to Balqa is primarily used for domestic and commercial purposes, with the exception of that used for some small industries and minor local farm irrigation. The water supply rates increased from 116 L/C/D in 1986 to 146 L/C/D in 1990, due mainly to the growth in water use for irrigation in the Ghor and rural areas in Balqa.

Starting in 1988, water rationing was implemented. Supply shortages in Balqa varied from an estimated 1.7 MCM in 1986 to 4.8 MCM in 1990, an increase of 3.1 MCM. Table 9 shows Balqa's municipal water supply and the shortages encountered from 1986 to 1990.

Municipal water supply to Karak Governorate. The population in Karak Governorate increased from 0.1201 million in 1986 to 0.14 million in 1990. Municipal water supply to the area rose from 3.861 MCM in 1986 to 5.886

Table 9
Monthly water supply in Balqa Governorate
MCM/month 1986-1990

Month	1986	1987	1988	1989	1990
January	0.58	0.64	0.81	0.82	0.97
February	0.53	0.59	0.69	0.77	0.74
March	0.57	0.63	0.76	0.98	0.87
April	0.55	0.61	0.81	1.16	0.98
May	0.69	0.77	0.95	1.15	1.03
June	0.74	0.82	0.79	1.12	1.04
July	0.89	0.99	0.94	1.82	1.09
August	0.90	1.00	0.93	1.22	1.19
September	0.81	0.89	0.95	1.15	1.17
October	0.72	0.80	1.01	1.04	1.14
November	0.64	0.71	0.90	0.93	1.13
December	0.63	0.70	0.79	0.96	1.19
Total annual production	8.23	9.14	10.33	13.11	12.54
Average monthly production	0.69	0.76	0.86	1.09	1.05
Maximum monthly production	0.90	1.00	1.01	1.82	1.19
Estimated annual shortages	1.70	1.70	1.70	1.70	4.82
Estimated annual demand	9.93	10.84	12.03	14.81	17.36

MCM in 1990, a five-year increase of about 52% (2 MCM). Water supplied to Karak is primarily used for domestic and local farm irrigation purposes, with the exception of that supplied for some commercial use. The water supply rates rose from 88 L/C/D in 1986 to 115 L/C/D in 1990, due mainly to the growth in water use for irrigation in the Ghor and rural areas in Karak. No supply shortages were encountered in this governorate. Table 10 shows Karak's municipal water supply from 1986 to 1990.

Municipal water supply to Tafileh Governorate. The population in Tafileh Governorate increased from 0.0414 million in 1986 to 0.0474 million in 1990. Municipal water supply to the area rose from 1.68 MCM in 1986 to 2.181 MCM in 1990, an increase of about 29% (0.5 MCM). Water supplied to Tafileh is primarily used for domestic and local farm irrigation purposes, with the exception of that supplied for some commercial use. The water supply rates rose from 111 L/C/D in 1986 to 126 L/C/D in 1990, due mainly to the growth in water use for irrigation and new municipal water connections. No supply shortages were encountered in this governorate. Table 11 shows Tafileh's municipal water supply from 1986 to 1990.

Municipal water supply to Ma'an Governorate. The population in Ma'an Governorate increased from 0.0975 million in 1986 to 0.1132 million in 1990.

Table 10
Monthly water supply in Karak Governorate
MCM/month 1986-1990

Month	1986	1987	1988	1989	1990
January	0.23	0.29	0.31	0.32	0.25
February	0.22	0.28	0.27	0.37	0.33
March	0.22	0.28	0.30	0.41	0.43
April	0.28	0.35	0.41	0.52	0.44
May	0.33	0.41	0.55	0.55	0.53
June	0.37	0.46	0.48	0.56	0.57
July	0.40	0.50	0.51	0.56	0.68
August	0.44	0.55	0.56	0.59	0.58
September	0.42	0.52	0.51	0.54	0.61
October	0.37	0.47	0.45	0.47	0.56
November	0.32	0.40	0.37	0.40	0.45
December	0.25	0.32	0.33	0.36	0.46
Total annual production	3.86	4.83	5.05	5.66	5.89
Average monthly production	0.32	0.40	0.42	0.47	0.49
Maximum monthly production	0.44	0.55	0.56	0.59	0.68
Estimated annual shortages	0.00	0.00	0.00	0.00	0.00
Estimated annual demand	3.86	4.83	5.05	5.66	5.89

Table 11
Monthly water supply in Tafileh Governorate
MCM/month 1986-1990

Month	1986	1987	1988	1989	1990
January	0.11	0.12	0.12	0.17	0.13
February	0.11	0.12	0.13	0.17	0.13
March	0.12	0.14	0.15	0.20	0.16
April	0.14	0.16	0.17	0.19	0.17
May	0.16	0.18	0.16	0.21	0.21
June	0.15	0.17	0.19	0.23	0.21
July	0.16	0.18	0.20	0.24	0.22
August	0.15	0.18	0.19	0.23	0.21
September	0.14	0.16	0.19	0.21	0.20
October	0.13	0.16	0.19	0.19	0.21
November	0.12	0.14	0.15	0.16	0.16
December	0.11	0.13	0.15	0.15	0.17
Total annual production	1.61	1.84	1.98	2.34	2.18
Average monthly production	0.13	0.15	0.17	0.19	0.18
Maximum monthly production	0.16	0.18	0.20	0.24	0.22
Estimated annual shortages	0.00	0.00	0.00	0.00	0.00
Estimated annual demand	1.61	1.84	1.98	2.34	2.18

Municipal water supply to the area rose from 12.448 MCM in 1986 to 15.875 MCM in 1990, an increase of about 27.5% (3.4 MCM). Water supplied to Ma'an is primarily used for domestic, industrial and tourism purposes, with the exception of that supplied for some local farm irrigation. The water supply rates varied from 350 L/C/D in 1986 to 384 L/C/D in 1990; this high per capita supply rate is due to industrial water use for the Jordan Fertilizer Industry and Thermal Power Station in the city of Aqaba. No supply shortages were encountered in this governorate. Table 12 shows Ma'an's municipal water supply from 1986 to 1990.

The pattern of water use varied from one governorate to the other between 1986 and 1990; it can therefore be concluded that the present pattern of municipal water use is not an accurate indicator of domestic water-consumption levels.

Municipal water demand

Many studies and reports have been completed to estimate the total demand for municipal water in Jordan. Demand is rapidly rising due to increased development and the high rate of population growth -- presently, at 3.6%, one of the highest in the world. Additionally, approximately 300,000

Table 12
Monthly water supply in Ma'an Governorate
MCM/month 1986-1990

Month	1986	1987	1988	1989	1990
January	0.82	0.95	0.83	0.99	1.10
February	1.06	1.24	0.84	0.96	1.06
March	0.90	1.05	1.01	1.16	1.08
April	1.03	1.20	1.14	1.20	1.28
May	1.10	1.28	1.39	1.52	1.47
June	1.14	1.33	1.32	1.58	1.42
July	1.24	1.44	1.51	1.57	1.62
August	1.26	1.47	1.55	1.57	1.65
September	1.11	1.29	1.47	1.44	1.52
October	1.03	1.20	1.40	1.32	1.33
November	0.90	1.05	1.13	1.11	1.20
December	0.86	1.00	1.11	1.05	1.15
Total annual production	12.45	14.50	14.71	15.45	15.88
Average monthly production	1.04	1.21	1.23	1.29	1.32
Maximum monthly production	1.26	1.47	1.55	1.58	1.65
Estimated annual shortages	0.00	0.00	0.00	0.00	0.00
Estimated annual demand	12.45	14.50	14.71	15.45	15.88

people returned to Jordan as a result of the Gulf war, causing a sharp increase in municipal water demand (estimated at 36 MCM in 1991).

Projecting municipal water demand

It is difficult to project municipal water demand, due to the discrepancy between the total quantity of water produced and that measured at consumer meters.

It was decided that the total water supplied from 1986 to 1990 -- in addition to supply shortages encountered -- be used to determine municipal water demand.

In general, such a projection depends on a country's available water resources, development of the resources to meet demand, future population growth, the increase in per capita water demand within acceptable social and health limits, and the percentage of projected losses from the municipal water system.

For the purpose of this paper, the following points were considered in estimating projected municipal water demand:

- The supply of municipal water services to 100% of the population.
- Improvements in socio-economic conditions -- especially in the less developed areas of Jordan.
- Different population growth rates in the governorates -- based on the actual rates quoted by the Department of Statistics, and taking into account the influx of returnees as result of the Gulf war.
- Different per capita water demand rates in the various governorates; implementing a plan to fix the country's average total water demand at a maximum of 180 L/C/D by the year 2005.
- Separating the water demand of the Fertilizer Industry and Power Station in Aqaba from municipal water demand projections.
- Minimizing the level of losses existing in the present water-supply system.
- Including water demand of small industries presently supplied from the network with the municipal water demand.
- Minimizing local irrigation water-use levels (taken from the municipal water system).

Population projections

Population growth rates varied from 3.4% to 3.7% in 1990 and are likely to range from 2.9% to 3.1% in 2010 (Table 13). Accordingly, it is estimated that the population of Jordan will reach 4.85 million in 2000, and 6.62 million in 2010. It is estimated that 41% will live in Amman Governorate.

Table 13
Population projection for Jordan 1990-2010

	Governorate								
Year	Amman	Zarka	Irbid	Mafraq	Balqa	Karak	Tafileh	Ma'an	Total
1990	1,444,400	530,900	814,600	127,200	235,300	140,000	47,400	113,200	3,453,000
1991	1,493,760	549,043	842,437	131,547	243,341	144,784	49,020	117,068	3,571,000
1992	1,546,048	568,261	871,926	136,152	251,859	149,852	50,736	121,166	3,696,000
1993	1,600,009	588,095	902,359	140,904	260,649	155,083	52,507	125,395	3,825,000
1994	1,656,480	608,851	934,207	145,877	269,849	160,556	54,360	129,821	3,960,000
1995	1,714,205	630,069	966,762	150,960	279,253	166,151	56,254	134,345	4,098,000
1996	1,773,604	651,902	1,000,262	156,191	288,929	171,908	58,203	139,000	4,240,000
1997	1,835,095	674,503	1,034,941	161,606	298,946	177,869	60,221	143,819	4,387,000
1998	1,898,259	697,719	1,070,563	167,169	309,236	183,991	62,294	148,770	4,538,000
1999	1,962,677	721,397	1,106,893	172,842	319,730	190,235	64,408	153,818	4,692,000
2000	2,028,351	745,536	1,143,931	178,625	330,429	196,600	66,563	158,965	4,849,000
2001	2,094,861	769,982	1,181,441	184,482	341,263	203,047	68,746	164,178	5,008,000
2002	2,162,626	794,889	1,219,659	190,450	352,303	209,615	70,970	169,489	5,170,000
2003	2,231,646	820,258	1,258,584	196,528	363,546	216,305	73,235	174,898	5,335,000
2004	2,301,503	845,934	1,297,981	202,680	374,926	223,076	75,527	180,373	5,502,000
2005	2,371,778	871,765	1,337,614	208,869	386,374	229,887	77,833	185,880	5,670,000
2006	2,442,059	897,597	1,377,251	215,058	397,824	236,699	80,140	191,388	5,838,016
2007	2,511,950	923,286	1,416,667	221,213	409,209	243,473	82,433	196,866	6,005,097
2008	2,581,075	948,693	1,455,652	227,300	420,470	250,173	84,702	202,283	6,170,349
2009	2,649,090	973,693	1,494,011	233,290	431,550	256,766	86,934	207,614	6,332,948
2010	2,718,898	999,351	1,533,380	2,394,438	442,922	263,532	89,224	213,085	6,499,831

Per capita municipal water demand

Table 4 shows that the municipal water supply in 1990 totalled 178.65 MCM, while the water supply in 1986 totalled 134.7 MCM. The increase in water production in those five years was 43.95 MCM -- equal to 33% of the total water produced in 1986. The total supplied L/C/D increased from 132 L/C/D in 1986 to 142 L/C/D in 1990.

Table 4 and Figure 4 show that the total water demand exceeded supply for the period 1986-1990. It also indicates shortages ranging from 6.7 MCM in 1986 to 30 MCM in 1990. Municipal water shortages in 1991 are estimated at 35 MCM, 17 MCM of which is estimated to be the demand of the Gulf war returnees to Jordan. The shortages were experienced in the summer months (June to October) from 1986 to 1989, and all year in 1990.

The 1990 shortages were concentrated in two governorates -- Amman and Irbid -- with 12.9 and 12.9 MCM, respectively. By taking these shortages into account, municipal water demand in 1986 would amount to 141.4 MCM, and 208.6 MCM in 1990; the total L/C/D demand would increase from 138.5 L/C/D in 1986 to 165.8 L/C/D in 1990.

Losses from the municipal water network in 1985 were estimated at 20% of the total water produced, or 23 MCM. Non-domestic uses were estimated at 14% of the total water produced, or 16 MCM (World Bank Report, 1988). Based on these figures, the total *domestic* water demand in 1985 would average 81 L/C/D. Consumption varied from 49 L/C/D in localities with less than 3000 inhabitants, to 130 L/C/D in Aqaba city. If the same percentage of losses and growth in uses for other than municipal purposes were taken into consideration, the average total per capita *domestic* demand would amount to 109 L/C/D in 1990.

Municipal water demand projection

Municipal demand projection for Amman Governorate. The population of Amman Governorate is expected to increase from 1.44 million in 1990 to 2.03 million in 2000 and to 2.72 million in 2010. Municipal water demand is expected to grow from 88.2 MCM in 1990 to 129 MCM in 2000, to 174 MCM in 2010 -- an increase of 46.5% (40.8 MCM) in the next ten years and 97.3% (85.8 MCM) in the next twenty. Per capita municipal water demand is expected to increase from 167.2 L/C/D in 1990 to 175 L/C/D in 2000, remaining at 175 L/C/D in 2010. Table 14 and Figure 5 show the projected growth in municipal water demand for the years 1990, 2000 and 2010.

Municipal demand projection for Zarka Governorate. The population of Zarka Governorate is expected to increase from 0.531 million in 1990 to 0.745 million in 2000, to 1.0 million in 2010. Municipal water demand is expected to grow from 25 MCM in 1990 to 45 MCM in 2000, and 62 MCM in

Table 14
Municipal water demand projection for Jordan 1990-2010

Administrative	1990 Projection			2000 Projection			2010 Projection		
divisions	Population	L/C/D	MCM/yr	Population	L/C/D	MCM/yr	Population	L/C/D	MCM/yr
Amman Governorate	1,444,400	167.0	88.1	2,028,351	174.5	129.2	2,718,898	175.4	174.0
Zarka Governorate	530,900	130.4	25.3	745,536	166.6	45.3	999,351	168.5	61.5
Irbid Governorate	814,600	130.6	38.8	1,143,931	144.8	60.4	1,533,380	146.6	82.1
Mafraq Governorate	127,200	326.1	15.1	178,625	342.4	22.3	239,438	343.1	30.0
Balqa Governorate	235,300	202.1	17.4	330,429	185.9	22.4	442,922	186.6	30.2
Karak Governorate	140,000	115.2	5.9	196,600	121.1	8.7	263,532	121.5	11.7
Tafileh Governorate	47,400	126.1	2.2	66,563	145.4	3.5	89,224	146.0	4.8
Ma'an Governorate	113,200	384.2	15.9	158,965	413.5	24.0	213,085	414.6	32.2
Grand total	3,453,000	165.5	208.6	4,849,000	178.5	315.9	6,499,831	179.7	426.4

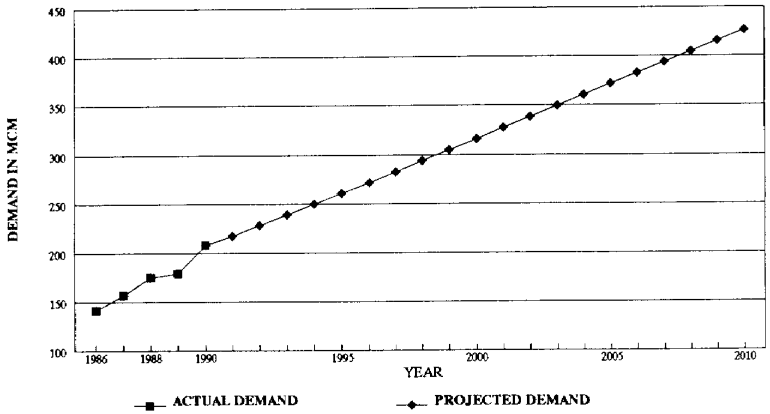


Figure 5. Municipal water demand projection, 1990-2010.

2010 -- an increase of 80% (20 MCM) in the next ten years and 148% (37 MCM) in the next twenty. Per capita municipal water demand is expected to increase from 130 L/C/D in 1990 to 167 L/C/D in 2000, and 168 L/C/D in 2010. Table 14 and Figure 5 show the projected growth in municipal water demand for the years 1990, 2000 and 2010.

Municipal demand projection for Irbid Governorate. The population of Irbid Governorate is expected to increase from 0.815 million in 1990 to 1.144 million in 2000, and 1.533 million in 2010. Municipal water demand is expected to grow from 39 MCM in 1990 to 60 MCM in 2000, to 82 MCM in 2010 -- an increase of 54% (21 MCM) in the next ten years and 110% (43 MCM) in the next twenty. Per capita municipal water demand is expected to increase from 130 L/C/D in 1990 to 145 L/C/D in 2000 and 147 L/C/D in 2010. Table 14 and Figure 5 show the estimated growth in municipal water demand for the years 1990, 2000 and 2010.

Municipal demand projection for Mafraq Governorate. The population of Mafraq Governorate is expected to increase from 0.127 million in 1990 to 0.178 million in 2000, to 0.239 million in 2010. Municipal water demand is expected to grow from 15 MCM in 1990 to 22 MCM in 2000 and 30 MCM in 2010 -- an increase of 47% (7 MCM) in the next ten years and 98% (15 MCM) in the next twenty. Per capita municipal water demand is expected to increase from 326 L/C/D in 1990 to 342 L/C/D in 2000 and 343 L/C/D in 2010. Table 14 and Figure 5 show the estimated growth in municipal water demand for the years 1990, 2000 and 2010.

Municipal demand projection for Balqa Governorate. The population of Balqa Governorate is expected to increase from 0.235 million in 1990 to 0.330 million in 2000, to 0.443 million in 2010. Municipal water demand is

expected to grow from 17 MCM in 1990 to 22 MCM in 2000 and to 30 MCM in 2010 -- an increase of 29% (5 MCM) in the next ten years and 76% (13 MCM) in the next twenty. Per capita municipal water demand is expected to decrease from 202 L/C/D in 1990 to 186 L/C/D in 2000, while it is expected to increase slightly, to 187 L/C/D, in 2010. Table 14 and Figure 5 show the estimated municipal water demand for the years 1990, 2000 and 2010.

Municipal demand projection for Karak Governorate. The population of Karak Governorate is expected to increase from 0.14 million in 1990 to 0.197 million in 2000, and to 0.263 million in 2010. Municipal water demand is expected to grow from 5.9 MCM in 1990 to 8.7 MCM in 2000, to 11.7 MCM in 2010 -- an increase of 48% (2.8 MCM) in the next ten years and 98% (5.8 MCM) in the next twenty. Per capita municipal water demand is expected to increase from 115 L/C/D in 1990 to 121 L/C/D in 2000, remaining at 121 L/C/D in 2010. Table 14 and Figure 5 show the estimated growth in municipal water demand for the years 1990, 2000 and 2010.

Municipal demand projection for Tafileh Governorate. The population of Tafileh Governorate is expected to increase from 0.047 million in 1990 to 0.666 million in 2000, and to 0.892 million in 2010. Municipal water demand is expected to grow from 2.2 MCM in 1990 to 3.5 MCM in 2000, and 4.8 MCM in 2010 -- an increase of 60% (1.32 MCM) in the next ten years and 120% (2.6 MCM) in the next twenty. Table 14 and Figure 5 show the estimated growth in municipal water demand for the years 1990, 2000, and 2010.

Municipal demand projection for Ma'an Governorate. The population of Ma'an Governorate is expected to increase from 0.113 million in 1990 to 0.159 million in 2000, to 0.213 million in 2010. Municipal water demand is expected to grow from 15.9 MCM in 1990 to 24 MCM in 2000, and to 32 MCM in 2010 -- an increase of 51% (8 MCM) in the next ten years and 100% (16 MCM) in the next twenty. Per capita municipal water demand is expected to increase from 384 L/C/D in 1990 to 413 L/C/D in 2000, and 415 L/C/D in 2010. Table 14 and Figure 5 show the estimated growth in municipal water demand for the years 1990, 2000 and 2010.

It can be concluded that the municipal water demand will grow from 209 MCM in 1990 to 316 MCM in 2000, while it is expected to be 426 MCM in 2010. The total average per capita municipal water demand is expected to increase from 166 L/C/D in 1990 to 179 L/C/D in 2000, while it is expected to be 180 L/C/D by 2010.

Shortages in 1990 were estimated at 30 MCM. If no additional water resources are developed in the future, the shortages will be an estimated 137 MCM in 2000, and 247 MCM in 2010.

2

Irrigated agriculture in Jordan

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Agricultural land in east Jordan -- particularly the highlands and northwest areas -- utilizes a water supply dependent upon rainfall. The rainy (winter) season usually lasts from October to April. Most of the land irrigated by surface water is located in the Jordan Valley and the flat land along the banks of the perennial streams. Jordan Valley land has been irrigated for ages; now, however, there is not enough water to supply necessary quantities for all the irrigable land. In the early fifties, a survey was conducted in the Jordan Valley to identify the irrigable land between Adasiya and the Dead Sea. Table 1 shows how that land was classified (for taxation purposes).

A land and water settlement law (no. 40) was enacted in 1952 to distribute water among farmers. Water is distributed as shares, with each dunum of land situated on a water source having one share. For example, if the total irrigated area is 5000 dunums and a farmer has 50 dunums of irrigated land, he is entitled to 50 shares out of 5000.

In some cases, water is broken into time units known as *fasl*. The *fasl* allows each farmer to use the entire flow of water from a channel for a fixed time -- usually 3, 6 or 12 hours.

Article 8 (5) of Law No. 40 of 1952 reads as follows:

"When settlement of water is carried out, the director shall fix the shares of water that should be recorded in the Schedule of Rights in proportion to the total area of the irrigated lands which are usually irrigated from the water under settlement -- provided that such shares are recorded in proportion to the number of dunums of the irrigated lands. Where any person owns more shares of water than he needs, such shares are given to other owners; the person or

Table 1
Classification of land for taxation purposes

Land category	Private dunums	State domain dunums	Total dunums	Percent Private	Percent State	Percent Total
Bananas	3022	-	3022	1.4	-	0.8
Citrus	1123	-	1123	0.5	-	0.3
Irrigated orchard	1089	-	1089	0.5	-	0.3
Dry orchard	35	-	35	-	-	-
Irrigated, class I	171072	1103	172175	77.2	0.7	44.6
Irrigated, class II	10319	-	10319	4.7	-	2.7
Dry, class I	735	42	777	0.3	-	0.2
Dry, class II	1955	299	2254	0.9	0.2	0.6
Dry, class III	17083	1185	18268	7.7	0.7	4.7
Dry, class IV	-	-	-	-	-	-
Bad land	15108	161856	176964	6.8	98.4	45.8
Total	221541	164485	886026	100.0	100.0	100.0

persons benefitting from such shares shall pay a just compensation to their owner, as may be determined by the director."

About the same time, the Irrigation Department published rough estimates for water allocation to the irrigable areas of the Jordan Valley. Results are given in Table 2, which shows that there were 208,017 dunums under irrigation in the East Bank and 39,652 dunums in the West Bank during the fifties. It was believed that these figures should be reduced by 30%; the actual irrigated areas would then be 145,000 dunums in the East Ghor and 27,500 dunums in the West Ghor.

Intensive irrigation projects were implemented in Jordan in 1958, when the government decided to divert part of the Yarmouk River water and constructed the East Ghor Canal Project. The canal was 70 kilometres long in 1961, and was extended three times between 1969 and 1987, to 110.5 kilometres, following a grade line from Adasiya (near Yarmouk) to Ramah (near the Dead Sea).

The East Ghor Canal construction, along with its extension to the south, has put more land under irrigation from the Yarmouk River and the side wadis.

Constructing five dams on the side wadis (Wadi Arab Dam, 20 MCM; King Talal Dam, 90 MCM) and diverting the flows from Wadi Jurum, Wadi Hisban and other side wadis in the northern and southern ghors allowed new lands-- most of those above the main canal and in the southern ghors -- to be irrigated.

Wells were drilled in the Jordan Valley to abstract groundwater for domestic use and irrigation during the fifties and the sixties in Ghor Kibd and Ghor Nimrin, around and south of Shuneh village.

Table 2
Distribution of irrigated areas according to villages

Village	Dunums
Adasiya	3717
Sukhour al-Ghor and Baqura	15455
Ghor Arbian (Qlie'at, Hamra, Bseileh Harawyeh, Jurum, Rassieh, Auja Shamalieh and Auja Janoubieh)	28864
Ghor Fara	8000
Ghor Wahadneh	11700
Ghor Balawneh	7000
Ghor Abu Ubeida (Deir Allah, Twal, Damia and Shiqaq)	62416
Ghor Nimrin	21760
Ghor Kafrain	22355
Ghor Rama	21112
Sweimeh	5638
Total East Ghor	208017
Fara'a	14652
Fassayel	2000
Auja	15000
Nuweimeh	5000
Dyouk	3000
Total West Ghor	39652

Deep groundwater wells dug during the seventies and eighties by the Jordan Valley Authority allowed larger areas to be irrigated by wells in Wadi Araba and in the north; Mukhaibeh supplied larger quantities of water to meet the increased demand caused by expansion and high cropping intensities. The irrigated areas in the valley are shown in Table 3.

Irrigation in the highlands

Irrigation in the highlands of Jordan is dependent mainly on groundwater resources. Wells 100-500 metres deep are drilled, and pumps are used to deliver water to agricultural land. There are three types of irrigated-farming entities in the highlands:

- Private holders who have received loans from the ACC for drilling, pumps and farm irrigation systems.
- Bedouin-settlement irrigation projects operated and maintained by the Ministry of Agriculture and the Water Authority.

Table 3
Irrigated areas in the Jordan Valley

Project	Dunum
King Abdullah Canal	122000
Extension, 8 km	14000
Extension, 18 km	36500
Zarka Triangle	15000
Northeast Ghor	17600
Wadi al-Arab	3900
Extension, 14.5 km	60000
Middle Ghor	7000
Hisban - Kafrain	15600
Total	291600
Southern Ghors	47000
Wadi Araba	2000
Grand Total	340600

- Companies operating large projects in the southeast of the country.

According to 1989 records, the irrigated highland areas dependent upon groundwater supply amounted to 295,000 dunums.

Expected irrigated areas up to the year 2010

Water demand in Jordan is increasing dramatically for all purposes (domestic, industrial and irrigation), due to intensive economic and social development and an increase in population due to forced immigration and very high birth rates.

To overcome these shortages and meet water requirements, Jordan is advised to do the following:

- Develop all water resources in Jordan, including the Unity Dam, Mujib Basin, Karameh Dam, and others.
- Implement water management programs to increase the irrigation efficiency on farms from 63% to 80%, and to increase overall irrigation efficiency from 60% to 70%.
- Establish a supervision and control program for groundwater resources and to prevent the mining of basins.
- Make expenditures for development, operation and maintenance of water resources a top priority.
- Use sewage treatment plant effluent for irrigation, and utilize the fresh water now used in irrigation for domestic purposes.

If these measures are taken into consideration, the total irrigated land and the water requirements in Jordan during the next two decades are expected to be as follows (Table 4):

Table 4
Irrigated areas in Jordan and their water requirements until the year 2010

Source of water	Area	Irrigated areas and yearly water requirements									
		1989		1995		2000		2005		2010	
		Dunums	MCM/yr	Dunums	MCM/yr	Dunums	MCM/yr	Dunums	MCM/yr	Dunums	MCM/yr
Surface water	Jordan Valley	228280	370	288000	338	310000	370	350000	419	360000	425
	Southern Ghors	47000	44	47000	44	85000	79	85000	79	85000	79
	Side wadi banks	15000	10	15000	10	20000	12	20000	12	25000	15
	Total	290280	324	350000	392	415000	461	455000	510	470000	519
Groundwater	Jordan Valley	20000	20	-	-	-	-	-	-	-	-
	Highlands	245000	170	245000	170	250000	175	250000	175	250000	175
	Disi-Mudawwara	50000	37	55000	40	55000	43	60000	43	60000	45
	Wadi Araba	2000	neg.	5000	5	10000	10	10000	10	15000	15
	Total	315250	227	305000	215	315000	228	320000	230	325000	235
	Grand Total	605480	651	655000	607	730000	689	775000	740	795000	754

3

Some aspects of modern alternatives and principles of water resources use

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Introduction

In spring 1991, crops in the Jordan Valley were severely damaged by polluted irrigation water, the cost of which was calculated to be JD 60 million. The most severe damages were south of the Zarka River mouth, and were therefore likely caused by King Talal Dam water, most of which comes from the Khirbet al-Samra treatment plant.

The other source of Jordan Valley irrigation water is the Yarmouk River; the Jordan River is too saline, due to the inputs of brine and irrigation return flows (drained water). In times of low Yarmouk River discharge, there is not enough water in the East Ghor Canal to reach the southern part of the valley and enable it to mix with the dam water, to reduce both the salinity and the concentration of toxic compounds.

After three successive dry years in the region, there is a critical shortage of groundwater and river water containing relatively low total dissolved solids, and an increase in treated wastewater in the King Talal Dam with high amounts of dissolved solids, heavy metals and toxic trace elements.

With increased irrigation needs in the valley -- and all over the country -- the situation described above is certain to reoccur with greater frequency.

General situation in arid and semi-arid regions

Jordan, like most arid and semi-arid areas, will continue to suffer from an increasingly critical water shortage, due to a regional hydrogeological situation characterized by low amounts of precipitation and high intensity of evaporation. Jordan, as a case in point, also suffers from a high rate of population growth. Agricultural and industrial needs are also increasing rapidly, and the continual upgrading in the living standard results in increased demand for water.

In Germany, about 1000 m^3 of the generated water is available annually per capita as runoff water, but only 50-100 m^3 is used. The water balance in Jordan shows that the total runoff (the difference between precipitation and real evapotranspiration) may be as high as 350 MCM, including input from Jordan's share of Yarmouk River water. The per capita demand in Jordan, excluding irrigation, is at least 40 m^3 a year; the 3.5 million people in Jordan may annually consume nearly 200 MCM -- all of the water that is recharged in the country without the Yarmouk water. The remaining 150 MCM supplied by the Yarmouk River is insufficient for irrigation purposes. The amount of irrigation water increases year after year and has now reached 500 MCM, equal to 150 m^3 annual, per capita use. Four hundred MCM/year of effluent water is generated by the hydrological cycle, while 50 MCM/year comes from waste water. Total annual consumption can be estimated at 650 MCM; the surplus of up to 200 MCM is currently being extracted from groundwater storage, including the Disi aquifer.

In such a context, better planning and management are crucial; better tools for assessing water resources are needed, however, to provide for optimum planning and management designs.

Water resources engineering, especially in arid and semi-arid regions, requires knowledge of the water balance and corresponding water use; overdevelopment of water resources could have catastrophic results and cause irreversible damage. Therefore, the management of watersheds and the safeguarding of water supplies from pollution should become top priorities. Groundwater modelling techniques provide for the most efficient utilization of water and allow developing countries to optimize their resources.

Some current aspects of water use are discussed in the following paragraphs.

Water quality

Discussion of water quantity is incomplete without reference to its quality; by the year 2000 about one half of the natural renewable fresh water will be used for human consumption, so this aspect becomes increasingly relevant. Water quality is determined by the natural environment and human activity. Requirements vary according to water-use purposes. Drinking water, for example,

requires certain dissolved inorganic compounds within a specified range and the total absence of organic, suspended and biological materials. About 80% of all disease in developing countries is related to either lack of water or poor water quality and sanitation. *Guidelines for Drinking Water Quality* (WHO, 1984) documents the microbiological, biological, chemical, physical and radioactive aspects of demands on this resource.

The total worldwide irrigated area in 1970 was 234 million ha (16% of the cultivated land); this figure will increase to 300 million ha by the year 2000. In addition to conventional techniques (open-channel irrigation), innovations like trickle irrigation and centre-pivot systems are used more and more. Regardless of the system used, good drainage is required to prevent a build-up of salts in the soil and subsequent plant damage. Depending on the irrigation system used, the climate, the soil characteristics and the crop to be produced, different water qualities and quantities are required. Between 2,000 and 18,000 m^3 per ha are consumed, with a total electrical conductivity range of about 200 to 20,000 μs/cm (Fig. 1); the "200" figure corresponds to 15,000 mg/l dissolved solids (mean sea water has 35,000 mg/l).

Poor water quality

Poor-quality water should be used for industrial and sanitation purposes--and even for the irrigation of certain plants (Fig. 1) -- so that fresh water can be

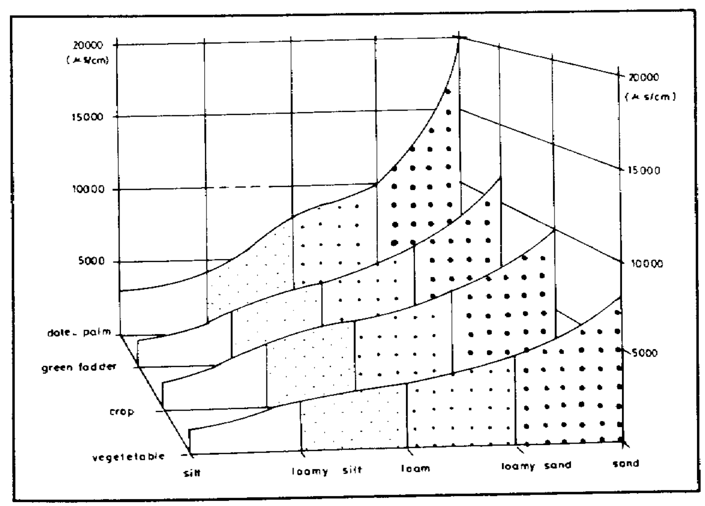

Figure 1. Required irrigation-water mineralization in relation to soil types and different plants.

saved for drinking. Sanitation water utilization in highly developed countries amounts to 70% of domestic water use and has the same characteristics as drinking water; usually, however, the quality requirements for sanitation water are lower. Where there is a water shortage, a differentiation between drinking and sanitation water is necessary, but a double-pipe water system is prohibitively expensive; nor is there any guarantee that people will not be consuming poor-quality drinking water so that governments or water utility companies can save money. It is possible to save water for domestic supply by using appropriate technology (Pickford, 1983). The lower limit for domestic water consumption in modern urban areas is about 100 litres per capita per day (L/C/D) without any industry or irrigation.

Saline water

Saline water is the only water-supply source in some arid regions. Sea water is mainly used as the feed water for desalination plants and, as such, technically has no upper limit. However, since current desalination technology relies almost exclusively on the use of fossil energy, the costs of developing this source are potentially very high and unpredictable. In addition, the availability of this source is equal only to the capacities of the processing plants. In this context, the use of solar energy for desalination is highly recommended; such stations could be set up in the southern part of the Jordan Rift Valley and the coastal area of Aqaba, where temperatures range from 35-50°C during the summer season.

Loss reduction

Up to 50% of water can be lost during distribution, but this is "only" a technical and financial problem. More serious are the natural losses occurring in various phases of the hydrological cycle; these can be reduced, but they require the expertise of hydrologists and engineers. Precipitation in Jordan ranges from 50 to 650 mm/year and is characterized by large variability, high intensity, and long periods between rainfall occurrences. These dynamics cause high surface run-off and floods. Collecting wadi flood water could increase the supply considerably, while capturing and storing/recharging excess surface water might also offer an additional amount. An example of this is the use of Yarmouk River water in winter for recharging the Amman - Wadi as-Sir aquifer system in areas where the aquifer is being overpumped -- as in Mukhaibeh and Wadi al-Arab (El-Naser, in preparation). The interception of subsurface springs in some places may also be useful.

Due to high reservoir evaporation rates, subsurface storage should be favoured. Subsurface water harvesting requires both an exploitable aquifer and a proper infiltration technique. Aquifers of fractured sandstone, fractured and karstic limestone, and Quaternary gravels can be used. The infiltration can be done by either injection wells, through flood-spreading within small catchment areas, or by diverting wadi floods into basins, which allows for more rapid infiltration.

Wastewater

Treated wastewater is becoming an increasingly appreciated resource. Wastewater reuse has been particularly common in agriculture, where quality considerations are less vital. Making wastewater suitable for human consumption involves a rigorous chemical, physical and biological process. This conversion requires high standards of quality control and advanced treatment techniques, some of which are not yet available or attainable in developing countries. Costs are high -- often more expensive than desalinizing sea water. Despite these drawbacks, the reuse of treated wastewater is a viable prospect for the near future. Different reuse needs determine the type of treatment required. Apart from its use for irrigation and industry, artificial groundwater recharge of certain aquifers seems to be a reasonable application, to prevent exhausting fresh-water resources. The biggest expense in wastewater reuse is the construction of a sewage system, which is nevertheless necessary to prevent groundwater contamination, especially within regions of highly permeable limestone.

Fossil groundwater

As most of the fossil water used today is derived from stored resources deposited in much earlier times, it has little or no relation to the current hydrological cycle. It is therefore not an "available" resource from a long-term-planning point of view. For management purposes, its availability is O MCM/year, although temporary and limited withdrawals are possible.

Irrigation projects require the withdrawal of nonrenewable groundwater; this causes a drop in the water table, which in turn increases production costs and reduces the quality of the exploitable water. Such projects will break down when the water reservoir is exhausted, leaving behind salty soils and man-made deserts. The importance of a good irrigation and drainage system can not be overstressed. For many years, a number of irrigated areas have suffered from over-saturation and soil salinity due to improper management of irrigation and drainage (20 million ha worldwide) (Merkel et al., 1985). Long-term irrigation can be managed only where there is a surplus of water with respect to the evaporation rate and a functional drainage system, or by the use of water with very low mineral concentrations (e.g., rainwater). Minimizing the water quantity (drip or subsurface irrigation) is effective, but allows the consumption of higher salt contents, so that annual or periodic outwash of the accumulated salts is required.

Future irrigation projects should be planned carefully, taking into account hydrogeological, hydrochemical, agricultural and economic aspects to ensure a long-term supply and the amortization of the investment. If a skilled expert is not available to supervise the entire project, irrigation programs should not be implemented at all.

If possible, pre-treated wastewater should generally be used in agriculture instead of groundwater; special treatment of wastewater is needed to prevent faecal and toxic (fertilizer and pesticide) contamination. Greenhouse farming appears to strike a reasonable balance between economic and ecological demands; more use could be made of the abundant solar energy for either cooling greenhouses or irrigation-water pumping.

Water preservation and protection

Water preservation and protection can be accomplished at the exploitation, distribution or utilization stages, as well as during recycling and storage. Water resources should be tapped as closely as possible to the area of discharge to prevent water loss by evapotranspiration or contamination. The construction, maintenance and usage of well installations are of great importance, requiring a trained staff and an educated population.

Water losses -- especially in large towns -- are high (up to more than 50%). Short circuits between water pipes and the sewage system are proven sources of disease transmission, so preventing water leakage from municipal systems is an important issue to address. Moyer et al. (1983) have demonstrated that the benefits outweigh the costs in such an undertaking. Groundwater, surface water and recharge areas used for domestic water supply must be legally safeguarded in protection zones. The development and management of water resources should occur within the framework of water rights found in existing legislation. The question of water price is a political one; higher prices might possibly discourage consumers from using water wastefully.

Computer-aided water resources management

Advanced computer techniques encourage the most efficient utilization of water resources and are particularly useful in arid and semi-arid developing countries where resource optimization is vital. Extensive and careful feasibility studies, supported by computer methods such as groundwater modelling, have to be done prior to plans for exploitation and the construction of water withdrawal facilities, to prevent irreversible changes in the system's natural equilibrium which could lead to the depletion of groundwater resources and drastic changes in groundwater quality.

Case study: north-northeast of Mafraq

Groundwater modelling techniques. The present abstraction rates from the Amman - Wadi as-Sir aquifer system (B_2-A_7) to the north-northeast of Mafraq (Fig. 2) have been tested, as part of a quasi three-dimensional groundwater modelling of the deep aquifers in the northern part of Jordan (El-Naser, in preparation). The computer code "MODFLOW" (McDonald and Harbaugh, 1988) has been applied.

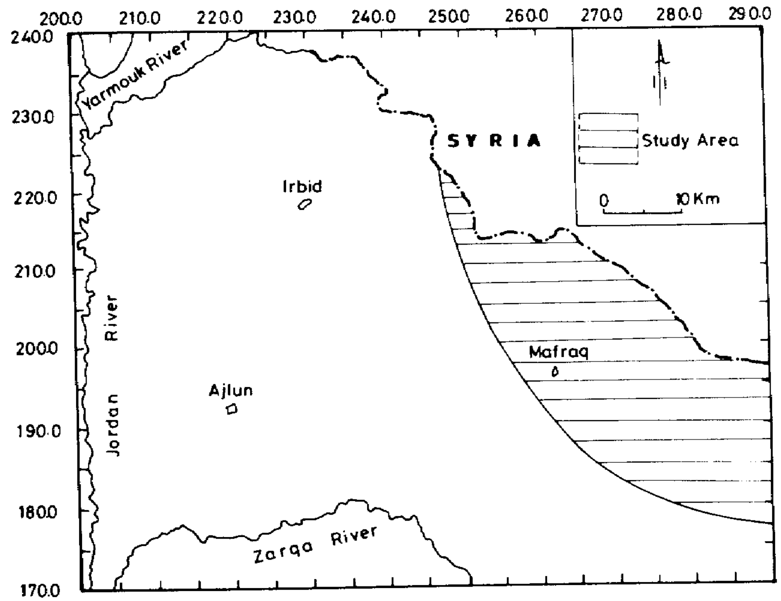

Figure 2. Location map of the study area.

Boundary conditions. The north-northeastern boundaries are essentially recharge areas (as subsurface flow) where the hydraulic head is known, and have therefore been treated as constant-head boundaries. The area south of Mafraq city is a groundwater divide, so it is assumed to be a no-flow boundary. The Ajlun region is treated as a constant-head boundary. In order to allow outflow from the confined section of the aquifer along the Jordan Rift Valley, these boundaries are assumed to be constant-head. All the constant-head boundaries are changed in the nonsteady-state to boundaries of constant-flux of non-zero, because constant-head boundaries may introduce a large amount of water to the aquifer when in a nonsteady-state (Rushton, 1977). The average areal infiltration -- 1.8 E-10 $m^3/s/m^2$ (Salem, 1984) -- which is equal to 4% of the total precipitation (150 mm/year), is added to the top layers of the aquifer.

Steady-state calibration. The calibration principle consists of simultaneously adjusting the permeability values of the aquifer against the subsurface recharge values.

- **Reproducing the 1970 situation.** The objective of calibrating in the steady-state was to reproduce the 1970 situation using the static water-level values before that year, and the corresponding subsurface flow amounts from the different sides -- exclusively, the areas where no data was available. Figure 3 shows both the simulated and the measured water levels.

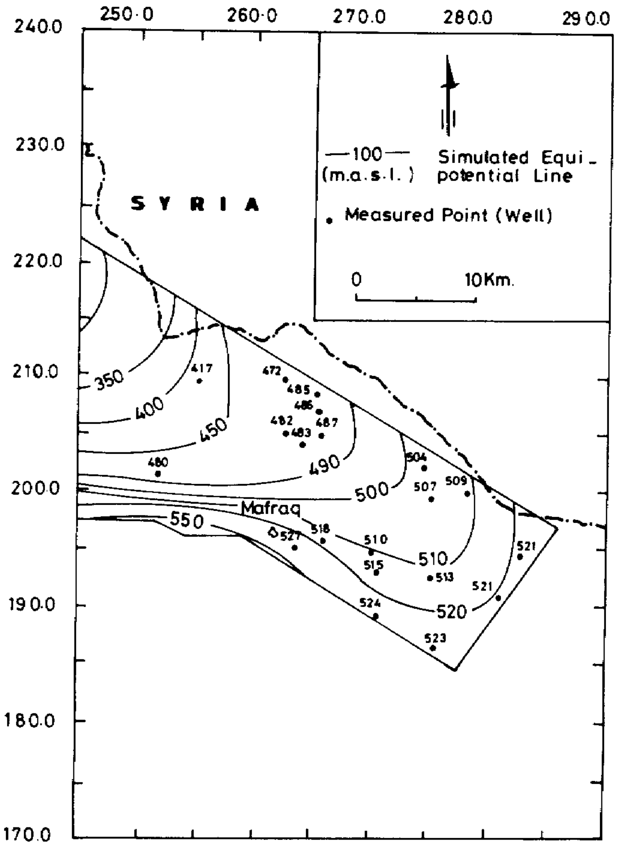

Figure 3. Simulated equipotential lines and measured points of the B_2 - A_7 aquifer.

Having established the conditions in 1970, where the horizontal permeability was adjusted against the subsurface inflow to the aquifer system, one can calculate the corresponding amount of subsurface inflow from different sides of the aquifer:

- Inflow from the northern boundaries of the modelled area (Syrian side) is calulated to be around 17 MCM/year.
- Inflow from the eastern boundaries is calculated to be 0.079 MCM/year.

Effect of the present abstractions. In the nonsteady-state runs, the storage coefficient of the aquifer is the most important parameter, due to the sensitivity of the model to this parameter. The storage coefficient of this section -- a range of one to three percent -- is well-known because of the many pump-test analyses carried out by Woshah (1979); the storage coefficient of that section should therefore not be calibrated, due to the availability of the analytical data.

Measuring the effect of the present abstraction rates on the health of the aquifer was one of the main objectives of the finished model. According to the Water Authority of Jordan (WAJ) files, approximately 25 MCM/year is being pumped for the governmental and private sectors (measured and estimated).

For comparison purposes, it was deemed necessary to test the present abstraction rates (25 MCM/year) over three time periods: 10 years, 20 years and 30 years (Figs. 4, 5 and 6). The year 1984/85 represents the overpumping point, so the three periods represent the years 1994/95, 2004/05 and 2014/15. It was clearly indicated that this area has been highly overpumped, which has thrown the aquifer out of balance; damage to the aquifer might result if the same rate is maintained.

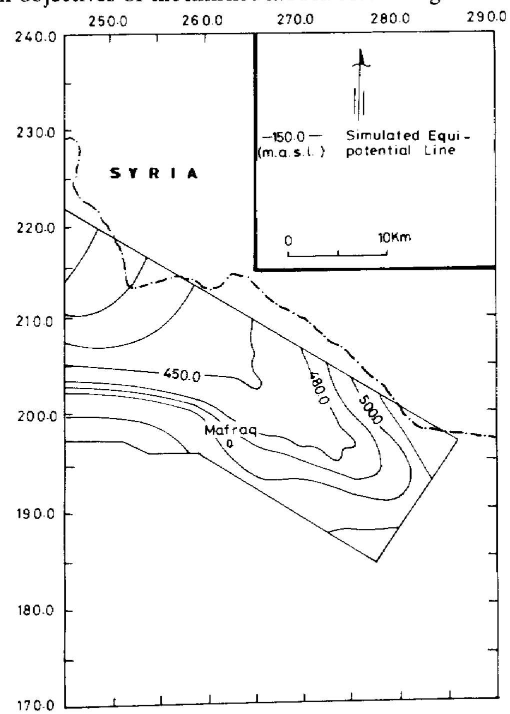

Figure 4. Simulation of the B_2-A_7 aquifer after 10 years (present abstraction).

After careful consideration of the previously discussed recharge mechanism, the results of the simulated model were seen to indicate increasing risk from north to south in that area with time, as shown by the dotted lines of figures 5 and 6. The area delineated by the dotted lines goes dry (inoperative) during that period, which means that maximum drawdown has been reached. In addition, the same figures show that the general flow direction of this area will be reversed from NE-W to NW-E; this will affect the recharge mechanism of the other parts of the aquifer.

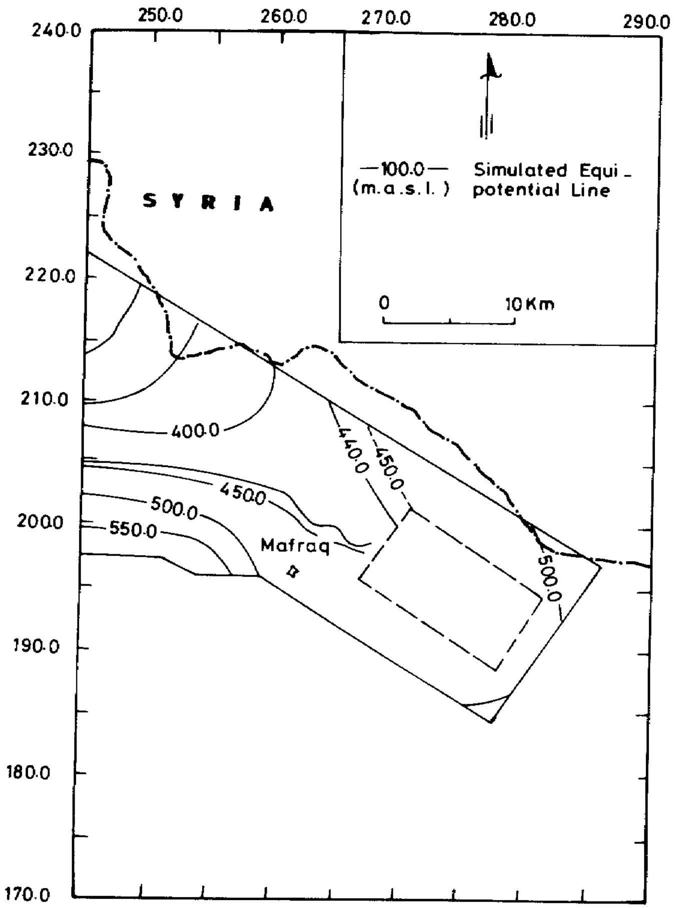

Figure 5. Simulation of the B_2 - A_7 aquifer after 20 years (present abstraction).

The above example demonstrates the importance of computer techniques in predicting the future conditions of the aquifers, especially if the groundwater system is at risk or is highly overpumped. An optimal water yield could also be simulated, to prevent such problems. Such techniques can give decision-makers warning signals, allowing them to make suitable decisions. If detrimental practices continue, the aquifer will be damaged either by saline-water intrusions or by depletion of water stores, reducing one of our most vital resources.

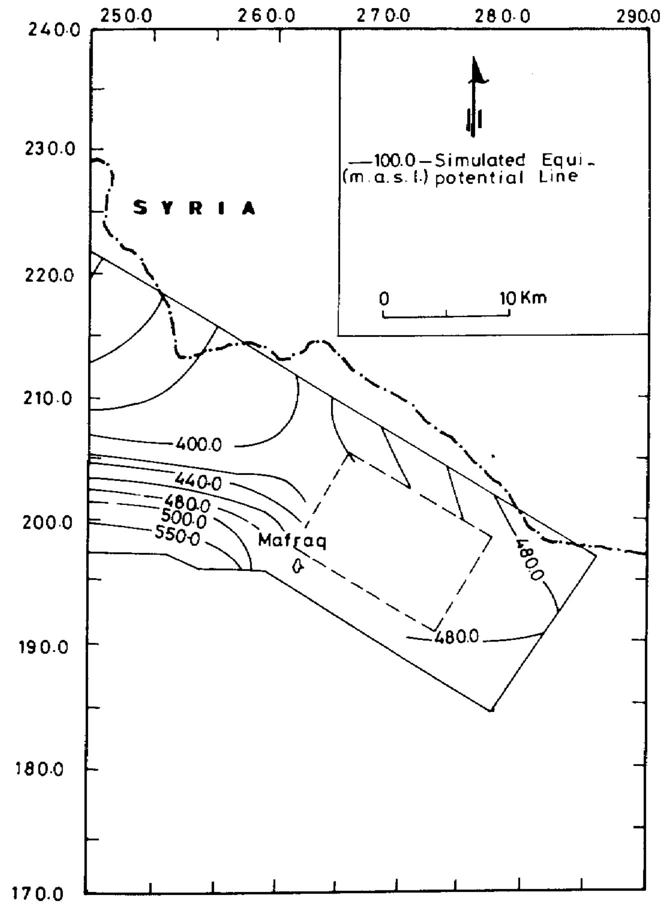

Figure 6. Simulation of the B_2 - A_7 aquifer after 30 years (present abstraction).

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4

Deep aquifers and the impact of their exploitation

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Introduction

The difficulties of deep-aquifer exploitation, with special reference to arid areas, are discussed below in the context of proper hydrogeological definition.

Any impact of deep aquifer development or exploitation may be considered in two ways -- first, by assessment of impact before exploitation and second, by remediation of impact during exploitation. Recourse to remedial measures can prove financially disastrous, so the preferred path is sensible impact assessment from the start with constant upgrading as abstraction progresses.

The problems commence with the cost of assessing relatively remote target aquifers and the initial reliance, therefore, upon relatively limited point sources of data. Because of the frequent sparsity of data, expensive subsurface techniques taken from the oil industry are often employed.

As most deep aquifers are multi-layered systems, development responses are controlled by a multitude of interrelated parameters; assessment following investigation work can therefore only be taken as a general guide to both resource and impact evaluation. Staged exploitation with careful monitoring and re-evaluation of responses and forecasting is recommended.

In the discussion below, emphasis is placed upon good hydrogeological techniques to obtain deep aquifer definition, and some of the more likely impact problems are described as well.

Aquifer definition

The study of deep aquifers is usually connected to oil exploration, and is expensive. Procedures are reasonably standard, involving a combination of regional geophysics and deep drilling.

Aeromagnetics and surface seismic techniques normally provide good base data but must be controlled with structure-hole drilling. Electrical techniques such as dipole-dipole can prove misleading, while gravity interpretations often lack definition, particularly in multi-layered systems. In regional systems where Precambrian rocks form the lower boundary, geophysical definition of the basement rocks is frequently thwarted by the presence of weathered zones.

Geophysical studies are essential for defining regions and recognizing structural discontinuities; however, the main data source for deep aquifers is the drilling record, combining both geological and aquifer characteristic data. Because of costs, much of the drilling is open-hole with returns of cuttings rather than core, although coring is essential at major lithological breaks and should be carried out as much as possible within the cost constraints. Clearly, both cuttings and core require very comprehensive descriptions (Fig. 1) and study.

For proper definition, multiple geophysical logging is required (Table 1). Such logging is directed at the primary features of the strata, but it is important to recognize the presence of fracture zones and possible faulting, particularly in the older rock types. To this end, cores are valuable -- together with fracture logging (Fig. 1) -- and formation microscanning images are now being used.

In many sequences -- notably in the large regional sedimentary basins -- the mode of deposition through geological time has been repetitious, so that similar lithologies occur in geological strata of differing ages. Straight lithological descriptions can therefore prove misleading and need to be substantiated with petrological and micropalaeontological/palanological studies.

Quite obviously, without good definition of the geological framework, the aquifer cannot be assessed and the impact of its utilization cannot be determined.

Groundwater resources assessment

Drilling

Proper drilling technique is the essential factor in any assessment. For reliable results, it is important that the drilling method:

- reach the required depths at the required hole diameter.
- provide good returns and maintain hole stability.

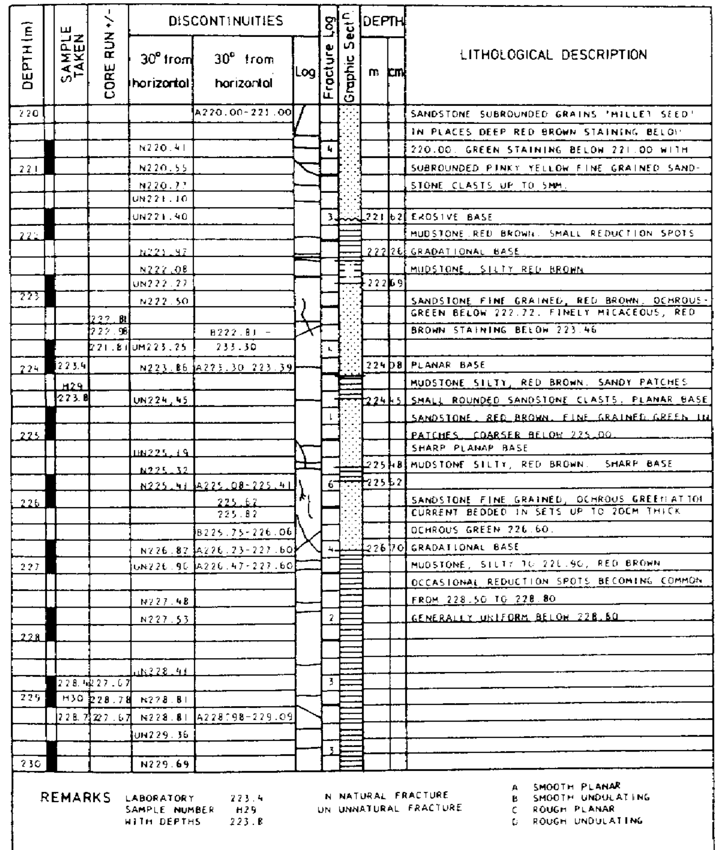


Figure 1. Detail of lithological and fracture-core-log description.

- not contaminate the aquifer, or reduce permeability.

To these ends, recourse is now frequently taken to reverse circulation drilling or to use aerated water or foam-on-air direct-circulation drilling. The use of bentonite muds is restricted as much as is feasible; biodegradable muds are preferred, if suitable or necessary.

Aquifer characteristics

The determination of any aquifer's characteristics is an enigma, but this is perhaps even more accentuated in deep aquifers. Standard pumping-test

Table 1
Borehole geophysical techniques

Log type	Brief description and main application
Caliper (one-arm, four-arm)	Measures borehole roughness and rugosity -- symptomatic of lithology and strength. Stress directions computed from orientated four-arm (break-out log).
Verticality	Verticality measured by gyroscope accelerometers or a combination of a compass and a pendulum or strain gauge. Determines position of borehole.
Temperature	Sonde measures heat transfer between strata and mud column to assess temperature gradient, etc. Important log for the determination of ice-wall design and mining environment.
Spontaneous potential	Recording made with reference to earth electrode at ground level. Detects mudstone against sandstone boundaries.
Focused electric	A point-resistance electrode with two extra guard electrodes to focus the direct current into the formation: improves penetration and resolution.
Microlaterolog	A pad-mounted FE tool with high resolution to assess salinity changes due to mud invasion. Very useful tool for measuring water quality and assessing possible zones of porosity and permeability.
Dipmeter	Computed correlation log using three, four or six microlaterolog traces gives values of local dip, fault hade, etc. Computed logs include vertical fracture frequency, and break-out logs often run in conjunction with verticality tools.
Induction logs (deep induction, medium induction, shallow induction)	Coils housed in the body of the sonde induce detected alternating currents in the formation. Record gives formation conductivity for use in water-saturation calculations. Penetration of logs picks up changes in conductivity due to mud invasion. Very useful in assessing zones of porosity and permeability.
Gamma ray	Natural radioactivity from absorbed ions, usually related to clay mineral content. A lithology log least affected by caving.

continued ...

Log type	Brief description and main application
... continued	
Natural gamma	Larger detectors count number of gamma rays having energies corresponding to potassium, thorium and uranium. Cross plots allow determination of clay mineralogy and evaporites.
Density logs (long-spaced density, high-resolution density, bed-resolution density)	Tools have gamma source and gamma detector. Provide measure of electron density proportional to bulk density. Assumed matrix density allows direct display of porosity.
Neutron neutron	Tool provided with a fast neutron source and a slow neutron detector: provides a measure of light nuclear density; essentially, hydrogen content therefore relating to water content. Log can be calibrated, scaled and displayed as neutron porosity. Hydrogen index also taken for low-porosity rocks to indicate micro-fracture frequency. Computed RocTec Log calibrated in terms of rock strength.
Sonic log or sonic delta t	Travel time recorded in micro-seconds/unit length between transmitter and receivers.
Multi-channel sonic	Sonic tool with three or four receivers and transmitters, very good for caved holes. Interval velocity a function of rock strength and rock-matrix porosity. When sonic porosity is cross-plotted against neutron or density porosity (i.e. total) a measure of fracture porosity is possible.
Survey ref inverse multi-offset vertical seismic profile	String of geophones are extended along the surface and an energy source downhole. With one or more sources located away from the borehole, 3-D VSPs may be shot, giving position strike and dip of local faults, etc.

procedures can be carried out, with observation holes being essential. Constraints on interpretation and eventual development impact include the following:

- Full aquifer penetration is frequently too costly, so transmissivity determination from pumping tests can be questionable.
- Hydraulic layering is frequently a feature and is difficult to account for in testing.
- Regional specific yields are impossible to assess from pumping tests; only guide values may be determined.

The constraints are summarized in Figure 2.

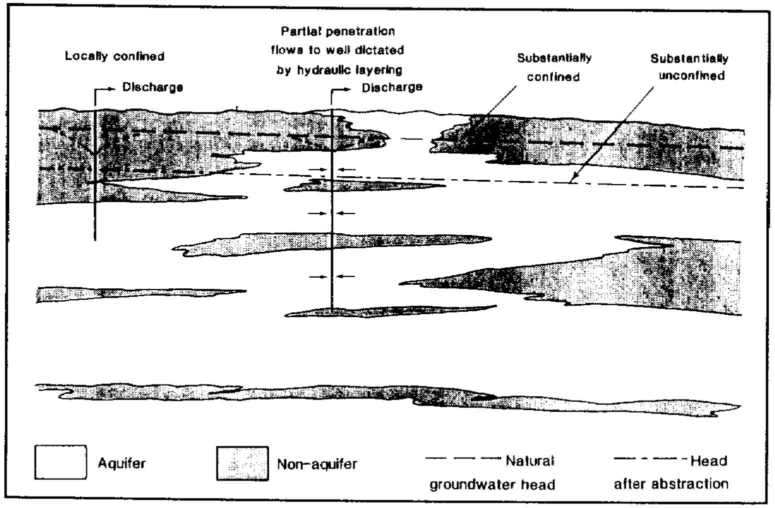


Figure 2. Summary of difficulties in determining aquifer parameters from pumping tests.

Table 2
Permeabilities (m day $^{-1}$)

Range	Average	Study date
2.05-1.35	1.80	1969
1.64-0.31	0.63	1977
2.40-0.30	1.50	1982[1]
2.00-0.30	1.50	1982
1.0-0.60	0.85	1985[2]
1.8-0.90	1.20	1988[2]
Saudi Arabia		
4.39-0.20	1.90	1985
1.65-0.46	1.00	1987

Source: Lloyd and Pim, 1990.
1 Core analyses -- all others from pumping-test interpretations.
2 Southern Jordan and Tabuk area of Saudi Arabia.

In deep aquifers, reliance is frequently placed upon oil investigation data in which drill-stem testing (DST) provides some indication of permeability for selected sections (Fig. 3). If available, DSTs help in understanding the hydraulic layering. Such data is useful but cannot replace conventional pumping tests, because although aquifer characteristics are of considerable importance, so are well yields.

For deep aquifers, it is normal to report permeability data rather than transmissivity, as the permeability has to be applied to a total thickness -- often not penetrated -- and in major schemes in unconfined aquifers, transmissivities may change significantly with time. Assessments will vary as data is accrued and upgraded; in Table 2 such an example is given of the Disi Formation data from Jordan and Saudi Arabia.

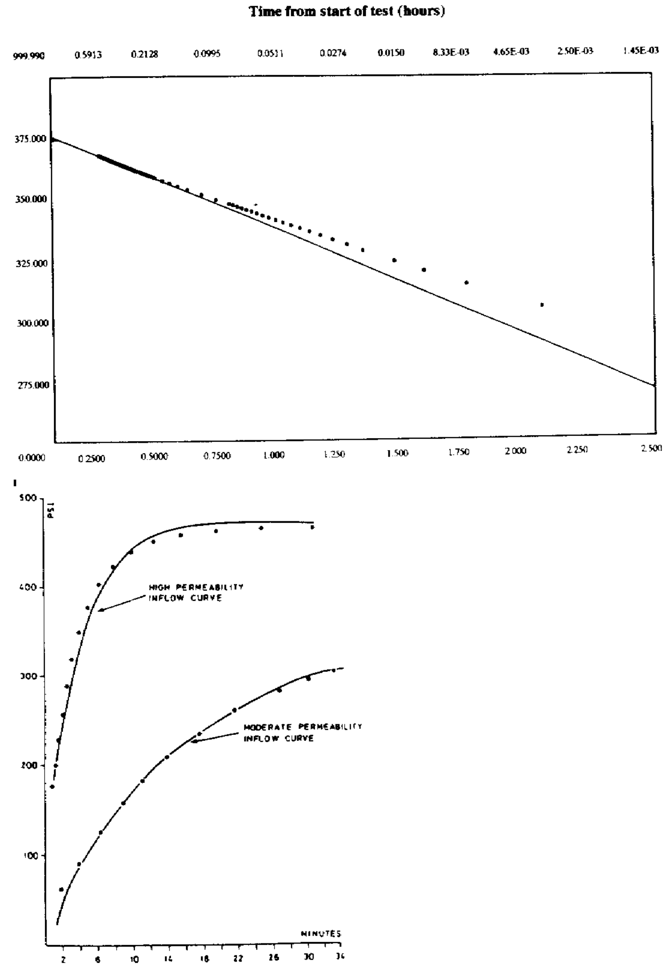


Figure 3. Permeability results from DST interpretation, Horner plot and radial flow model.

In multi-layered systems, vertical permeability is frequently important and can be partially examined in core samples or through piezometer tests. Aquiclude vertical permeability can have a large influence upon the transfer of groundwater between aquifers under abstraction, and therefore upon the impact of aquifer development; unfortunately, it can only be realistically assessed during aquifer development.

In unconfined systems, a similar problem exists with specific yield, which is the dominant aquifer characteristic in terms of major abstractions. For the Disi Formation aquifer, the range of specific yields determined are given in Table 3. Pumping tests tend to underestimate specific yield, and core analyses (Fig.4) overestimate the value. Interestingly, in Table 3 the 1987 value is from regional modelling of abstraction in Saudi Arabia.

Groundwater heads

Because of the problems related to aquifer recharge and discharge in arid zones, discussed below, groundwater head distribution is generally relied upon

Table 3
Aquifer storage data

Porosity Range (%)	Porosity Average (%)	Specific yield Range (%)	Specific yield Average (%)	Study date
-	-	5-0.2	2	1969
-	-	3-1	1.5	1977
23-17	20	16-1	8	1977[1]
-	18	14-8	10	1982[1]
-	-	-	11	1982
-	-	1-7	3.5	1985
-	-	-	7	1986
-	-	-	12.5	1987
-	-	3-7	5	1988

Source: Lloyd and Pim, 1990.
[1] Core analyses -- all others from pumping-test interpretations.

Table 4
Rates of evaporative losses from playa surfaces as groundwater discharge

Country	Method	Amount (mm/yr)
Saudi Arabia	Energy balance	700
Libya	Energy balance	500
Australia	Stable isotope + Cl-	170
Australia	Br- + Cl-	200
Australia	Lysimeter	120

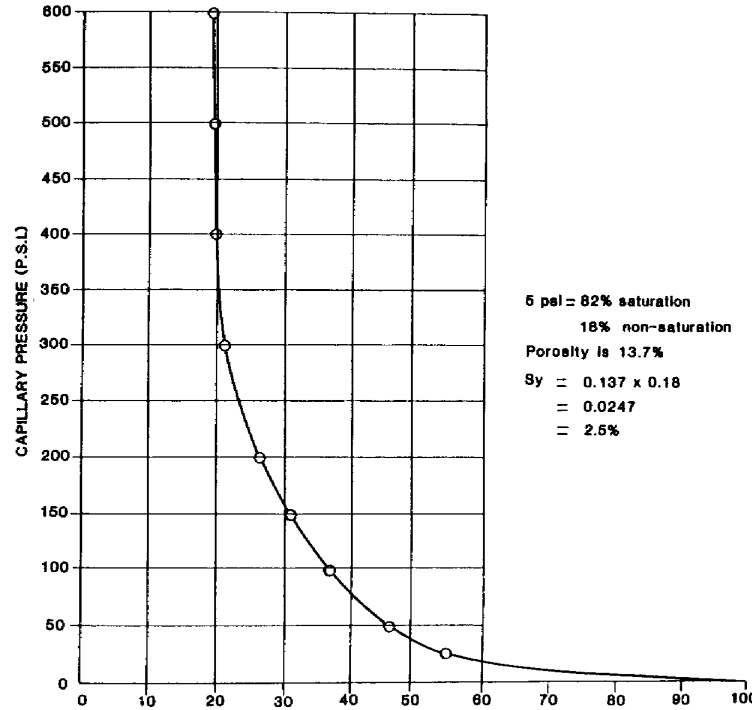


Figure 4. Determination of specific yield (Sy) from laboratory brine-saturation centrifuge testing. Subjective 5 psi used for natural drainage limit.

for aquifer-assessment modelling. Under proper drilling circumstances, these can usually be determined accurately, although in some cases the averaging effects of thick open-borehole saturated sections have to be treated with care. Direct reliance on oil exploration DST data is also dangerous, as head (formation pressure) is usually extrapolated. In some deep-aquifer studies, variations in head are now being examined using micro-formation pressure-testing techniques which are most appropriate in medium-permeability, primary-porosity materials.

Recharge and discharge

Much has been written about recharge in arid areas, and it is generally accepted that, although some intermittent recharge may occur, its assessment in regional terms through a surface hydrological study is virtually impossible (Lloyd, 1986).

Natural discharge is equally difficult to assess. In many aquifers, discharge is to the sea or to distant geological formations or structures which are virtually unknown. Where *sabkhas* or playas exist, careful examination is necessary because evaporation losses are undoubtedly far less than classical energy balances or Penman calculations imply (Table 4).

Because groundwater hydrograph data rarely show recharge instances in arid areas, the value of such long-term data is negated to some extent; but hydrographic data is essential to set a base, and in any abstraction phase. For any proper understanding of development impact, monitoring of abstraction discharge and head responses are vital.

Hydrochemistry

Hydrochemistry is clearly vital in terms of the eventual use of the water, but in deep aquifers two additional features -- usually more important here than in shallow aquifers -- are quality distribution and corrosion/incrustation.

A major potential impact of deep aquifer development, particularly in multi-layered systems, is the drawing-in of poor-quality water. Hydrochemical definition in three dimensions is therefore important, and data should be obtained in strata below the target aquifer in case upward vertical leakage of poor-quality water ingresses. The use of conductivity-temperature logging is invaluable in this type of work (Fig. 5).

Corrosion/incrustation problems frequently pose considerable problems because many groundwaters have moved to significant depths in the systems; and because of hydraulic layering and other such features, variations in groundwater chemistry may result in precipitation effects when mixing occurs up the open section of a well.

Of particular importance in corrosion are the degassing effects of CO_2, and the generation of H_2S, normally by sulphate-reducing bacteria. While hydrochemical studies can provide invaluable indications of corrosion/incrustation potential, recourse is usually made to corrators in deep-well studies (Fig. 6) so that bulk effects can be assessed.

The recognition of any corrosion/incrustation problems is essential as the cost repercussions can be enormous, both in terms of abstraction-well design (Fig. 7) and the distribution system.

Resources assessment

For any major development and in order to understand its impact, the inevitable mathematical model is essential. The conventional procedures are applied, but a multi-layered model is usually required.

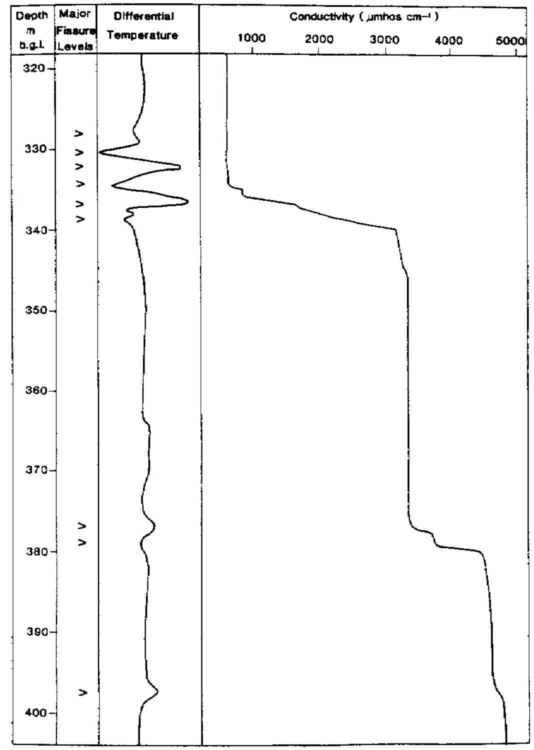


Figure 5. Conductivity-temperature log of deep limestone in Qatar showing palaeo-karst at top of aquifer.

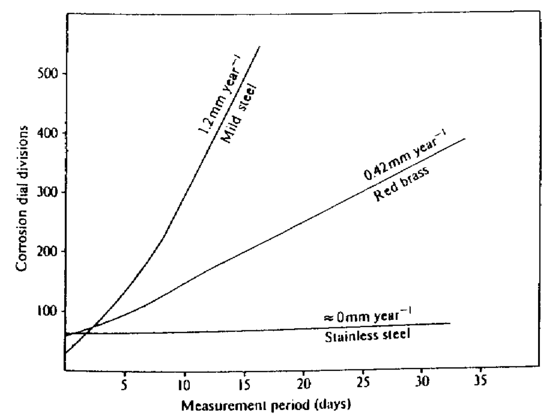


Figure 6. Corrator tests of various well materials from sandstone aquifer in North Africa.

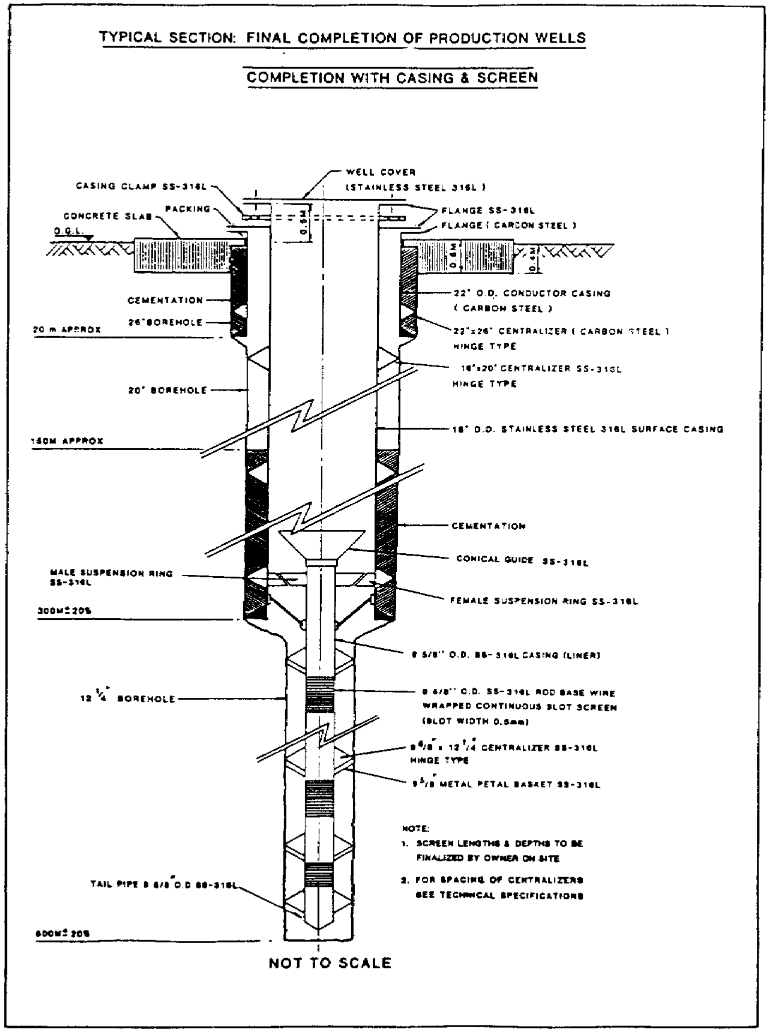


Figure 7. Example of a very expensive well design in a deep aquifer construction to offset corrosion.

In the example given in Figure 8, a finite-element model for a multiple-aquifer system in North Africa is shown. Automatic network-generation has been adopted so that the areas of main interest (potential well fields) have the smallest elemental areas. In many studies, an initial understanding of the system and the modelling requirements are established through a two-dimensional vertical-strip model (Fig. 9). Such models are very helpful in determining the simplification that can be made for the distributed models.

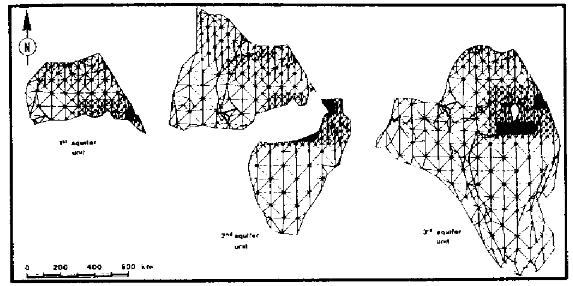
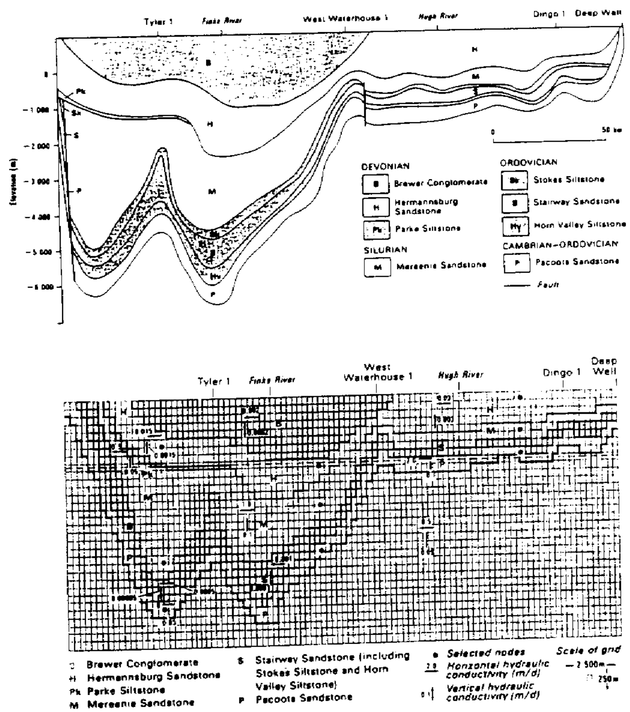


Figure 8. Network-generated finite-element model for triple-aquifer system in North Africa.



Source: Brown et al., 1990.

Figure 9. Two-dimensional vertical model of multi-aquifer system in the Amadeus Basin of central Australia.

Development impact

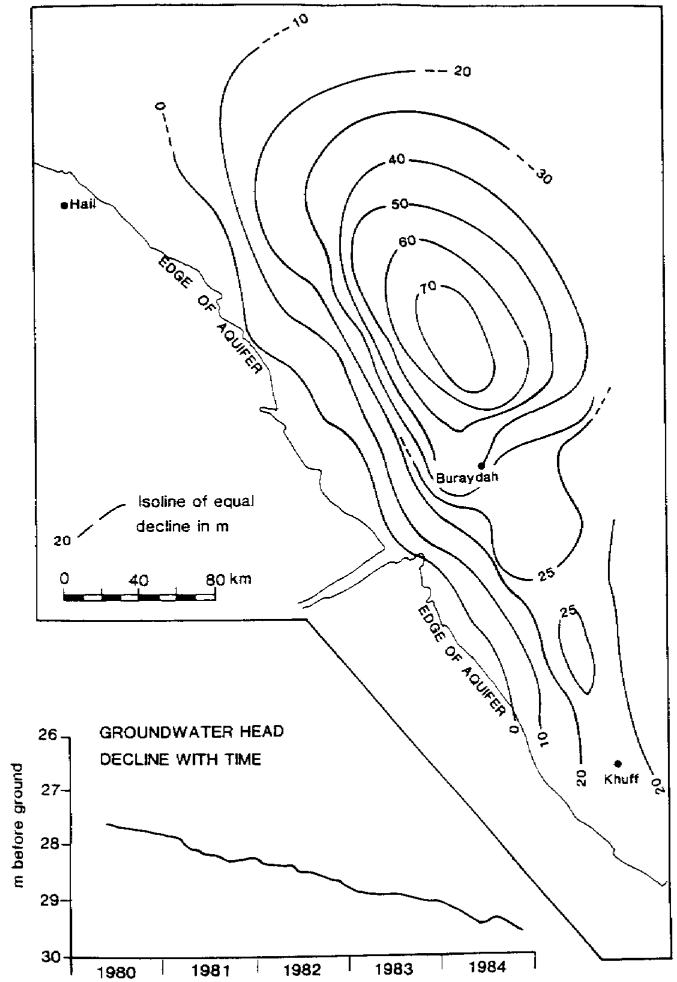
As noted above, a proper understanding of the aquifer geometry and the aquifer parameters, together with a good model representation, are prerequisites to any assessment of the developmental impact. Normally only major schemes will have an impact and clearly -- other than for small strategic supplies -- large quantities of groundwater need to be abstracted to make development effective.

In the absence of natural recharge or discharge in arid areas, model calibration is very difficult without abstraction. This often means that impact cannot be reliably assessed until some abstraction has taken place and the model has been "re-calibrated." For proper resources development in such areas, therefore, staged abstraction should be undertaken, although this might not necessarily be politically acceptable.

Groundwater abstraction in an arid area is a mining operation, so the main impact is in terms of drawdown and supply derogation. Regional cones of depression can develop and eventually sterilize the resources unless technological advances allow greater depths of groundwater withdrawal. An example of a major cone is shown in Figure 10 for northern Saudi Arabia. The cone has developed in a confined section of the aquifer which is clearly less suited to groundwater development than the unconfined section (Fig. 11). However, while groundwater considerations may point one way, water utilization may point another, and in the Saudi case the location of good irrigable land is a major factor.

The recognition of major cones of depression is readily understood, but more difficult is the assessment of the impact of a major development on juxtaposed aquifers. Because of the difficulties associated with multi-parameter systems, any modelling assessment can only be taken as a guide which inherently has greater error the smaller the drawdown forecast. Unfortunately, in many arid areas, the meagre natural vegetation is totally susceptible to small drawdown effects where shallow groundwater is the only water source. Two or three metres of drawdown can totally destroy an ancient oasis or desert flora and fauna habitat. Because of the possible far-reaching effects of major deep-aquifer development, small drawdown effects can occur at considerable distances from well fields. An additional problem is that many small desert supplies are obtained from shallow aquifers, so that derogation can occur and may only be offset by the implementation of expensive compensation supplies.

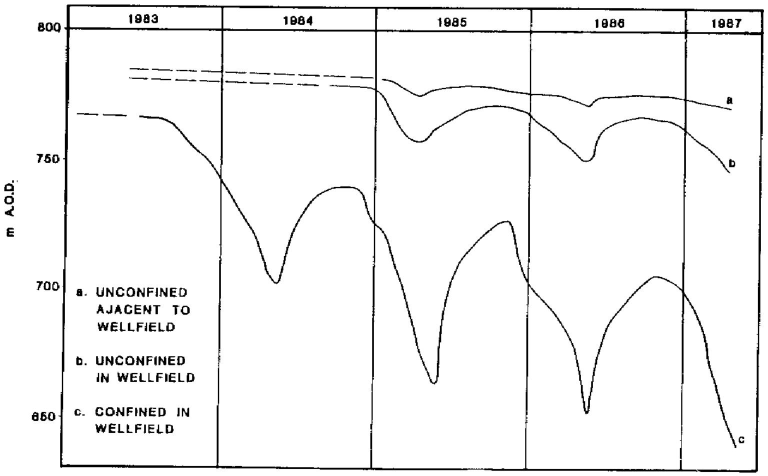
While deep-aquifer development of unconfined aquifers utilizing specific yield is preferred, deep-confined aquifers are frequently developed. When drilled, many such aquifers give rise to flowing artesian wells which can be difficult to seal and therefore flow to waste; an example from western Egypt is shown in Figure 12. Uncontrolled flows of this type unnecessarily draw down



Source: BRGM, 1985.
Figure 10. Development of a cone of depression in the Saq (Disi) aquifer in northern Saudi Arabia.

the aquifer -- eventually leading to the need for pump installation -- and also cause local ground deterioration through waterlogging and salination.

Figure 13 gives a regional example of uncontrolled flowing well abstraction from the Great Artesian Basin of Australia. Interestingly, drawdowns are still considered manageable there and recharge to the basin has increased with



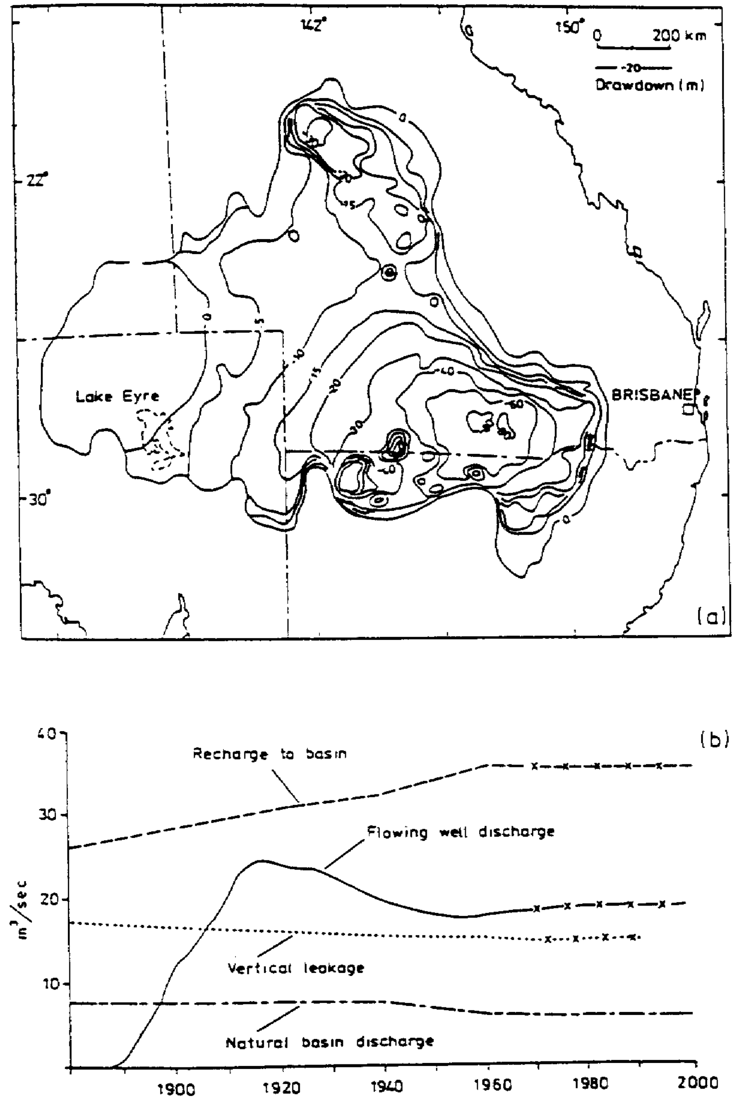
Source: Lloyd and Pim, 1990.
Figure 11. Hydrographs from the Saq (Disi) aquifer in northern Saudi Arabia showing differing impacts under differing aquifer conditions.

Groundwater abstraction		
	m^3/day	% free-flowing
1962	118,984	100
1980	215,320	43
Estimated 30% water wasted		
1980 total abstraction 39 MCM		
50-year projected abstraction 186 MCM		
(Drawdowns 90 m)		
Allocation		
1980 Irrigation 4,200 ha		Available 25,000 ha
Projected irrigation 7,000 ha		156 MCM/year
Phosphate		30 MCM/year

Source: Lloyd, 1990.
Figure 12. Details of abstraction and aquifer potential in the Kharga Oasis in the western desert of Egypt.

"abstraction." In groundwater terms, the latter feature appears attractive, but as the recharge is indirect -- from rivers crossing the aquifer outcrop margin -- the resultant decline in river flows has detrimentally affected river supplies for farming at the margin. The figure also illustrates the classical decline in flowing-well discharge, later influenced by more recharge.

Most major schemes based upon deep aquifers are used for irrigation-supply purposes and as a consequence introduce a considerable amount of



Source: Habermehl, 1980.
Figure 13. Details of drawdown due to flowing wells and the groundwater balance for the Great Artesian Basin, Australia.

water into areas probably largely devoid of water. The impact of the importation can be significant, not only for its intended purpose but also for ground drainage. For any major utilization, therefore, careful long-term planning is essential to offset groundwater-logging and salination by the creation of local water tables.

Perhaps some of the most dramatic impact features of deep-aquifer exploitation are seen in the poorly consolidated sediments that are susceptible to subsidence. Poland (1984) extensively catalogues examples and methods of assessment for subsidence, so all that needs to be mentioned here is that proper account should be taken of both well construction and surface-distribution lines.

Conclusions

Interest in the exploitation of deep aquifers is increasing with the growing need for water supplies in many countries. Deep reserves are considerable in such areas as North Africa and the Arabian Shield, but exploitation is expensive and the engineering/economic assessment of resources difficult. As a result, although likely impacts can be identified, it may be difficult to gauge the degree of impact of exploitation from initial investigation and interpretation. Staged development with comprehensive monitoring and frequent re-appraisal is therefore necessary.

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5

Meeting the needs of a growing population: scenario for 2000 and 2010

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Water demand in Jordan far exceeds supply; the gap is widening, and urgent measures must be taken in the near future. Before this subject is explored, however, it is deemed prudent to present a conceptual framework characterizing the water problems in Jordan and their related socio-economic impacts. This diagnosis of the overall water situation does not solve the problems, but it does serve to clarify them. Operational tools must be designed to provide feasible and acceptable solutions; however, identifying the components of the problems facing the water sector is a necessary first step toward developing the integrated and comprehensive solutions to be discussed later.

Table 1 identifies the major physical manifestations of the water resources problems in Jordan and presents both their consequences and a qualitative statement of their economic and social significance. The format follows largely from Bauer and Hufschmidt (1984). Inherent water supply-demand imbalances, if not alleviated, may very well prevent Jordan from ever realizing its full potential for socio-economic development.

To bridge the gap between supply and demand, two basic solutions are proposed: increasing supply, and decreasing demand by promoting greater efficiency and conservation -- all within an integrated, comprehensive planning and management framework. Though this is easier said than done, this chapter will present some options for consideration -- broadly classified as technical, managerial, pricing, and regulatory, as shown in Table 2.

Table 1
Characterization of water resources problems in terms of social and economic significance

Physical manifestation	Consequences	Economic and social significance
Semi-arid climate, low precipitation, high evaporation rates	Fluctuations in water supply, periodic droughts, naturally limited water resources base	Planning, development targets plagued with uncertainty
High population growth rate	Increased demand and competition for water, nonrenewable ground-water depletion, pollution	Reduced living standards, health problems
Conflicting demands	Inequitable allocations and subsidies, regional price structuring	Emergence of water lobbyists
Riparian conflicts	Critical supply augmentation projects cannot be undertaken.	Destabilizing to the economy
Absence of effective conservation programme	Water logging, environmental impacts, overall inefficiencies, losses	Decline in productivity
Financial constraints	Supply augmentation cannot meet demand requirements.	Increasing health problems, loss of productivity (chain reaction)
Lack of integrated water policy	Most of the above apply.	Low potential for social and economic development

Source: Bauer and Hufschmidt, 1984.

Before the aspects of each option are discussed, it should be mentioned that an integrated management framework, using the options shown in Table 2, is utilized in these proceedings (Abu-Taleb et al., 1991).

The fundamentals of such an integrated planning approach for Jordan are based upon (1) the national objectives of the country, (2) the available water sector options and strategies, and (3) the determination of which strategies contribute the most toward the national objectives at fixed investment levels. This planning approach could ultimately lead to the formulation of a comprehensive decision-support system (DSS), using multi-criteria analysis, to assist the Jordan government in improving the planning and management processes in the water sector.

Table 2
Options for an integrated management framework

Goals: increase supply and decrease demand		
Technical options	Conservation options	Managerial, pricing & regulatory options
Conventional:		
Abstraction from new and existing aquifers	Reduction of losses from municipal water-supply network	Modification of pricing policy using LRMC with adjustments
Surface- water dams	Reduction of losses from irrigation networks	Rationalization of growth rate
Regional projects	Drip irrigation	Annual volumetric allocations
Non-conventional or marginal:		
Irrigation with saline water	Evaporation minimization	Incentives for recycling
Desalination	Cultivation of plants using less water	Education
Recycling treated wastewater	Optimization of industrial-water consumption	Conservation subsidies
Rain-water harvesting	Adopting certain residential measures	Improving metering, billing and revenue collection
Cloud seeding	Changing pattern of consumption	Monitoring well extraction
	Prevention of pollution	Restructuring of MWI, JVA, WAJ
	Prevention of over-extraction	Training
		Privatization (i.e. networks, drilling operations)
		On-farm water management
		Optimization of cropping pattern

Technical options for increasing conventional water resources

Groundwater

Aquifers in the Disi/Mudawwara, Jafer and Hammad areas are prime fresh-water sources, able to supply an additional 80-100 MCM/year for 100 years; however, full utilization of these sources should be monitored to insure against salination and should be accompanied by reducing extraction from over-utilized aquifers.

Available information on the Hammad and al-Sarhan basins is very limited; plans are under way for an extensive exploration programme to determine their potential. The total available groundwater, then, is estimated at 400 MCM/year, including mined water.

Surface water

Following is a description of several resources which are not fully utilized.

Yarmouk River. Comprehensive development of Jordan's surface water resources is impeded by regional political considerations and related riparian issues, and exacerbated by the extreme scarcity of regional water resources.

The main surface water resources are: the Yarmouk River, flowing westward between Jordan and Syria to its confluence with the river Jordan south of Lake Tiberias; and the Jordan River, flowing outward from Lebanon through Israel, west of Syria, into Lake Tiberias, and on to the Dead Sea. With such geographical considerations, development plans for these rivers have involved all concerned riparians. Given the extreme scarcity of water resources in the region, the importance of developing acceptable resource-allocation strategies was recognized as early as the 1930s. Eleven plans pertaining to water use were prepared between 1939 and 1955; the Johnston Plan of 1955 was the last. (A formal agreement was, however, signed between Jordan and Syria in 1987, under which all Yarmouk water at elevations 250 metres above sea level would be at the disposal of Jordan.)

According to the Johnston Plan, all Yarmouk River water -- with an annual flow estimated at 377 MCM (Naff, 1991) -- was to be allocated to Jordan, except for 90 MCM for Syria. The residual water, estimated at 17 MCM/year, was to be used to irrigate the Yarmouk Triangle (Taubenblatt, 1986). In addition, 100 MCM/year was allocated to Jordan from the Upper Jordan River water.

The latest proposal regarding the al-Wehdah Dam project (a joint Jordanian-Syrian effort) would regulate less water than the previous proposal; a diversion weir and channel at Wadi Raqqad in Syrian territory (near Maqarin) -- permitting storage of an additional 48 MCM/year currently entering the Yarmouk downstream of the proposed dam and upstream of Adasiya -- is excluded from the present project. The storage dam upstream of Adasiya, which would have permitted efficient regulation of the entire flow of the Yarmouk water, was not constructed, and a diversion weir has not been built. Without these additional storage facilities, Jordan's share of Yarmouk water will remain less than envisaged under the Johnston Plan -- even if the al-Wehdah Dam project is taken into account.

Jordan Valley side wadis. One proposal involved constructing dams at Wadi al-Yabis and Wadi Kufranjeh, and raising Kafrain Dam, providing an additional 15 MCM. A feasibility study, however, revealed that only the Kafrain Dam project was viable (yielding an additional 6 MCM/year), while the other two dam projects were not (JVA).

Mujib Basin. This basin's total surface water amounts to about 59 MCM/year. Currently only about 6 MCM/year is used for local agriculture, while an additional 12 MCM/year is earmarked for pumping to Amman for municipal purposes. The remaining 38 MCM/year is available for various uses (JVA, WAJ). A comprehensive plan is needed for the prudent utilization of this source. A feasibility study is being prepared for the construction of two dams at Wala and Mujib, designed to harness flood flow.

Zarka, Ma'an and Zara. This source averages 20 MCM/year of mineralized water with a salt content of 2000 ppm (WAJ). A study should be carried out to utilize this source for irrigating salt-tolerant crops.

Importation of water from outside Jordan. There are water resources in the region which Jordan could exploit, though technical and financial feasibility studies -- as well as consideration of political issues -- would be necessary first steps. These resources are abundant and could be useful under certain conditions; examples include the Euphrates River and the Turkish Peace Project. An economic and technical feasibility study was conducted in 1980 on the waters of the Euphrates, and the cost was estimated at one Jordanian Dinar per cubic metre (Ministry of Planning).

Technical options for increasing non-conventional water rescources

Non-conventional water resources are seen as supplements to, and not substitutes for, conventional large-scale water supply and proper management.

Little is known about promising technologies for the use and conservation of scarce water supplies in arid areas. With further research and adaptation, some such technologies may prove to be less costly and more efficient than conventional methods of increasing water supply. Following are a number of options to increase non-conventional water resources.

Irrigation with saline water

Beneath many of the world's deserts are reserves of saline water; in addition, many surface water estuaries, coastal lagoons, land-locked lakes, and irrigation return flows contain fairly large amounts of salt. If saline water could be used for irrigation, more desert land could be cultivated; non-saline water now used in agriculture could then be released for human consumption, reducing the need for expensive desalination schemes now being considered for urban supply.

Although saline-water irrigation holds exciting possibilities for the future, it does not promise the conversion of vast stretches of arid land into cultivated fields. Many crops cannot tolerate it, and its indiscriminate use may severely damage the soil; furthermore, suitable soil, climate and water are not always found in the same location. Using saline water for irrigation requires sophisticated management; such detailed requirements are not fully understood, necessitating further careful investigation.

Treated wastewater

Using wastewater effluent for irrigation is becoming increasingly popular in several countries, especially in arid and semi-arid areas. There are several advantages to recycling human and animal wastes, especially when used for agriculture and aquaculture.

Uncontrolled wastewater irrigation practices, however, may have major detrimental effects on the health of both people who consume the irrigated crops, and farmers who are directly exposed to wastewater. Also, soil salinity could be gravely affected if the concentration of salts in the wastewater exceeds certain limits. Industrial wastewater should not be used for irrigation, as it may contain high trace-element and heavy-metal concentrations. If untreated wastewater is used in irrigation, then the major threat to human health comes from microbiological contamination.

Jordan is very conscious of the need to conserve its water resources, given its geography, climate and population pressure. Conservation measures include the recycling of wastewater, along with nutrient recovery to prevent eutrophication of receiving surface waters. Several studies dealing with wastewater reuse have been completed in different countries; however, more specific research is needed for the application of wastewater reuse in Jordan, as there is a great diversity in each country's social and cultural activities -- and therefore in their waste composition.

Treated wastewater quantities in 1989 were estimated at 44 MCM/year (WAJ); however, the quantity discharged to wadis and reservoirs -- where it was diluted then utilized for agriculture -- was reduced to an estimated 25 MCM/year, due to evaporation losses. This figure is expected to rise to about 75-100 MCM by the year 2000 (WAJ).

Rain-water harvesting

Rain-water harvesting can be defined as the utilization of rain water which has been collected through macro- and micro-catchments and from rooftops.

In macro-catchments, water over a large natural drainage area is made to collect in wadis, where small, low-cost dams are built and water is stored for future use in agriculture (utilizing runoff and supplementary irrigation methods), or for recharging groundwater aquifers.

In micro-catchments, rain water is collected in man-made reservoirs of suitable size and used to irrigate trees planted in the lower catchment area.

Because rainfall in arid lands is intermittent, storage is usually integral to any rain-water-harvesting system. When such techniques are used for runoff or farming, however, the water is "stored" in the cultivated soil itself. It is sometimes possible to build catchments to feed existing -- or even ancient -- water-storage structures.

Rain-water harvesting has never been subjected to long-term economic analysis. Extensive field trials in different areas are needed to build up a database that could provide a better understanding of the economic viability of different methods in various economic environments (WAJ).

The following activities are currently being carried out in Jordan:

- A pilot project in the northeast of the country (al-Hammad area), where a few million cubic metres of flood water is being stored in large, man-made lagoons and used for cattle and small-scale agriculture.
- A study is being conducted in Karak and Tafileh governorates (Bani-Hamida area) to collect rain water using micro-catchments and contour-furrowing techniques. The study identifies several thousand hectares that can be cultivated in this marginal area, which receives between 100 and 200 mm of rain (Japan International Cooperation Agency).
- The University of Jordan is currently implementing the first phase of an experiment on water harvesting at a 200-ha site 50 km southeast of Amman, seven km east of Muwaqer village. Early results are encouraging and could lead to a breakthrough in this field.

Desalination

Low-cost desalination of sea water would benefit arid lands bordering seas or salt lakes; over the past few decades, numerous proposals for building huge desalination plants to produce water for agriculture have been widely advertised and promoted. Although new, improved desalination methods (using membranes and exchange) have been developed, no method can yet promise truly low-cost fresh water. Current assurances of cost reduction for desalination plants are based on the assumption that the product cost decreases as the plant size increases -- but there is a practical limit to such means of cost reduction. There are also problems in disposing of huge quantities of hot brine, and in pumping and conveying treated water to the utilization point.

Most proponents of desalination schemes now agree that such water would be too expensive for use in irrigation as practiced today. However, desalination of sea or brackish water could prove economically feasible in special stituations or areas such as tourist centres.

Desalination plants producing up to several million gallons per day are commercially available, and are currently used for domestic and industrial purposes in some very arid regions where the local economy can support it. The average cost of plant-desalinated water is currently between US$1.50 and $3.00 per cubic metre, depending on the desalination method (Keenan, 1991).

Cloud seeding

Certain cloud formations contain super-cooled water; precipitation is hastened by a rainfall-augmentation method known as cloud seeding, accomplished by adding ice, frozen carbon dioxide, and silver iodide, whose crystal shapes promote condensation and produce rain.

Successful cloud seeding depends upon precise meteorological conditions. Even then, the process can sometimes lead to more or less precipitation than is needed; at other times the nuclei have no effect.

Though there is keen interest in cloud seeding for arid lands, the best opportunities for increasing precipitation exist in areas where cold, wet air masses are swept upward over mountain ranges. Prospects for increasing precipitation over low-lying arid lands do not seem promising, primarily because of the scarcity of water-rich clouds. Arid lands benefitting from cloud seeding will probably be those fed by streams originating in mountains.

The results of cloud seeding are difficult to predict, due to an incomplete understanding of the physical processes causing precipitation, and because of engineering difficulties in seeding the clouds in optimum amounts and at the right time and place. It is also unknown whether seeding clouds in one area modifies precipitation in another. Detailed physical analysis of some cloud systems may, in the future, allow one to predict the effects of cloud seeding, but research is in the early stages. In Israel, cloud seeding has been practiced for over 20 years, and results indicate an estimated 10% increase in rainfall in the seeded areas (U.S. National Academy of Science).

Cloud seeding was used in Jordan for three years, between 1986 and 1989; however, the results were not evaluated, and further research in this area is recommended.

Decreasing demand

Following are a number of efficiency and conservation measures to be considered.

Reducing physical losses from municipal water supply networks. Losses are currently estimated at 25% of water supplied by these networks. These losses could conceivably be reduced to 10% by performing much-needed maintenance work on problem areas as they are identified (WAJ). The WAJ has completed a comprehensive study of system losses for the Greater Amman area, and now plans to conduct the maintenance work in stages.

Reducing losses from irrigation canals. If losses caused by the inefficient operation of major irrigation canals (including the King Abdullah Canal) and secondary delivery systems were reduced, savings could reach 50 MCM/year. JVA plans are currently under way to increase the quantity of available water supplies by reducing these losses (JVA).

Expanding drip irrigation. This technique is used in Jordan, though further research and experiments should be conducted to improve methods and reduce negative side effects such as salinity.

Minimizing evaporation. Evaporation from dams and agricultural areas can be minimized after research determines the best and least expensive materials available for this purpose.

Cultivating plants that require less water. Such a practice would save large quantities of water in a country like Jordan, where this commodity is scarce. Further study and research is needed to identify the water quantities necessary for different plants in different areas of the Kingdom. It is believed that more water is used in agriculture than is required, resulting in unnecessary waste and a negative effect on production.

Optimizing the water consumption of plants. Irrigation losses can be minimized by using agricultural methods which increase water storage in the soil and prevent its leakage to lower levels -- especially in sandy soil.

Reducing industrial water demand. This could be accomplished through a comprehensive study on the current methods of industrial water use and the adoption of appropriate water-saving technologies.

Reducing residential water demand. A comprehensive study has been initiated by the Royal Scientific Society, with support from the Ministry of Planning, on the possibility of saving water by adopting simple household conservation measures such as smaller flush cabinets and shower heads, and reduced water pressure. Potentially, tens of millions of cubic metres could be saved by changing personal consumption practices.

Changing patterns of personal consumption. Domestic water can be saved by changing patterns of water use, through awareness of the waste involved in using bathtubs, washing cars using water hoses, leaving taps open while shaving, dishwashing, etc.

Preventing water pollution. This can be accomplished by preventing pollutants from mixing with surface and groundwater.

Preventing over-extraction. Over-extraction reduces the quantity of water and increases its salinity, making it unsuitable for use. The quantity of water pumped from basins should equal the quantity charging them, and over-extraction should be stopped.

Managerial, pricing and regulatory options

Modifying water-pricing policies. Water prices should reflect actual cost to the whole population (with some subsidies for low-income groups and others), and should take population growth and the marginal cost of providing new supplies into account.

Numerous economic and political influences are presently moulding the Jordanian water sector. Management options are more important now than ever before, and further project development is required as well. It is highly recommended that research into pricing, conservation subsidies and the like be performed on a country-wide basis. Such research would provide valuable input to plans for a full-fledged, efficient management policy.

Rationalizing growth rate. Jordan's 3.6% annual population increase is considered high, and there are not enough water resources to cover all needs. This issue should be given due consideration, so that a balance between the supply and demand for water resources can be achieved.

Other options include the following:

- Volumetric allocation of water on an annual basis.
- Incentives for recycling.
- Educational initiatives.
- Water conservation subsidies.
- Subsidy modifications.
- Improving metering, billing and revenue collection.
- Monitoring extraction rates from wells.
- Restructuring of MWI, JVA, WAJ.
- Training.
- Privatization (i.e. networks, drilling operations).
- On-farm management.
- Optimizing cropping patterns.
- Optimizing industrial water consumption.

Conclusions

- Local conventional sources can be increased by 200-300 MCM/year if all sources are utilized.
- Importation of water from outside Jordan is costly and risky, but appears inevitable.
- Non-conventional resources are either small, too expensive or still in the research stage.
- Additional quantities of water resulting from various conservation measures are difficult to assess, as they are contingent upon the extent of adopted measures.

- Rationalizing the population growth rate must be seriously addressed.
- Agricultural activities may not expand -- and may in fact be curtailed -- if no large additional water supplies are found.
- Settlement of riparian rights for surface and groundwater is vital.

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6

Multiobjective decision support for water resources planning

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Abstract

This paper describes the development of a decision-support system for the evaluation and selection of water resources investment portfolios in Jordan. An investment option is defined as a single measure which may potentially affect water demand or supply. The many options available and the variety of conflicting and intangible policy objectives contribute to the complexity of deciding how to allocate budgets among alternative projects and programs in order to alleviate pressure from the impending water crisis in the most efficient manner. To systematically address these complexities, the decision-support system is based upon an integrated multiple objective approach, and

is used to assist policy-makers in analysing the economic, social, and environmental ramifications of development strategies in the water sector. In its operation, the decision-support system generates options specific to the water resources sector, and uses physical information and policy-maker insight to provide a logical basis for evaluating a large number of diverse technical projects, research priorities, and management programs in a systematic and defensible manner. An illustrative example is provided for the following purposes: (1) to explain the solution procedure; (2) to shed light on implementation concerns; (3) to describe the system's flexibility and ease of use on an annual basis, or on a project-by-project basis; and (4) to portray the system's potential for generalization to other sectors of the economy and to other countries in the region.

Introduction

Over the past thirty years, development planning in Jordan has focused primarily on the achievement of income growth. Such planning endeavors by the government resulted in Jordan having the highest per capita income growth rate among all developing countries for the period 1964 to 1982 (McCarthy et al., 1987). Within the last few years, however, externalities appeared that made the income growth objective too limiting for development policy, and income distribution and environmental concerns came into prominence. Certain regions and subsectors were being developed at the expense of growth in others; currently, water pollution problems are placing additional constraints on water supplies. It is now clear that the policy impact on the environment and the equitable distribution of income has to be considered for efficient decision-making.

The water resources constraints in Jordan are increasing. Based upon previous studies and detailed observations (Abu-Taleb et al., 1991), the authors conclude that there is a need now to focus greater attention on future impacts of water resources planning and development vis-à-vis the objectives and directions of the nation. This will require the use of "technical" analysis to be applied whenever significant strategies and policies are being formulated to systematically structure the underlying problems and to gain insight into solution procedures. These analyses will provide the mechanisms for optimal public-policy decision-making in water resources, ultimately resulting in less investment risk, a higher degree of equity in the distribution of benefits, and a sustainable level of water resources development. Multiobjective/multicriteria systems analysis is one such mechanism.

The work described herein arose out of the problems encountered by government planners in setting up their annual water resources sectorial plans; the planners were unable to visualize the impacts of their decisions on Jordan's national objectives. Encouraged to a large extent by the potential

benefits of employing multiobjective methods, and by the World Bank's emphasis on the optimal and integrated use of water resources (World Bank, 1988), the authors explored how water-resources policy-making could be improved by fusing new decision-aiding technologies into least developed countries, especially in Jordan. Such decision-aiding technologies have become an important focus of theoretical and applied literature on the use of systems analytic methods in water resources planning. This literature has indicated that through the use of optimization procedures -- namely multiobjective analysis -- water services can be priced, allocated, developed and utilized efficiently. This paper, then, describes the development, on an annual basis, of a multiobjective decision-support system to enable decision-makers to optimize water resources planning in Jordan.

In the course of the paper we will document the extent of the water crisis in Jordan, and describe the many ways in which it manifests itself. We will also establish the fundamentals of a decision-support system (DSS) to assist water managers with complex planning decisions. Finally, we examine the ways in which the proposed system can be generalized to apply to other sectors of the economy, such as energy or public works, and to other countries in the region.

Background

Problem description

In Jordan, the water management problem can be characterized by water shortages, environmental quality issues, and supply distribution concerns. Two major factors impact water availability and demand: the semi-arid climate, which contributes to water scarcity; and the high population growth rate, which overstresses existing water supplies.

The major physical manifestations of the water resources problems in Jordan include low precipitation and high evaporation rates, high population growth rates, the existence of conflicting domestic demands and external riparian conflicts, and severe financial constraints. The present result is a severe water shortage which will only increase in severity as the population grows and demand continues to exceed available supply limits. The consequences have a direct bearing on the socio-economic structure of the country, and on the quality of water resources in general. In simple terms, if the inherent water supply-demand imbalances are not alleviated, Jordan can never realize its full potential for social and economic development.

Based upon comprehensive information on Jordan and the problems and constraints mentioned briefly above (and in more detail in Abu-Taleb et al., 1991), it may be concluded that (1) demand will begin to exceed supply by 1995, even if all conventional sources have been developed; (2) there is a clear necessity for developing non-conventional water supplies; (3) there is a clear indication of the need for conservation and efficiency-enhancement measures within the water sector; and (4) there is a clear need for overall integrated water resources planning and development. It is these issues that the decision-support system described in this paper addresses.

Proposed solutions

Heretofore, efforts to resolve the above-mentioned problems have focused almost exclusively on the development of additional water supplies. The governmental institutions that have evolved to deal with water scarcity have been committed to the construction of storage and conveyance facilities (primarily for irrigation), while at the same time neglecting to deal fully with groundwater over-extraction and environmental problems. At present, these institutions need to look elsewhere to deal with that projected water scarcity because of the rapidly increasing costs of developing new water supplies. This new direction of water resources planning, engineering and management must incorporate appropriate objectives, constraints and methods which cover all related sectors of the economy and utilize all aggregate water data.

On that basis, recommended solutions can be divided into four broad categories. These include: (1) measures to increase supply from conventional sources, (2) measures to increase supply from non-conventional sources, (3) measures to promote greater efficiency and conservation, and (4) development of an integrated comprehensive planning and management framework.

Generally speaking, the first three categories have received a significant amount of attention in previous studies, reports and proposals. Conversely, the fourth category has received scant consideration in Jordan, despite the fact that it represents an important approach to solving complex water resources quality and quantity problems in a number of more developed nations. The first three categories have been addressed elsewhere (Abu-Taleb et al., 1991), so that in this paper, attention will be devoted solely to the fourth category.

The fourth solution category for solving Jordan's water problems involves the adoption of an integrated comprehensive planning and management framework which would encompass all the potential options and measures that affect water demand and supply. The framework consists of a mutliobjective analytic methodology to help water planners devise and select optimal plans for the future.

The decision-support system

The decision-support system (DSS) incorporates a data management component and a multicriteria decision-making (MCDM) component. The data management component contains functions for data entry, modification, sensitivity analysis and graphical output. The data set consists of the different options available which may potentially affect water demand and supply, such as the construction of dams, reservoirs and irrigation canals; pricing options and physical water transfer projects; and a set of multiple criteria which include socio-economic and environmental factors. This set of data, which is still being collected from physical investigations and elicited from water resources planners and engineers, is presented to the user in graphical or tabular format, and can be manipulated in a spreadsheet-type environment. The MCDM component, which is based largely upon the powerful PROMETHEE technique, will facilitate the selection of a strategy that optimally satisfies the relevant water resources criteria set developed from the overall national objectives of Jordan. The multicriteria method of PROMETHEE has been successfully applied in many fields, including medical diagnosis (Du Bois et al., 1989), nuclear-waste management (Briggs et al., 1990), and hydro-power plant location (Mladineo et al., 1987).

Decision support is a natural result of the evolution in database management and in computer-based problem solving. It has evolved over the last 15 years and continues to evolve rapidly, thereby defying "precise definition at any given time," (Andriole, 1989). However, a DSS can be defined in general as a computer-based information system used to support decision-making activities by thoroughly structuring a problem to prevent the user from having to address complex problems holistically. A DSS can be based upon a number of analytic approaches, such as cost-benefit analysis, linear programming, or multiobjective decision analysis, to incorporate user input for modelling and solving a problem. It can also include geographic information systems (GIS), to add insight to the spatial aspects. In this chapter, we take multiobjectives and constraints into consideration simultaneously. GIS were considered for use, inasmuch as GIS maps of topography, present land use, and depth to water, for example, can be overlaid to determine such impacts as the change in groundwater-irrigated acreage in a specific region (Stansburg et al., 1991). Such systems in Jordan are still under development by the Royal Geographic Centre in Amman; it is envisaged that a GIS component may be added in the future to this DSS to enhance its analytical capability.

Multiobjective analysis (multicriteria decision-making) is concerned with decision-making processes that involve several conflicting objectives. Multiobjective methods have been developed over the years because of "the recognition that the solutions to complex problems must explicitly embrace a range of competing concerns" (Porter et al., 1991). These concerns translate into a set of multiple conflicting objectives which must be taken into account before the selection of alternatives. Evans (1984) identifies three reasons why there is an increasing awareness that most decisions are inherently multiobjective. First, the outcomes associated with management and engineering-type decisions are multidimensional. Second, there are numerous stakeholders in many problems. Third, there has been a rapid increase in the speed, flexibility, and storage capabilities of computing systems. This last category has also affected the development of decision-support systems. As Andriole (1989) suggests, new decision-support systems are mostly being developed for micro-computer use because of the flexibility, power and predominance of microcomputers.

Because of the inherent complexity in multiple-objective decision-making and the variety of possible ways in which decision-maker preferences can be formulated, a large number of methods have been developed to solve such problems. Recent taxonomies showing the variety of techniques developed for multiple-objective decision-making can be found in Deason (1984) and Tecle (1988). In our solution technique within the DSS, we concentrate on the PROMETHEE outranking approach (including the PROMCALC and GAIA systems) -- because of our task, user and organizational requirements -- as the fundamental model base in the system. Some of the details of such requirements analysis are presented below.

Identification of task and user requirements

In general, policy planning can be thought of as maximizing (or minimizing) certain social objectives subject to the feasibility constraints imposed by the overall economy. The goal of this project is to assist water resources managers and policy-makers with the increasingly complex problems of water resources planning. The major task of the DSS is to provide a large water database and relevant criteria to be used in a model base to rank strategies. Other subtasks were also identified, such as the ability to perform sensitivity analysis on some inputs, display graphical presentations, and allow for user modification of the database and of the value judgments at any stage of the DSS operation. The identification of policy-maker requirements was of paramount importance to the study; therefore, a user profile (as defined by Andriole, 1989) had to be determined. These requirements, including the selection of an appropriate model base, are briefly described.

It was apparent, early on in the study, that the overriding method of analysis would hinge on the specific requirements of decision-makers in the water resources planning field. These requirements were determined by reviewing the planning process (previous three- and five-year development plans), and by close coordination and communication (personal meetings and interviews) with senior water and planning officials. The decision-makers identified for this process include those responsible for formulating plans of action and setting priorities for future water programmes and projects, and together form what may be called a water resources planning subcommittee. They prepare and present a prioritized list of projects and programmes to the National Planning Committee, which in turn is entrusted with translating these

plans into a national strategy. It is the authors' belief that the water subcommittees would benefit immensely from a structured method of prioritizing their projects and programs more comprehensively so that all Jordanian water resources issues and objectives may be addressed.

In the DSS design, it was agreed that the applied methodology should be wholly consistent with customary operating and planning procedures, so as not to adversely affect its later implementation and use or to undermine resulting confidence in it as an aid in decision-making. Thus, above all else, the DSS would have to support the decision-maker and his conventional planning process as much as possible. These two criteria -- user requirements and decision support for conventional planning -- were finalized through a set of surveys which produced a final operational DSS based on a preliminary conceptual model.

Many multicriteria methods cater largely to the needs of decision-makers; due to the trade-offs inherent in MCDM and the accessibility and wide use of computers, most of these techniques are developed as interactive procedures which require the decision-maker to play an active role during the entire decision-making process, thus allowing him to progressively articulate his preferences. These methods are generally easy to use and understand, but by their very nature are time-consuming. In a recent comparative study, Klein et al. (1986) found that the prior-articulation-of-preference approach gave more insight into the problem structure, and was hence more of an aid to cognitive thinking. Klein et al. (1986) also suggest that it would be useful to develop an interactive process for a prior-articulation approach, i.e. a hybrid approach which exploits the advantages of each procedure. In that way, the need for the decision-maker to allocate time for articulating certain preferences at every iteration and for every annual planning cycle would be obviated. In this DSS, the authors will utilize an interactive extension to the prior-articulation approach called PROMETHEE (preference ranking method for enrichment evaluations) developed by Brans et al. (1984). Preliminary details of the method are presented later in the case study.

Identification of national objectives

Jordan's national objectives and directions have been developed by the Jordan government as part of its planning policies over the past 20-30 years (e.g., Jordan Ministry of Planning, 1986). The objectives articulated in such reports are very broad and have not been specified in a manner conducive to easy application of the technical methods envisaged here. These general objectives, to be useful in a decision situation, have to be broken down and structured for operational purposes.

Keeney and Raiffa (1976) have shown that the objectives in almost all complex problems can be structured into a hierarchy. At the top is an allinclusive objective that takes into account all policy-maker concerns; however, this is generally too vague to be of use in an integrated methodology. At each level of the hierarchy, the objectives become progressively better defined but larger in number.

Keeney and Raiffa (1976) also address the question of how far to disaggregate such a hierarchy. They suggest that an appropriate set of objectives is found at the level of the hierarchy at which the number of objectives is as small as it can be, while still maintaining enough specificity that contributions of alternatives toward each objective can be measured; that is, the objectives must be both minimal and operational.

An objectives set for Jordan was developed from an analysis of Jordan government policy statements, and augmented by the collaborative work of experts from the Ministry of Planning and others. The objectives hierarchy is illustrated in Figure 1. It was primarily intended to be comprehensive, to provide a basis for modification within the decision-support system, depending on the major direction of the economy, social structure, and environmental protection standards.

The major objective of this study is to produce a system capable of analysing the impact of water-resources strategies on a multiple set of criteria. The assumptions are that such criteria appropriately measure the higher order national objectives (economic, environmental, socio-economic and health) and are sufficient to characterize the strategy-selection problem. In our analysis, initial cost comes into the picture as an overall budget constraint

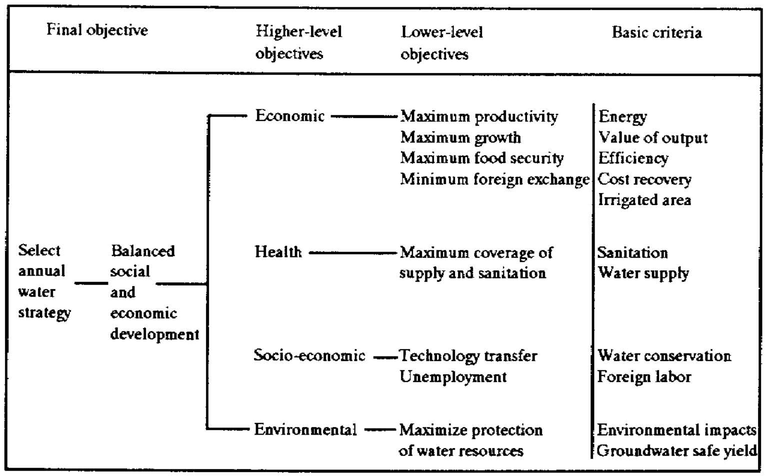

Figure 1. Objectives hierarchy.

against which the ranked strategies are evaluated. As such, the ranking will define the sequence of strategy elimination as funds are reduced. A description of the main impacts is provided.

The underlying features and assumptions of this criteria set include the following:

- Each policy objective can be translated into a quantitative policy criterion.
- For each criterion, there is an ideal value which may change with time as a result of changes in technology, external economic factors, etc.
- The best water policy should consist of a portfolio of options to reach the ideal values of all criteria.

Given the propensity of water planning specialists to interact with experts on limited time constraints, the weights were obtained a priori, through the use of various communication techniques and questionnaires. The decision-makers were consulted only once, at the onset of the study. The weights were synthesized from different planning groups in Jordan. A similar approach was adopted by Barda et al. (1990) to develop weights for criteria using the ELECTRE III method; experts and policy-makers in the water-resources field were approached and weights were elicited by use of a specialized survey, or questionnaire. The individuals consulted included experts from the Ministry of Water and Irrigation, Ministry of Planning, Royal Scientific Society, Higher Council for Science and Technology, Royal Corps of Engineers, and experienced private sector water resources consultants. The assumption was that individual experts have a significant amount of knowledge about different aspects of the problem; group knowledge would therefore cover all relevant issues more substantially. The results are preliminary; at this stage, they represent more of an emerging viewpoint than a substantial tool for decision-making. It was interesting to note, however, that a similarity in views did emerge in the first questionnaire. The results revealed that environmental impacts as a whole were significant, indicating a need to subdivide the impacts into component parts. This was performed in the second and more comprehensive questionnaire.

Identification of options and strategies

In the DSS, a number of disaggregated options are linked to form sets of coherent portfolios, called strategies. An option is defined as a single action affecting water management, such as raising the height of a dam or applying water conservation subsidies. Under the proposed integrated approach, the resulting strategies would be evaluated in terms of some feasibility criteria, in order to render each strategy sufficient in terms of its purpose as a "stand alone" policy. A relevant set of criteria is needed, then, to perform the prescreening and identification of strategies, and must include measures of comprehensiveness, relevance, and cost effectiveness. These criteria will be discussed shortly.

To illustrate conceptually the manner in which the aggregation was achieved, a list of feasible options was developed from recent literature on Jordan's water situation and through collaboration with a number of agencies in Jordan. To develop new options, the authors examined budget documents, project proposals, technical reports, and options designed to solve certain problems. This data-collection phase is continuing.

In Table 1, the classification employed by Walker and Veen (1987) is used to list some important options, classified as those that affect water supply (technical and managerial) and those that affect water demand (pricing and

Table 1
Some water resources options for Jordan

Options affecting water supply	Options affecting water demand
A. Technical options	**C. Pricing options**
1. Construction of dams/multi-purpose reservoirs (see proposed dams)	15. Pricing water at cost
2. Projects for reuse of marginal-quality waters	16. Subsidy modifications
3. Computerized system of water control in Jordan Valley irrigation	17. Sewerage tariffs
4. Exploitation of new wells, e.g., Wadi Seer aquifer, Wala Springs	18. Water conservation subsidies
5. Projects to increase urban-runoff collection	19. Setting prices for wastewater discharge for industries
6. Desalination of brackish water at Azraq, Jordan Valley, Wadi Araba	
7. Desalination of sea water	
8. Further development of Disi aquifer	
B. Managerial options	**D. Regulatory options**
9. Limiting agricultural self-sufficiency	20. Improving metering, billing and revenue collection
10. Cessation of pumping from Qa-Disi aquifer	21. Monitoring extraction rates
11. Research studies, e.g., simulation of all water movement in Jordan	22. Conservation programs
12. Higher compensation for workers in control of diversions, inspections, etc.	23. Changing allocation procedures
13. Incentives for recycling	
14. Educational initiatives	

regulatory). Other useful classification schemes exist -- especially the one proposed by Munasinghe (1990) -- but the supply-demand classification below is adequate for the purpose of illustrating this technique. The following equations represent the supply and demand functions for water.

$$Wd = F(P,R,Z) \text{ ....(1)}$$

Water demand is a function of pricing, regulation and a collection of other variables, represented by Z. These other variables are not directly under our control, and include such factors as population level and associated growth.

$$Ws = F(T,M,U) \text{ ....(2)}$$

Water supply is a function of the technical and managerial factors responsible for providing water to the public, and relevant stochastic factors such as water losses.

A few general remarks concerning options to help solve water problems are useful at this point. First, it can be seen from the classification of options that most are directed at the agricultural and municipal subsectors, the largest users of water. Second, options can be further classified spatially (by region) if required, or in other manners. Third, if a larger set were generated for Jordan, a sizeable portion of them would fall under the general framework of "management." This is the case because a substantial infrastructure is already in place, indicating that managerial-type options are promising sources for future improvements. As such, components such as research and education, water conservation subsidies, and monitoring programs may ultimately constitute major features of water resources planning and management initatives in Jordan.

For each of the options to be generated, we have defined a number of parameters relevant to defining strategy impacts:

- t_i = time in years for option completion;
- v_i = type of option: technical(=1), managerial (=2), pricing (=3), regulatory (=4);
- r_i = designates region: North (=1), Amman-Zarka (=2), Dead Sea-Azraq (=3), South (=4);
- s_i = category of strategy within which option could be included;
- q_i = present discounted value of option over its anticipated life cycle;
- p_i = probability of success of option.

In order to further link a number of disaggregated options to form sets of coherent portfolios (strategies), a mechanism had to be applied that would be a reflection of the political policy process, where strategies are defined according to current and future policies. For example, if a conservation policy is in order, then the options that fall within this category -- along with other required options as needed to magnify or reduce the effects -- would constitute a strategy. That strategy would then be evaluated and screened in terms of its comprehensiveness, relevance, and cost effectiveness. These steps of aggregation, evaluation and prescreening alone could provide more insight into water problems and their potential solutions than ever before.

Operation of the DSS

The decision-maker or user involvement in the overall DSS occurs in four distinct phases: (1) initialization and modification of database, (2) preference-structure determination, (3) analysis and determination of weights, (4) sensitivity analyses and modifications. Each of these stages is described below as part of the case study.

The data-management component of the DSS contains functions for data entry, data modification and analysis, and data output. The data is presented to the user in graphic or tabular form, and can be manipulated in a spreadsheet-type environment. A number of relevant criteria have been applied to evaluate presentation to the user, including ease of use, efficiency of implementation, and specifics of user environment in Jordan.

The main objective of a flexible DSS is enabling the decision-maker to modify any part of the input or add new information which is perceived to be very important. During the analysis, the database can be modified frequently to add new information as it is developed, to include only certain subsets of the criteria and different preference structures and weights, or to design new strategies from existing options.

The following procedure is used by the DSS in strategy evaluation and selection:

1) The user identifies the set of criteria to be utilized in an assessment, together with any set of weights and preference structures; the initial set obtained from the surveys would be an appropriate starting point. The DSS will eventually be capable of assisting the user interactively in the selection of an appropriate set of weights and preference structures.

2) The user then identifies options from the DSS database to design new strategies.

3) The user then commands the DSS to rank the strategies; sensitivity analysis can be used at this point to enhance and clarify decisions.

Illustrative example: annual water-strategy determination

A hypothetical case study is now presented to illustrate the proposed methodology for evaluating potential water strategies; it involves five criteria. It should be noted that, to demonstrate the methodology, the data used for this study were crude estimates; the results should therefore be viewed solely

for illustrative purposes, especially since only a limited number of alternative strategies and objectives were considered. The PROMETHEE multicriteria models were used in this preliminary study (Mareschal and Brans, 1991). One of the authors is working on an extension of the PROMETHEE by making it more interactive in terms of the weight and preference-structure determination. It will be shown that the thresholds for the preference functions associated with each criteria cannot take arbitrary value , and their choices can be easily guided.

Some of the positive features of PROMETHEE methods include the ability to obtain a complete ordering of the strategies, while at the same time allowing for incomparabilities that may be present. The methods are also independent of scaling effects. This is achieved through allocating intensities of preference between any pair of strategies as functions of the difference in their evaluations. More details on these methods can be found in Brans et al. , Briggs et al., and Du Bois et al.

Following is a description of the main parameters of the case study.

Study area - Jordan.

Budget constraint - JD 50 million for 1992.

National objectives - The following quantitative policy criteria were used to approximate the policy objectives of environmental, economic and health impacts. The relative weights of the criteria and the type of preference function (defined below) were assigned independently by the authors for this case study. The first value in brackets is the weight, the second the threshold parameter for Type II preference function.

Groundwater pollution (3, 5); land quality (1, 1); water supply (4, 5); energy use (2, 100); and water conservation (3, 5).

In terms of the preference structure, we refer to the ideas introduced in PROMETHEE. Martel and Aouni (1990), who applied these preference structures to a multiobjective goal programming problem, found that it not only leads directly to differences of performance between two actions on a given criterion, but also to a more easily understandable consideration of value functions which express the intensity of the decision-maker's preferences. Six types of generalized criteria were presented by the originators of the method. Figure 2 below illustrates the Type-II preference function that we will use in

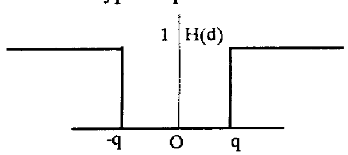

Figure 2. Type-II preference function.

this example. The function H(d) gives the preference intensity of one alternative over another. The decision-maker, in this case, has one threshold parameter to determine, which generally has a concrete significance since it is directly associated with the goals and scales of measurement specific to each objective. The interactive model to be designed by the first author would allow the generalized criterion to be easily determined by the user for the specific criteria at hand.

Water resources options - The list is shown in Table 1; the options themselves are quite general in nature, so they would not be used in a detailed analysis. However, for the purposes of this example, the list of options will suffice.

Identification of potential strategies - Four alternative strategies were formulated, screened and finally evaluated. To simplify the case study, these strategies reflect four very different policies. The first strategy does not involve development projects, reflecting a policy of pure management of the existing infrastructure. The second focuses on providing the irrigation subsector with all of its water requirements, providing an allocation preference to the municipal and industrial subsectors, de-emphasizing agriculture. The fourth strategy involves the use of water with increased efficiency, water conservation policies and pricing structures, reflecting a conservation and efficiency policy. These strategies contain the following options designated by numbers from Table 1.

Management strategy (S1): includes options 3,4,13,14,17,20,21,22.
Agricultural strategy (S2): includes options 1,3,4,8,12,13,6,21.
M&I strategy (S3): includes options 2,4,5,6,10,14,19,21.
Conservation and efficiency strategy (S4): includes options 3, 5, 9, 12, 13, 14, 16, 17, 18, 19, 20, 21, 22.

Impact analysis-Table 2 illustrates the impacts of each of the strategies on the chosen criteria for a Type-II preference structure. The impacts for each strategy were aggregated from the individual options.

Table 2
Results of the impact analysis

Criterion (Weight)	Measure	Min. or Max.	Strategies S1	S2	S3	S4
Groundwater pollution (3)	Salinity, mg/l	Min.	100	150	90	60
Water supply (4)	MCM	Max.	10	15	100	90
Land quality (2)	Subjective*	Max.	4	3	4	4
Energy use (1)	kWh	Min.	1000	2000	4000	3000
Water conservation (3)	MCM saved	Max.	20	10	0	30

* Subjective assessment on a six-point qualitative scale (5=best, O=worst).

Trade-off analysis - Using the mathematical relationships in the DSS -- which consider PROMETHEE decision-maker preference structures and the relative importance of the criteria -- a final ranking of the four strategies can be achieved as shown below. The estimated cost for each strategy is a net present-value figure, consisting of capital costs for the programs and projects within the strategy, and the operational, maintenance and running costs associated with each option. The choice of a discount rate will be handled in subsequent analyses, once more refined data is collected.

The final ranking shows which of the strategies should be retained in any planning period, within a specified budget. This is the case because in any one planning period, the strategies developed will tend to exceed the financial resources available. Therefore, given an initial budget of JD 50 million for new strategies, we would retain only the first three. If additional funds were made available, others could be added in the same order.

Since some strategies.have overlapping options, the total cumulative cost would actually be less than the values depicted. For example, strategies 4 and 3 each have the following options that are common to both: 5, 14, 19, 21. Therefore, if the policy-maker required both of these strategies to be implemented, then the cost of these overlapping options would be deducted from the cumulative cost. Of course, this applies to any number of chosen strategies that have overlapping options.

Sensitivity analysis - Within the decision-support system, sensitivity analysis can be performed to determine how the alternatives fare under different weighting schemes and preference structures. For example, if large oil deposits were discovered in Jordan, the "minimize energy use" criterion might be weighted very low, or not even considered in the analysis. In addition, as part of sensitivity analysis, the decision-support system supplies the interval of weights for which the ranking does not change. This potentially measures the validity of a weighting scheme and greatly contributes to policy-making endeavors. In other words, after analysing the interval of weights and opting

Table 3
Final ranking of strategies proposed in the case study

Rank	Strategy description	Cost (,000 JD) Per strategy	Cumulative
1	Strategy #4	30,000	30,000
2	Strategy #3	13,000	40,000
3	Strategy #1	7,000	50,000
	Budget cutoff line		
4	Strategy #2	10,000	60,000

for no change, the policy-maker is able to impart broad confidence in the final ranking.

For this case study, an analysis of the weights indicated that if we doubled the relative importance of the water-supply criterion from 4 to 8, then strategy number 3 would be ranked first. Other input modifications are also possible.

Discussion - There are three points in this case study that merit further attention: the effects of uncertainty on the optimization procedure, the use of the DSS in policy analysis, and the generalization of such a procedure to a wider range of problems.

Uncertainty can be traced back to its potential effect on demand-supply relationships, and its effects on the evaluation of options with respect to the multiple set of criteria. That is, uncertainty is a main issue in evaluating the options with respect to the criteria; the value judgments are taken as certain once the decision-maker has stated his preferences. The issue of uncertainty in the evaluations is handled by allowing the DSS to perform different rankings of strategies based upon probable evaluations. By defining some statistical distribution for each evaluation, the DSS may be able to define a range of evaluations for which the ranking does not change. This would provide clear results to decision-makers, and inspire confidence in the overall DSS. However, it is apparent from the case study that accurate information on each possible option, in terms of its overall cost and contribution to the objectives, should be gathered and used. Only then can the performance of the DSS be evaluated and improved.

On the use of the DSS in policy analysis, Loucks (1975) indicates that it may be important to identify the values of the weights that make significant changes in the values of the objectives, and to define the strategies that reflect certain policies that are efficient for different weight ranges. This is exactly what the PROMETHEE and its extension program GAIA (Geometric Analysis for Interactive Assistance) achieve in their weight-sensitivity analysis. This aspect is further emphasized in the current system through an interactive procedure for the weights and preference structures.

There is definite potential for the generalization of the decision-support system to other sectors of the economy, and to other countries with similar constraints. Because it is flexible, the DSS has the potential to deal with a wider range of problem settings. For example, a list of objectives relevant to the energy sector could be developed to evaluate future energy strategies, using the same methodology of options and strategies. The system could also be utilized to rank a number of alternative projects using a detailed set of criteria; clearly, the potential applications are numerous.

The only impediment to applying such a DSS to other countries' water sectors would be the inability or unwillingness of policy-makers in different countries to admit value judgments regarding trade-offs among conflicting

objectives. This phenomenon is usually a reflection of the support given by distinct interest groups (farmers, labour unions, industrialists and others) to politicians. In this DSS, however, the problem could be partially alleviated by using the range of weights to define rankings, a process Mareschal and Brans (1991) term "walking weights."

Conclusion

In Jordan, the socio-economic and environmental dimensions of the water sector are so important that any technical planning process neglecting these issues would be a non-starter. Any suitable "technical" mechanism must operate on a multidimensional or multiobjective basis and should enhance rather than hinder the current decision-making framework. Such mechanisms include the powerful multicriteria technique of PROMETHEE and its possible extension within the framework outlined here. The paper has described this technique by taking into account both user requirements and an enlarged national-objectives hierarchy relevant to the water sector, to provide assistance at the decision-making level.

As Stansbury et al. (1991) indicate, even with the support of a decision system, the burden of the final decision lies with the policy-makers.

The possible benefits of employing an integrated approach, however, include the following:

- The approach reflects the ultimate economic scarcity of water and, with the use of a multiobjective optimization model, permits the allocation of limited water supplies among competing demands with relative flexibility.
- The integrated DSS draws a complete picture of the country's current and future water supply and demand problems. It is thus able to describe in quantitative terms the potential contribution that "options" could make toward resolving supply-demand imbalances.
- The integrated DSS makes a case for inter-regional transfers by providing a decision-making framework for the spatial allocation of water from water-surplus regions (such as the south) to regions where economic growth is constrained (e.g., Amman-Zarka region). In fact, it is conceivable that the decision-support system will enhance the operations of a proposed national supply network running from the Disi wells in the south to the Yarmouk Basin in the north.
- The DSS produces a budget allocation for strategies which is easily justified and reproduced.

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7

The Jordan River system

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Resources and projects

The headwaters of the Jordan River originate from three main springs: Hasbani, in Lebanon; Dan, in Israel; and Banias, in Syrian territory occupied by Israel (Fig. 1). The three streams join in Israel to form the Upper Jordan River. The surface catchments of the springs do not alone account for the large quantities of water discharged from them; therefore, their underground watershed must extend further to the north, northeast and eventually northwest, beyond the surface catchments and into Syria and Lebanon.

The Upper Jordan River once flowed into Lake Hula, where more water joined the river course. In the 1950s, however, Lake Hula and the surrounding area were drained and dried; since then, the water has flowed through the so-called Hula Valley, joining Lake Tiberias further to the south.

Downstream of Tiberias is the onset of the Lower Jordan, where different streams join the main river course. The biggest of these are the Yarmouk and Zarka rivers, which join the Lower Jordan from its eastern side; the Yarmouk flows from Jordan's borders with Syria and the Occupied Territories, while the Zarka River lies within Jordan. The Jordan River then flows into the exitless Dead Sea.

The total discharge of the Jordan into the Dead Sea -- prior to the implementation of the different water projects in Jordan, Syria and Israel -- was 1370 MCM/year. This amount has now declined to a mere 250-300 MCM/year -- mostly as irrigation return flow, inter-catchment runoffs or saline spring discharges.

Israel uses all the water of the Upper Jordan (a net total of 650 MCM/year), so that no fresh water flows downstream of Lake Tiberias from the Upper into the Lower Jordan River.

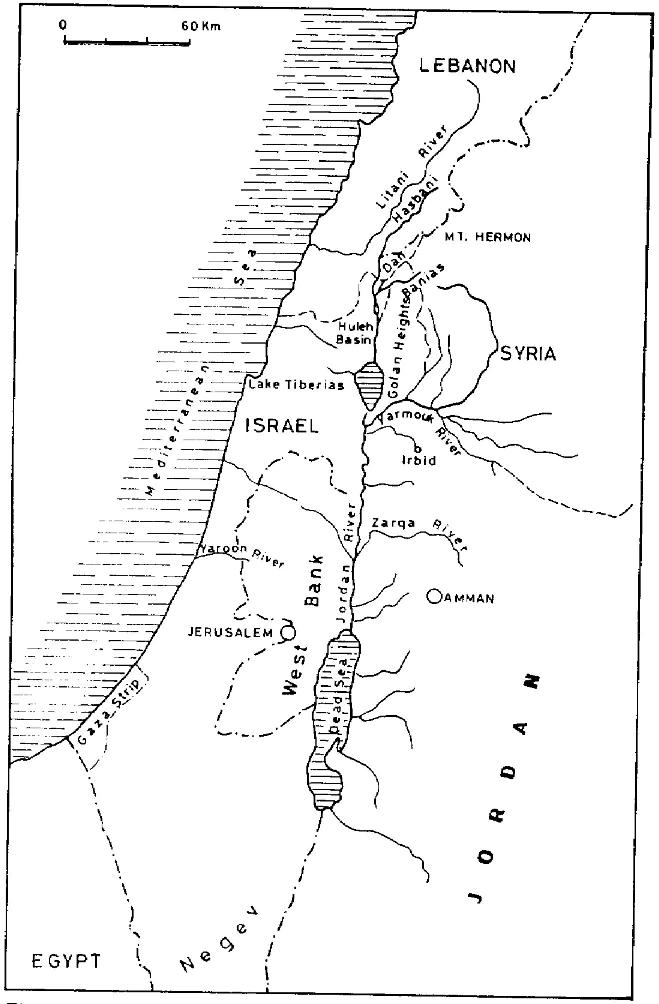

Figure 1. The Jordan River and its main tributaries.

Saline springs in the immediate surroundings of Lake Tiberias and at its bottom are channelled downstream of Tiberias into the headwaters of the Lower Jordan River.

The discharge of the Yarmouk River into the Jordan River was around 400 MCM/year prior to the use of the water by the different riparians. In the last few years, this amount has gradually declined to very small discharges only as a result of large floods which cannot be accommodated by the existing extraction facilities.

The other wadis and springs on both sides of the Jordan Valley are dammed or captured by other constructions. That which remains -- runoffs due to rains over areas downstream of water collection constructions, return flows or saltwater discharges -- then joins the river.

From the Yarmouk River, Syria extracts 160-170, Jordan 100-110 and Israel around 100 MCM/year.

Water sharing: recent history

In the case of the Jordan River system, there are no valid agreements pertaining to sharing the jointly-owned water resources. An agreement was signed between Syria and Jordan in 1953 regarding water allocation of the Yarmouk River, providing for the construction of a dam on the Yarmouk River and the subsequent division of water resources at a ratio of about 1:3 between Syria and Jordan, respectively. Revisions were made in 1987, and according to the new agreement, Jordan was supposed to construct the Unity Dam on the Yarmouk River, designed to collect 180-200 MCM/year of water for its own use.

Because of water scarcity in the Jordan area, a very small river like the Jordan represents a vital source of water for its riparian states.

Plans to develop water resources go back to the 1940s and 1950s, when different countries developed individual plans for water utilization. The disparities found among these plans led President Eisenhower to send a special envoy, Eric Johnston, to the area in 1953 to design a comprehensive proposal for sharing the Jordan River water. After two years of negotiations, Johnston offered a plan which was accepted by both the Arab and the Israeli technical committees, but the Arab League refused to ratify the plan for political reasons.

According to that plan, the Upper Jordan and the Yarmouk waters were to be shared as follows:

Table 1
Johnston Plan allocations: MCM/year

	Syria	Lebanon	Jordan	Israel
Jordan River	42	35	100	375*
Yarmouk River	90	00	377*	25**

* The rest: what remains in the river after extracting the fixed shares.
** The Yarmouk Triangle: water allocated for irrigating the Yarmouk Triangle between the Jordan River, the Yarmouk River and Lake Tiberias.

At present, Jordan takes only 100-110 MCM/year from the Yarmouk River and no water from the Jordan River. Syria takes 160-170 MCM/year from the Yarmouk and nothing from the Upper Jordan. Lebanon takes nothing from the Jordan River, while Israel takes 650 MCM/year from the Jordan and around 100 MCM/year from the Yarmouk.

By comparison, Jordan is the biggest loser and Israel the biggest winner.

Socio-economic importance and political implications of water resources and uses

The Jordan River riparians -- Syria, Jordan, Lebanon and Israel -- are in an official state of war with each other. The Jordan River constitutes a major source of fresh water for Israel and Jordan (including the West Bank), both of whom are currently facing and are expected to continue facing severe water shortages in the next decade.

With a population growth rate of 3.6% per year, Jordan will have to double its current annual domestic water supply by the year 2000 to meet its growing demand.

As a result of the Gulf war, Jordan received around 300,000 Jordanian and Palestinian returnees from Kuwait and the other Gulf states, and around 100,000 Iraqis, increasing the population of the country by 13% within a few months. This migration put a great deal of pressure on the country's already severe drinking water supply situation, especially during the dry season.

Early in 1991, around 3000 ha of irrigated land were damaged in Jordan, when water shortages forced farmers to use bad-quality water for irrigation. In September of the same year, the Ministry of Water and Irrigation asked farmers in the southern Jordan Valley to cultivate only a quarter of their lands, because of water shortages and the government's inability to provide more water.

The citizens of the major urban centres in Jordan suffered this year from a catastrophic water shortage. Water was pumped only once or twice a week through the networks, then collected and stored in roof tanks for use during the following week or so; almost everyone was living at the hygiene brink, where water use was concerned.

This problem of rapidly diminishing resources is also acute in Israel, which obtains 40% of its water supply from the West Bank and Gaza Strip -- territories Israel occupied in the June 1967 war. Another 40% of its water comes from the Jordan River. Because it is scarce -- and so closely associated with economic development -- water takes on a whole new dimension in the hostile (uncooperative) political environment of the Middle East. Israel is said to have been partly motivated by its lack of resources -- especially water -- when it initiated the 1967 war. Since that time, Israel has become increasingly dependent on the West Bank's water resources.

In 1991, water in Lake Tiberias dropped to its lowest-ever recorded levels, and Israel's Water Authority was considering emergency measures to restrict pumping, to prevent the water level from dropping below the danger point of 212.5 metres below sea level. For the last five years, Israel has been rationing water -- mostly affecting the politically sensitive farming sector, which consumes around 75% of the country's water supply.

The *Perestroika* of the former Soviet Union is likely to aggravate Israel's water problems. In this decade, Israel is expected to build 100,000 new homes to accommodate between 250,000 and 300,000 Soviet Jewish immigrants, putting more pressure on the Israeli Water Works to supply sufficient water.

Syria still has other resources to develop, and does not depend on the Jordan River system for any vital or irreplaceable uses.

Lebanon has large quantities of surface and groundwater at its disposal, so the water resources of the Jordan River are of very little importance for this country.

Future prospects

Jordan, Palestine (the West Bank and Gaza) and Israel are presently over-exploiting their water resources by 15%, 20% and 10%, respectively.

To summarize: water levels are dropping, fossil-water resources are being mined, salination of aquifers is occurring, salt-water intrusions are almost unavoidable, irrigated soils are showing salination, and the domestic water supply of the population does not satisfy the hygienic and living standard demands.

To augment domestic water supplies, irrigated agriculture has to be curtailed in all three countries. The area is experiencing an escalating water crisis; the water shortages are already chronic.

Various measures might be considered to alleviate or eliminate the water shortage:

- Importing water from water-rich countries like Turkey, through the proposed "Peace Pipeline," which would channel water from the Ceyhan and Seyhan rivers through two pipes -- one running through Iraq to the Gulf States and Saudi Arabia, and the other through Syria to Jordan, Palestine and Saudi Arabia. (Although this project is regarded as a supplement to existing water supplies, it should be considered very seriously whether such a vital commodity should, for such a large area, be controlled by one country -- especially one like Turkey, which has been alternately rival, friend and enemy to others in the region.)
- Desalination of sea water, though expensive, could alleviate the water problems of coastal communities. Due to its high cost, desalination could be justified for drinking purposes, but not for irrigation uses -- regardless of the products.

- Curtailing irrigated agriculture even further might increase domestic water supplies and alleviate shortages; but such a measure would result in declining food production and foodstuff coverage, lower export revenues, higher hard currency expenditures for food imports, and higher unemployment -- with all its socio-economic ramifications in the different countries. Curtailing irrigated agriculture must therefore be coupled with a transfer to industrialization, to guarantee jobs and revenues, and to stabilize the social and political systems. Such restructuring -- from an agrarian to an industrialized economy -- would require large investments of time and money, as well as a great deal of skilled planning, training and technological expertise.

The potential for armed conflict within the Jordan River system seems to be low, because all the water in the system is already utilized; a gain for one riparian would therefore mean a loss for another.

Environmental impacts

Using the Jordan River system's water for various purposes has led to a drastic decrease in the amount of water reaching the Dead Sea -- from about 1900 MCM/year from the different sources to about 550 MCM/year at present. With the prevailing evaporation rates, the level of the Dead Sea has gradually fallen from 392 m to 407 m below sea level over the last 27 years. In the last few years, the annual drop has averaged 85 cm.

This decline in sea level is accompanied by a seaward salt/fresh-water interface movement, and hence a general drop in fresh groundwater levels which are in hydrodynamic equilibrium with Dead Sea water.

One proposed solution to the declining Dead Sea level is its connection to either the Mediterranean Sea or the Red Sea via a canal or tunnel; the transfer of water would raise the level of the Dead Sea again and sustain it at a certain elevation. The accelerated water flow resulting from the differences between the levels of the Mediterranean Sea or Red Sea and the Dead Sea could be utilized in hydropower production.

The irrigated soils along the Jordan Valley are currently showing the first signs of salination, a situation which has occurred repeatedly throughout history.

For the last four millennia, inhabitants of the area have developed their water resources and irrigated their land. Irrigated areas extended further and further, and the unit of land was allocated less and less water; unbeknownst to the farmers, salt accumulated in the soils, gradually decreasing productivity to a point where the land had to be abandoned, forcing the population to move elsewhere, to more fertile and water-rich areas. Decades later, rainfall and floods would flush the soils, and the cycle would start again.

Nowadays, tests and experiments can predict these events. Soil salination is becoming more common, and can only be halted by reducing the total irrigated area, giving the remaining area enough water to meet plant needs and soil-flushing requirements.

A series of dry years caused by reasons such as global warming can accelerate the environmental impact, including rapid drops in the Dead Sea and fresh groundwater levels, and increased soil salination.

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8

Water scarcity, resource management, and conflict*

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Scarcity and maldistribution constitute the two basic models of riparian problems in the Middle East that between them contain a representative typology of water issues that policy-makers in governments and international agencies such as the World Bank and United Nations may expect to encounter in their attempts to devise political and economic policies.

The Jordan Basin best represents the model of scarcity, with attendant problems of overpopulation, insufficient financial resources, poor management, and an imbalance of power among its riparians. The Euphrates represents the model of serious maldistribution -- despite current sufficiency -- with parallel problems of money, personnel, and power. For the political analyst and modeller, perhaps the most interesting aspect of these basins is that together they demonstrate the systemic, political, and socio-economic interconnections of water issues which, by their nature, make piecemeal planning and investment strategies less effective or counterproductive in the long run.

Moreover, in the Middle East, where aridity, scarcity, and some of the world's most atavistic rivalries exist, it is an inescapable reality that there is little hope for the resolution of water-based conflict -- or cooperation -- until sustainable political settlements are put in place. At the crux of conflict in the region is the denial of a state for the Palestinian people; water is a keystone

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* This paper is being published in a different version by the World Bank.

of this issue because it is integral to the other crucial factors of security, ideology, and politics.

The Jordan Basin is a semi-arid region encompassing some 18,300 km^2, with an average annual precipitation of less than 200 mm; it is an area occupied by four riparians -- all of whom are belicose toward one another -- where demand for a dimishing water supply is increasing rapidly. The issue here, then, is how to manage a scarce vital resource in conditions of hostile rivalry and avoid open conflict.

The four riparians in the Jordan Basin system are Jordan, Israel, Syria, and Lebanon; however, some eighty percent of the basin is situated in Jordan, Israel, and the West Bank, whose populations are most dependent on its waters.

From surface, ground, and marginal sources Israel normally has available about 1950 MCM/year of renewable fresh water supplies. Owing to drought, Israel can presently count on only about 1600 MCM/year, but is consuming some 1820 MCM/year, running up an annual deficit of 220 MCM. Jordan, which usually derives about 900 MCM/year of usable water from all sources, is down to 700-750 MCM/year for the same climatic reasons. Jordan's consumption is between 825-850 MCM, producing an annual deficit of about 75-100 MCM. Both Israel and Jordan have accumulated a water deficit equivalent to a year's total supply.

The Occupied Territories (the West Bank and Gaza) have a productive capacity of about 700 MCM/year, but the current drought-stricken supply is roughly 500-550 MCM/year; the Territories' supplies are being overdrawn by about 75-100 MCM/year. Seventy percent of the groundwater on which Israel depends -- and more than a third of its sustainable annual water supplies -- originates in the Occupied Territories. Put differently, 83% of the Territories' waters is consumed by Israelis on both sides of the Green Line.

Jordan's population and that of the Occupied Territories are increasing at a rate of 3.8% annually -- with a doubling time of only 18 years, if sustained-- and Israelis are increasing at an annual rate of about 2%, but anticipate an absolute increment of 750,000 to a million immigrants from the Soviet Union by the end of the decade. At these rates, within the next two decades, Jordan's population will increase from 2.7 million to 7 million, Israel's will rise from 4.4 million to 7 million (including the Russian immigrants), and the Palestinians in the Territories will jump from 1.75 million to 4.2 million.

The present average domestic consumption of water in Israel is about 300 litres per capita per day (L/C/D); that of the Jordanians is about 80 L/C/D, and the Palestinians in the Territories consume some 70 L/C/D (though in some areas it drops to 45 litres).

The prognosis for the next two decades is for persistent water shortages and the continuing tendency to over-exploit unless drastic corrective measures are taken basin-wide. These would involve: economic restructuring; basin-wide administration, management, and data sharing; reduction of irrigated agriculture; alterations in crop patterns; sustainable population growth; and greater efficiency through application of water technologies and conservation. These essential steps will be politically and economically difficult without considerable outside mediatory and financial assistance.

The effects of ongoing water deficits, already exigent in the Jordan Basin, are cumulative and could quickly become irreversible. Neither known natural sources nor water technologies available now or by the end of the decade have the capacity to generate new, usable water in needed quantities at an affordable cost. Without a solution to this scarcity, both Israel and Jordan will have to curtail their social and economic development. The result is likely to be heightened competition among riparians and among domestic sectors within each country for decreasing amounts of degraded water, with concomitant destabilizing internal and regional repercussions. Scarcity and environmental degradation will also have an impact on other water-related resources within the basin.

Because of the current disparity of power among the Jordan Basin's riparians -- with Israel possessing hegemonic force -- there appears to be no immediate prospect of a water war; however, water-based hostilities are possible. Water issues are central to the strategic planning of all the basin's riparians, and water problems contribute vitally to the basin's inter-riparian tensions. If current policies and patterns of consumption in Jordan and Israel persist, a mounting series of crises could be touched off before the end of the decade -- particularly if economic conditions deteriorate further or if the present drought continues or worsens. Between 1995-2005, Israel, Jordan, and the Occupied Territories might begin to experience acute and progressively worsening perrenial water shortages and quality degradation, resulting in the three areas running out of renewable sources of fresh water. Consequently, rather than outright warfare among the riparians (which is possible), internal civil disorder, regime changes, political radicalization, and instability are more likely to ensue.

Moreover, the waters of the Occupied Territories are now so integral to Israel's water needs that the delicate balance of Israel's water system has become dependent on them. Israel satisfies up to 40% of its water requirements from the West Bank. It is inconceivable that an Israeli government would ever give up any part of the West Bank without an effective plan -- replete with a full array of guarantees and inducements -- that would give Israel secure permanent access to sufficient quantities of the Territories' waters or guaranteed access to other comparable sources in the area -- probably the Litani River in Lebanon.

It might eventually be possible to effectively counter Israel's security and ideological reasons for retention of the Territories, but not its hydrological arguments, which will persist until the water issue is settled. It is water -- which is constituent to security, political, and ideological factors -- that will in the final analysis determine the future of the Occupied Territories, and by extension, the issue of conflict or peace in the region.

Despite the daunting obstacles to a peaceful settlement, there are nevertheless opportunities for fresh thinking about old situations. In this regard, it is useful to recall that the unique importance of water for human life can lead to either severe conflict or solid cooperation. If the participants in a water rivalry can be made to see themselves as confronting a common fate, resolvable only through their cooperation and thus being responsible to and for one another, then a positive interaction very different from the familiar hostility may occur.

The most effective way to manage the basin's water crisis would be the creation of a basin-wide authority with sufficient independence, power, expertise, and funds to perform its tasks. Such an authority would first require an equitable solution of the Israeli-Palestinian-Arab conflict which conforms to the principles of law, but this happy solution is not likely to occur in time to stave off a major water-driven crisis. But even in the absence of a formal political agreement and of trust among the principal actors, there are still various hydrological incentives for taking some positive actions to prevent conflict or crisis. Chief among these incentives is the fact that unless the current situation is eased, the basin's states seriously risk destabilization, radicalization and conflict, the effects of which could be devastating and spill out beyond the confines of the basin to other key regional actors.

One of the most fruitful ways to alleviate the basin's problems of water scarcity and overpopulation is through the restructuring of economies away from heavily irrigated agriculture toward other sectors, such as service and industry -- a difficult but not impossible task given proper incentives and dedicated assistance. If Jordan and Israel, for instance, were to reduce their irrigated agriculture by 40%, they would roughly break even in water supply and demand, assuming simultaneous improvements in efficiencies and conservation (Israel has temporarily reduced irrigation water by 37% this year).

Experts have for some time argued that Middle Eastern governments should realize that their energy and water resources would serve them better if they were exchanged, through an appropriate market situation, for foodstuffs produced with far lower energy and water subsidies in locales with climates better suited to agriculture. This strategy would enable Middle Eastern water authorities to transfer enormous quantities of water from inefficient agriculture to far less consumptive industrial applications, which

presumably could simultaneously increase GNP; the contribution of light industry to GNP is about 30 times greater (per unit of water used) than the contribution of agriculture.

Understanding and easing the transition from agriculture to light industry would be complex for many reasons, not the least of which pertain to the political issues involved. The shift from farming to industry (or, for example, to electronics, service or transportation) is difficult because agriculture is culturally imbedded, highly symbolic, and militarily significant. Investment in research and practice oriented toward encouraging and making possible the smooth transition would yield high dividends. The U.S., the EC, various governments and the World Bank could provide incentives for planning and implementing economic restructuring and for mitigating the attendant hardships.

Perhaps the best way to initiate economic restructuring is to provide incentives for one country to act as a demonstration model for others, not only in the Middle East, but also in other parts of the world. Jordan might be a good candidate because of its pressing economic and water-related problems, and its perceived willingness to be innovative. The programme would have to be implemented gradually, with rigorous periodic evaluations, flexible planning, and built-in measures for easing transitional hardships. Should this endeavor enjoy even mild success without exorbitant cost, it could be attractive to other basin actors, with a region-wide or even global impact. A positive impact could even result simply from the success of the project's initial stages. This is an undertaking that lends itself to collective endeavor, so many governments and agencies could act jointly, thereby spreading the risks.

Important technical developments are constantly emerging, such as new methods of desalination; "Medusa bags" for transporting water by towing the bags behind ships; and technologies that improve purification, efficiency, and conservation. Seeking and selecting such new ideas require continuous and systematic effort. Investment in new, promising developments -- particularly those that are unlikely to be funded by standard sources -- should have high priority.

In the Middle East, as well as in many industrial nations, international fresh water use, allocation, and preservation suffer from a lack of inter- and intrabasin cooperation, poor data, and uncoordinated, piecemeal approaches that result in fragmented policies and actions. Since it is unlikely that cooperation can be coerced or induced at the highest political levels, another approach must be found. The most promising is to encourage cooperation -- at a lower but still significant level -- among officials and technical experts. If officials and scientists in the region communicate sufficiently to develop a shared understanding of the water situation, available technologies, and potential solutions, they could become a strong force for cooperation -- a community of informed officials and experts throughout the region to press for and guide effective water policies.

Another possibility would be to promote cooperative desalination at basin or regional levels. Such arrangements, although requiring considerable political agreement, would yield great economic, political, and social benefits, especially in such landlocked countries as Jordan.

The key to achieving these goals -- and, in some respects, the prerequisites to successful economic restructuring -- would be the establishment of a technical infrastructure for hydropolicy that addresses problems at three levels: basin, regional, and global. Specifically, this would involve the establishment of three interrelated types of water institutes: 1) an institute for each of the three major river basins in the region (Euphrates-Tigris, Jordan, and Nile); 2) a comprehensive Middle East regional water institute; and 3) a global water institute, perhaps under the auspices of the U.N. or World Bank.

These institutes, comprising staff, fellows, trainees, and other personnel from the world's major basins, would perform several functions: 1) provide the expertise, research, educational opportunities, and data necessary to develop the entrepreneurial, human, and technical resources presently lacking; 2) generate databases and hydrological, economic, and other social-scientific analytical tools; 3) act as conference settings; 4) serve as centres for accurate record keeping and information dissemination; and 5) foster interaction among basin and regional specialists.

Water is the earth's most essential resource. No other substance carries greater potential for conflict or disaster when scarce or poorly distributed. Thus, approaches, concepts, and actions must be commensurate with the magnitude of the problem -- and where water is concerned, the problem is nothing less than survival.

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Summary and recommendations*

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Resources and uses

Jordan is an arid to semi-arid country of 90,000 km^2 located east of the Jordan River. Due to Jordan's variable topographic features, rainfall distribution varies considerably with location -- from around 600 mm/yr in the northwest to less than 50 mm/yr in the eastern and southeastern deserts, which form about 91% of the country's surface area.

The amount of rainfall in Jordan ranges between 6,200 MCM in a dry year and 10,600 MCM in a wet year; some 85% evaporates directly from the soil cover to the atmosphere, while the rest flows in rivers and wadis, and recharges the groundwater.

Only about 3.2% of Jordanian territory receives an average amount of precipitation exceeding 300 mm/year -- the minimum amount required for wheat growth in the dry farming reaches of the country.

All over Jordan, potential evaporation exceeds precipitation. In the relatively rain-rich highlands, the potential evaporation is about three times the amount of precipitation, while in the eastern and southern deserts it is some 100 times the precipitation.

Jordan's surface water is distributed in 15 basins as permanent and flood flows. The Yarmouk Basin contributes 40% of the total surface water resources in Jordan, including water contributed from the Syrian part of the basin. Other

* This article summarizes the conference papers and the recommendations given by the different authors.

major basins include Zarka, Mujib, Dead Sea, Hasa, Wadi Araba and Jordan River side wadis. The Jordanian government has given priority to the construction of dams and irrigation projects in the Jordan Valley, in order to maximize water use before its drainage to the Dead Sea.

Groundwater resources, however, whether renewable or nonrenewable, are considered the major water source in many areas. Some renewable groundwater resources are presently exploited at maximum capacity and are even approaching the red-line limit. Though many studies have estimated the safe yield of the renewable groundwater resources at only 275 MCM/year, some 520 MCM/year is presently extracted.

The main nonrenewable, presently exploited groundwater resource in Jordan is the sandstone fossil aquifer of Disi-Sahel as-Siwan, in the Mudawwara area of southern Jordan. The annual (quasi-mining) extraction of groundwater is estimated at 80 MCM.

Other nonrenewable resources are those of the Jafer Basin at Shidiya, with an annual extraction of 18 MCM.

The total amount of surface water in the country, excluding the Yarmouk River, is 430 MCM/year. Part of this water is brackish, like that of Wadi Zarka Ma'in. It is very difficult to collect some surface waters, such as the runoff between the Wadi Arab, King Talal and Ziqlab dams, and Jordan River course; it is therefore difficult to make all surface water resources available for use in Jordan.

The renewable extracted groundwater amounts to an estimated 275 MCM/year. In addition, groundwater flows to the surface as springs, and feeds rivers and wadis, and is used there for different purposes.

Approximately 190 MCM/year of nonrenewable groundwater is extracted, meaning that one-third of the produced resources comes from fossil water; its extraction is currently affecting the quality and quantity of these resources. Many groundwater resources have been abandoned due to a degradation in quality and reduced exploitable quantities -- the results of over-exploitation.

Groundwater production in 1990 for all purposes amounted to 520 MCM, while surface water production and utilization amounted to 360 MCM. Existing production levels exceed the potential renewable groundwater resources by far; nonrenewable resources are mined at a very fast rate.

Despite Jordan's water scarcity, the country must still face the continuous increase and upgrading in the standard of living, agriculture and industry, in the context of an annual population growth rate of 3.6%.

Water used for irrigation all over Jordan in 1990 amounted to 650 MCM, and to 880 MCM for all purposes. Agriculture consumed around 74% of all the available water -- 92% of all collected surface water and 63% of all extracted groundwater.

Irrigation with surface water is practiced mainly in the Jordan Valley, Wadi Araba and along perennial wadis; whereas irrigation with groundwater occurs all over the country.

The last few decades saw extensive water projects set up in the Jordan Valley and along the major wadis leading to it. Dams were constructed, irrigation canals were built, and lands were reclaimed and put under irrigation; billions of dollars were invested in agricultural production.

The declining amount of available water is now affecting the supply. Rationing the domestic water supply, curtailing agricultural uses by as much as 30%, and damage to vulnerable groundwater resources are becoming more common.

Future needs and possible coverage

The demand for water is increasing continuously, due to a natural population growth rate of 3.6% per year and the influx of immigrants -- especially from the Gulf area following the recent crisis. Population increase generates a greater need for food products; hence, larger quantities of water are needed for increased irrigation requirements. The water demand also increases with the competitive upgrading of industry and the standard of living.

In 1990, the total water shortage reached 208 MCM/year; the highest uncovered demand was for irrigation.

It is estimated that municipal water demand will increase to 315 MCM by the year 2000 and to 426 MCM by 2010. The demand for irrigation water will likely be 689 and 754 MCM/year for the years 2000 and 2010, respectively. Industrial uses, which consume 5-10% of the supplied water, are expected to increase to 70 and 90 MCM/year for the years 2000 and 2010, respectively.

To bridge the gap between supply and demand, two basic solutions are proposed: to increase supply, and to decrease demand by promoting greater efficiency and conservation.

One technical option for increasing conventional water resources is the increased exploitation of fossil groundwater in different areas of Jordan. These resources are, however, considered a strategic reserve in Jordan, so higher exploitation would mean depriving future generations of their livelihood.

Different options are available to increase surface water supply -- such as developing the Yarmouk River resources -- but progress is impeded by regional political considerations. The Jordan Valley side wadis, the Mujib Basin and the Zarka Ma'in-Zara area could supplement supply by a few tens of million cubic metres of water per year. The capital expenditures and running costs of such projects are currently too high to justify them, though they may be unavoidable in the future.

Non-conventional water resources projects include irrigation with saline water, irrigation with treated wastewater, rain-water harvesting, desalination and cloud seeding -- and are seen as supplements to, rather than substitutes for, conventional large-scale water supply and management methods.

Decreasing demand by promoting greater efficiency and conservation could be achieved through the adoption of technical and managerial initiatives; however, these options are lengthy, expensive, and difficult to assess. Their effects would only be apparent after many years, and the amount of water saved by their implementation would not dramatically increase available resources.

Obtaining Jordan's share of international waters (Yarmouk and Jordan rivers) would add some 275 MCM/year to its present available resources; this would be expected to satisfy Jordan's water demand until the year 2010.

Importation of water from outside the country (e.g., the suggested Turkish Peace Pipeline or the Euphrates Project) might also be feasible, though such projects require peace settlements and cooperation between the involved states. The appeal of such projects is that they solve various water shortage problems, while at the same time promoting greater socio-economic co-operation between Middle Eastern countries.

Administration and optimization procedures

Decreasing water demand through promoting greater efficiency and conservation could be achieved by reducing physical losses from municipal water supply networks (estimated at 25%); losses from irrigation canals could also be reduced by some 50% through increased operational efficiency of major secondary delivery systems.

Expanding drip irrigation systems is another possibility, though experiments and research should be conducted to reduce negative side effects such as salinity.

Minimizing demand

- Research and studies should concentrate on identifying which materials are best suited to minimizing evaporation.
- Plants requiring less water should be cultivated, and their water consumption optimized.
- Reducing industrial water demand could be accomplished through a comprehensive study on the current methods of industrial water use and the subsequent adoption of water-saving technologies.
- Industries should be encouraged to use poor-quality water so that fresh water can be saved for drinking.

- Residential water demand could be reduced by using smaller flush cabinets and shower heads -- and by changing personal consumption patterns to prevent waste (e.g., use of bathtubs, water hoses and running taps).

Preventing surface and groundwater pollution

Preventing over-extraction, which increases the salinity of the water resource, is vital; the quantity of water pumped from the basins should equal the quantity charging it, and over-extraction should be stopped.

Managerial, pricing and regulatory options

- Water prices should reflect actual cost to the whole population (with some subsidies for low-income groups), and should take into account population growth and the marginal costs of providing new supplies.
- Advanced computational techniques are of permanent importance for the efficient utilization of water resources; they are particularly useful in developing countries, where they can provide methods of resources optimization. Intensive and careful feasibility studies supported by computer methods (groundwater modelling) must be done before the planned exploitation and construction of water withdrawal facilities, to prevent irreversible changes in the natural equilibrium system which could lead to the depletion of groundwater resources and to drastic changes in groundwater quality.
- Rationalization of growth rate: the 3.6% population growth rate is considered high, and there are not enough water resources to cover all needs; a balance between the supply and demand for water resources must soon be reached.
- Volumetric allocation of water on an annual basis.
- Incentives for recycling.
- Education initiatives.
- Water conservation subsidies.
- Subsidy modifications.
- Improving metering, billing and revenue collection.
- Monitoring of extraction rates from wells.
- Restructuring of the Jordan Valley Authority, the Water Authority and the Ministry of Water and Irrigation.
- Training.
- Privatization (i.e., networks, drilling operations).
- On-farm management.
- Optimization of cropping pattern.
- Optimization of industrial water consumption.

Water resources planning is of the utmost importance in coping with the drastic water shortages; a decision-support system for evaluating and selecting water-resources investment portfolios in Jordan should be developed. An investment option is defined as a single measure which may potentially affect water demand or supply. The many options available and the variety of conflicting and intangible policy objectives contribute to the complexity of deciding how to allocate budgets among alternative projects and programmes, in order to deal with the impending water crisis in the most efficient manner. To systematically address these complexities, the decision-support system is based upon an integrated multiple-objective approach which is used to assist policy-makers in analysing the economic, social, and environmental ramifications of development strategies in the water sector. The decision-support system generates options specific to the water resources sector, and uses physical information and policy-maker insight to provide a logical basis for evaluating a large number of diverse technical projects, research priorities, and management programmes in a systematic and defensible manner.

Characterization of water resources, conflicts and possible solutions

Scarcity and maldistribution -- and to some extent, inefficiency -- are the basic water problems in the Middle East confronting political and economic policy-makers.

The Jordan Basin represents a model of scarcity, with the attendant problems of overpopulation, insufficient financial resources, poor management, and a power imbalance among its riparians. In the Middle East -- where aridity, scarcity and some of the world's most atavistic rivalries exist -- there is little hope for the resolution of water-based conflict until sustainable political settlements are put in place.

There are five riparians in the basin system (Jordan, Syria, Lebanon, Palestine and Israel); some 80% of the system is situated in Jordan, Israel and the West Bank, though the amount of available water is diminished owing to drought. The pivotal factor is the location and flow direction of the West Bank aquifers, together with the fact that Israel derives significant amounts of water from those aquifers that flow across the 1948 Armistice border. In fact, 70% of the groundwater on which Israel depends -- and more than one-third of its sustainable annual water yield -- orginates in the Occupied Territories; this is bound to have a significant impact on the future status of the Territories and on the question of Palestinian statehood.

Because of their complexity, domestic and international water problems tend to be dealt with piecemeal, thus fragmenting a strategic foreign affairs issue. The relationship between water dependency and security is perceived as

absolute, especially where two or more mutually antagonistic actors compete for the same water source.

The basin's principal riparians, Jordan and Israel, have been consuming about 110% of their total usable water stocks, and this over-exploitation will continue unless drastic, remedial actions are taken immediately. These include economic restructuring, basin-wide administration and sharing, reducing irrigated agriculture, crop-pattern alterations, controlled population growth and greater efficiency through increased application of water technologies and conservation.

Several practical steps should be taken:

- Encourage all policy-makers to give water top priority.
- Revive negotiations over the Unity Dam project, provide as many incentives for a fair agreement as necessary, and offer Jordan financial assistance to complete the dam as quickly as possible.
- Urge Israel to reverse its hydropolitical policies in the Occupied Territories as soon as possible; otherwise, the condition of Palestinian agriculture -- particularly citrus fruits -- could deteriorate irreparably within a very few years. Beyond that, water re-allocation could be considered and undertaken with the assistance of an acceptable international group of experts who would accurately evaluate the hydrological condition of the Territories.
- Divert the saline waters in the Lake Tiberias area into the Dead Sea, to raise the quality of the lower stem of the Jordan River to usable levels.
- Encourage all parties sharing the basin to acquire the most suitable water and agricultural conservation technologies, to improve efficiencies, and to conserve water in all sectors. Israel and Jordan need to reduce their agriculture by 40% in order to strike a supply-demand balance, which would then ensure simultaneous improvement in efficiency and conservation.
- Invest in manpower training for the water sector and associated fields -- not only in science and technology, but in relevant social sciences as well.

One of the most difficult problems is understanding and easing the transition from agriculture to light industry. Investment in practice-oriented research to encourage and facilitate a smooth transition would yield high dividends.

High priority should be given to important technical developments such as new desalination techniques, "Medusa bags" for transporting water, and new methods to improve purification and conservation.

In the Middle East, the issues of international water use, allocation and preservation suffer from the lack of intra-basin cooperation, poor data and uncoordinated, piecemeal approaches which result in fragmented policies and actions. Cooperation should be encouraged among officials and scientists, to facilitate the development of comprehensive, consistent approaches toward the water problem, available technologies and potential solutions -- and to promote cooperative desalination on the basin or regional levels. The key to achieving these goals would be the establishment of a technical infrastructure for hydropolicy that would address the problem at three levels: basin, regional and global.

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