Multiobjective water resources planning under demand, supply and quality uncertainties.

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Civil Engineering

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Abstract

This research aims at formulating a water resources planning model for optimum allocation of water resources supplies (groundwater, surface water, desalinated water, and treated wastewater) to the various demands (domestic, agricultural, industrial and landscaping demands). Since by design the study included more than one objective and constraint (multi-objective decision making), the methodology employed for the formulation and solution of the model was goal programming. Uncertainty is associated with three parameters, i.e. demand, supply and quality of ground water. The model is applied to Saudi Arabia. Historical data for all the parameters were collected and, using the moment average method the data were forecasted. Uncertainty of demand is mainly due to unexpected behavior of the population; this was assumed to follow a normal distribution. Uncertainty due to supply (chiefly groundwater) is because of the gaps among the proven, probable, and possible reserves. There are three parameters here; Reserves are assumed to follow triangular distribution, and the quality in terms of TDS was also assumed to follow triangular distribution. Random numbers were generated and used in order to simulate the process and the basic concept of reliability analysis was applied to the results of the model, which was run upto the year 2020. The multi-objective model was run for two cases, one in which there is no restriction on the use of desalinated water and the second case in which the desalinated water is restricted to the current total capacity of the desalination plants all over the Kingdom. The results of the model showed that there is severe deterioration of the quality of the industrial and agricultural water with reliability of achieving the prescribed quality equal to 1.62% and 1.2% respectively in the year 2020. The effect on the groundwater reserves was minimal with plenty of reserve available in the year 2020. In the second case, the quality of the domestic water is severely affected (the reliability of achieving the prescribed quality in terms of TDS, less than or equal to 1000 mg/l, is as low as 2.4% in the year 2020), this shows the inevitability of needing to increase the production of desalinated water.

Multi-Objective Water Resources Planning under Demand, Supply and Quality Uncertainties

by

Mohammed Mujtaba Shareef

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

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This Thesis written by **Mohammed Mujtaba Shareef** under the direction of his Thesis Advisor, and approved by his Thesis Committee, has been presented to and accepted by the Dean, College of Graduate Studies, in partial fulfilment of the requirements for the degree of

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بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

Dedicated to my Parents

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THESIS ABSTRACT

NAME OF THE STUDENT	Mohammed Mujtaba Shareef
TITLE OF THE STUDY	Multi-objective Water Resources Planning under Demand, Supply and Quality Uncertainties
MAJOR FIELD	Civil Engineering (Environmental and Water Resources
DATE OF DEGREE	March 1998

This research aims at formulating a water resources planning model for optimum allocation of water resources supplies (groundwater, surface water, desalinated water, and treated wastewater) to the various demands (domestic, agricultural, industrial and landscaping demands). Since by design the study included more than one objective and constraint (multi-objective decision making), the methodology employed for the formulation and solution of the model was goal programming. Uncertainty is associated with three parameters, i.e., demand, supply, and quality of groundwater. The model is applied to Saudi Arabia. Historical data for all the parameters were collected and, using the moment average method the data were forecasted. Uncertainty of demand is mainly due to unexpected behavior of the population; this was assumed to follow a normal distribution. Uncertainty due to supply (chiefly groundwater) is because of the gaps among the proven, probable, and possible reserves. There are three parameter here; Reserves are assumed to follow triangular distribution, and the quality in terms of TDS was also assumed to follow triangular distribution. Random numbers were generated and used in order to simulate the process and the basic concept of reliability analysis was applied to the results of the model, which was run upto the year 2020. The multi-objective model was run for two cases, one in which there is no restriction on the use of desalinated water and the second case in which the desalinated water is restricted to the current total capacity of the desalination plants all over the Kingdom. The results of the model showed that there is severe deterioration of the quality of the industrial and agricultural water with reliability of achieving the prescribed quality equal to 1.62% and 1.2% respectively in the year 2020. The effect on the groundwater reserves was minimal with plenty of reserve available in the year 2020. In the second case, the quality of lomestic water is severely affected (the reliability of achieving the prescribed quality in terms of TDS, less than or equal to 1000 mg/l, is as low as 2.4% in the year 2020), this shows the inevitability of needing to increase the production of desalinated water.

Master of Science Degree

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خلاصة الرسالة

اسم الطالب : محمد مجتبى شريف
عنوان الرسالة : تخطيط مصادر المياه لمختلف الأغراض تحت متغيرات الطلب ، العرض والنوعيه .
التخصص : هندسه مدنيه (هندسة مصادر المياه والبيئه) .
تاريخ الدرجة : مارس ١٩٩٨م

يهدف هذا البحث إلى تطوير صيغه نموذجيه للتخطيط الأمثل لتخصيص موارد المياه المتوفره (المياه الجوفيه ، المياه السطحيه ، المياه المحلاه ، المياه المهدره المعالجه) لمختلف طلبات الاستهلاك (المنزلي ، الزراعي ، الصناعي ، ري المسطحات الخضراء) . وقد تم تطوير النموذج باستخدام إحدى طرق البرمجه المسماه « برمجة الأهداف » . ووجد أن هذه الطريقه الأنسب تبنيها عند التخطيط لموارد المياه وذلك لوجود الكثير من الأهداف المراد تحقيقها والتي تتعارض مع بعضها البعض .

وقد تم التعامل مع بعض العوامل في النموذج المطور وهي الطلب والعرض على المياه ونوعية المياه الجوفيه كعوامل متغيره وغير ثابته . وطبق النموذج المطور على الموارد المائيه في المملكه العربيه السعوديه بناء على المعلومات المائيه المتوفره في الماضي والحاضر وتخمين العرض والطلب على المياه مستقبلاً عن طريق بعض الطرق الإحصائيه المعروفه . وأعتبر التوزيع الأمثل للطلب على المياه للإستهلاك المنزلي «توزيع قياسي (او غاسي) » . بينما تم التعامل مع المتغير الكمي والنوعي (TDS) للمياه الجوفيه «كتوزيع مثلثي» ومن خلال توزيع المتغيرات تم توليد القيم المناسبه لها ومن ثم تمت محاكات الطلب والعرض على المياه باستخدام النموذج المطور من عام ١٩٩٨م إلى عام ٢٠٢٠م إضافة إلى ذلك فقد تم إدخال نظرية الإحتمالات في قرارات تخطيط المياه المستقبليه بناء على النتائج المتوفره .

وأختبر النموذج المطور تحت حالتين مختلفتين . الحاله الأولى تمثل عدم وجود سقف أعلى لإنتاج المياه المحلاه ، والحاله الثانيه تمثل عدم تجاوز الكميه القصوى من المياه المحلاه المنتجه من محطات التحليه بالمملكه العربيه السعوديه . وأوضحت النتائج ، في الحاله الأولى ، التدهور الشديد لنوعية المياه المستخدمه للأغراض الزراعيه والصناعيه . كما بينت الدراسه أن نسبة تحقيق المعدلات المطلوبه للمياه للإستخداما الصناعيه والزراعيه في عام ٢٠٢٠م تقارب الـ ٦٢ر١٪ و ٢ر١٪ على التوالي . كما أوضحت الدراسه عدم التأثر الكبير للمخزون الجوفي المائي . وفي الحاله الثانيه ، أوضحت الدراسه تدهور المياه المستخدمه للأغراض المحليه حيث كان إحتمال إنتاج مياه للإستهلاك المحلي بنوعيه أقل من ١٠٠٠ ملغ/لتر TDS مايقارب ٤ر٢٪ في عام ٢٠٢٠ . مما يؤكد الحاجه الملحه إلى زيادة إنتاج مياه محلاه من أجل الحصول على مياه ذات نوعيه مناسبه للإستهلاك المحلي .

درجة الماجستير
جامعة الملك فهد للبترول والمعادن
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1. INTRODUCTION

The term management of water is meant to describe people's control of water as it passes through its natural cycle, with balanced attention to maximizing economic, social, and environmental benefits. To effectively manage a resource, good planning is needed. Management of water resources also requires wise planning, that is why it follows that planning for water management is a critical activity. The fundamental difficulty is to strike a balance between consumption today and conservation tomorrow. To achieve this goal, effective water planning needs to be adapted and implemented through an optimum and sustainable management of available resources.

1.1 Water Resources Planning

Water resources planning is a process that attempts to achieve appropriate uses of vater in the face of competing and often conflicting demands, and with due consideration to many alternative schemes (Abraha, 1995). Water resources planning aims to find a balance between water demands and available water resources. Moreover, it is needed at different levels and for different purposes of water management (Simonovic, 1989). Planning is needed to site a new water supply reservoir or a wastewater treatment plant.

Planning is also needed to develop integrated, multipurpose development plans for a river basin. In addition, planning is needed to develop the best policies for the regulation of contaminants that are discharged into waterways.

Internationally, the subject of water management is recognized as critical. The desertification of parts of Africa in the 1970s, great losses from floods and drought every year, lack of access to sources of safe drinking water and even the problem of world hunger all underscore the need for good water management and planning.

1.2 Benefits of Planning

It is surprising that not everyone believes in planning. Some think that the world is so politically incremental and so shaped by private interests that there is no reason to plan for public policies, inspite of obvious need to plan for better use of water resources. It becomes a problem of natural resources management to allocate the resources so that everyone's needs are met without damages. Water resources planning might result in social and economic benefits. Socially speaking, conflicts can be eliminated among different communities, on the water sharing issue, by wise planning of water resources. In addition, planning may result in regulatory programs, in conservation, in agreements to share resources, in non structural projects, and in structural water development projects (Grigg, 1985).

1.3 Water Resources Planning In Saudi Arabia

1.3.1 Necessity for water resources planning in Saudi Arabia

Scarcity of water has become a serious problem for Saudi Arabia because of water's limited supply and ever growing demand. The country has scanty rains and no lakes, rivers, or streams. Faced with a steadily and substantially rising demand for water, the Saudi government has directed a substantial amount of public spending to building new water supply sources while also expanding the older facilities. For the period 1985-90, the government had allocated approximately SR 30,000 million for water supply projects; 66% of which was meant for building new desalination plants, and for operation and maintenance of the existing ones. In the fifth development plan (1990-95 period), the government has allocated SR 16,798 million for the production of desalinated water, out of the SR 40,000 million total water budget (MOP, 1995). The government has placed considerable emphasis on the development of supply while water demand management and conservation practices have not received adequate attention to date, although their importance is recognized.

As a result, wasteful water consumption patterns have developed and spread across the country. These patterns, if continued unchanged, will result in substantial increases in the cost of potable water development and more importantly in the fast depletion of ground-water resources and severe deterioration of ground water quality. For

Saudi Arabia, groundwater is the most valuable water resource, and its rapid depletion may have serious socioeconomic and environmental implication.

Alternate water supplies such as building more desalination plants and using treated wastewater for industrial and agricultural purposes are needed to meet the growth rate of water demand in Saudi Arabia. In addition, controlling measures such as public awareness, price control and installation of water saving devices should be undertaken in order to conserve water.

The factors discussed above, necessitate effective water resources planning and management in Saudi Arabia.

1.4 Problem Statement

The scarce water resources available within the Kingdom of Saudi Arabia make it difficult for the Kingdom to keep pace with the ever-increasing water demand. The limited availability of groundwater presents a problem of a trade-off between present consumption and conservation. Consequently, increased production of expensive desalinated water, the only viable alternative, is necessitated. To ensure a sustainable supply of water to all consumers (domestic, agricultural, industrial, etc), sound planning of water resources is required. This study was aimed at formulating a water resources planning model, which incorporates multiple objectives considering the practical constraints facing the decision-makers.

The model is formulated to take into account the uncertainties associated with both supply and demand of water. Uncertainty associated with supply can be explained by

the fact that there are gaps between proven, probable and possible resources. On the other hand, uncertainties of demands are expected due to the steep rises of the population levels that vary with time. Moreover, there is large variation in the quality of groundwater at different locations in the same aquifer as well as from the different aquifers all over the Kingdom. Accordingly, the uncertainty due to groundwater quality is considered in the model.

The model is capable of incorporating these uncertainties i.e., demand, supply and groundwater quality, uncertainties.

In this problem, because we have multiplc objectives, such as to meet the demand of water, to minimize the groundwater depletion, etc., and we have multiple constraints such as demand quality and quantity requirements, cost reduction etc., a multi-objective criteria decision-making technique is appropriate and was adapted in this study.

1.5 Objectives of the Study

Specifically, following were the objectives of the study:

I. Develop a multi-objective model with the following objectives:

1. To fulfill the domestic demand for water.

2. To meet the water quality requirements for domestic use.

3. To satisfy water demands for agricultural, industrial, and landscaping purposes.

4. To meet the water quality for agricultural and industrial water.

The constraints of the model are the limited availability of the resources and the required quality of the water for the consumers.

II. Solve the developed multi-objective model, treating the supply, demand and quality as uncertain variables.

III. Incorporate the notions of risk and reliability to the model output.

2. LITERATURE REVIEW

2.1 Water Resources in Saudi Arabia

Saudi Arabia is located in an arid and severely arid region. It is the largest country in the Middle East with an area of approximately 2,240,000 km^2. Saudi Arabia is located between latitude 12^0 and 38^0 North. Since the location is just 12^0 above the equator Saudi Arabia is largely a hot and desert region. The principal types of water resources are Groundwater, Surface Water, Desalinated Water and Treated Wastewater. These will be discussed in more detail in the following paragraphs.

2.1.1 Groundwater

Geological and hydogeological studies have shown that the Kingdom's groundwater is stored in more than 20 principal and secondary layered aquifers of different geological ages. The Arabian Shelf aquifer are the deep sedimentary aquifers (non-renewable groundwater) which are formed mostly of limestone and sandstone, that overlies the basement rock formations known as the Arabian Shield, and covers about two thirds of Saudi Arabia or 1.485 million km^2 (MAW, Water Atlas 1984). Groundwater

resources are divisible into two types: non-renewable groundwater and renewable groundwater.

2.1.1.1 Non-Renewable Groundwater

This type of groundwater is stored in the principal aquifers. The principal aquifers of Saudi Arabia are Saq, Wajid, Tabuk, Minjur, Dhruma, Biyadh, Wasia, Dammam, Umm Er Radhma and Neogene as shown in Table 2.1. Isotropic analysis shows that the fossil (non-renewable) groundwater in the above aquifers is 10000 to 32000 years old (MAW, Water Atlas 1984). Several consulting companies under the supervision of Ministry Of Agriculture and Water (MAW) conducted numerous studies throughout the country to estimate the volumes of groundwater in these aquifers. The subjective assessments of proven, probable and possible reserves for the groundwater aquifers have been made as shown in Table 2.1. The proven reserve is the groundwater amount which can be developed with a high degree of confidence given that the aquifer properties are as anticipated. The probable and possible reserve estimates are less certain than the proven reserves. Recharge of these aquifers mainly comes from the leakage from shallow alluvial aquifers and rainfall at the outcrops.

The estimated groundwater reserve to a depth of 300 meters below the ground surface is about 2,185 billion m^3 (BAAC, 1980). These aquifers supply more than 75% of the water needs of the Kingdom. The water requirements of the Kingdom in 1995 were about 18,206 MCM (MOP, 1995) and the annual recharge 2,762 MCM (BAAC, 1980). This shows that withdrawal far exceeds the natural recharge of these aquifers.

Table 2.1 Non-renewable Groundwater data*

Aquifers	Salinity	Annual recharge	Groundwater reserves (MCM)			Groundwater reserves**
	mg/l	MCM	Proven	Probable	Possible	MCM
Saq	300-3000	310	65000	100000	200000	290000
Wajid	500-1200	104	30000	50000	100000	220000
Minjur&Dhruma	1100-20000	80	17500	35000	85000	180000
Wasia/Biyadh	900-10000	480	120000	180000	290000	590000
Umm-Er-Radhma	2500-5000	406	16000	40000	75000	190000
Dammam	2600-6000	200	5000	25000	18371	45000
Tabuk	250-2500	455	205000	485341	753234	210000
Negene	3700-4000	290	120000	284102	440917	130000
Total			778405	1199443	1962522	1960007

* Data from El-Khatib (1974); Aburiziaza et al (1989); MAW, Water Atlas (1984).
** Dabbagh , Abdullah E (1997); MCM = million cubic meter.

2.1.1.2 Renewable Groundwater

This type of groundwater is stored in secondary or alluvial aquifers. The main characteristic of this type of aquifer is that it can be recharged. These aquifers extend mostly to the southwestern parts of Saudi Arabia and have varying thickness that rarely exceeds 100m, and the width ranges between 1 and 2 km. These are named as Al-Jauf, Al-Khuff, Al-Jilh, the upper Jurassic, Sakaka and the lower Cretaceous, Aruma, Basalt and Wadi sediments. All these aquifers are not rechargeable except the last two (MAW, Water Atlas 1984). Table 2.2 shows the aquifers and the reserves. As estimated by the British Arabian Advisory Company 1980, these aquifers store about 84 billion m^3 with an average annual recharge of 1,196 million m^3. According to Aburiziaza and Allam 1989, the mean annual recharge of these aquifers is estimated as 900 M m^3 (approximately, the recharge is 1.247% of the stored value).

2.1.2 Surface Water

The absence of perennial rivers and low precipitation across the Kingdom create limited surface runoff and thus limited surface water to be utilized. Rain in the country varies widely for example the southwestern part receives the most (500mm) and the northern part the least (20mm). The quantity of the annual surface runoff in the Kingdom is estimated to be between 2,000 to 2,400 MCM of which 30% is diverted for agricultural purposes, 45% recharges the groundwater aquifers, and the rest is lost in evaporation (Al-Ibrahim, 1990). In 1995 the total precipitation in the Kingdom was 3344.7mm (MFNE, 1995). The approximate surface runoff for this amount of precipitation is 6000MCM (using a factor of 1.793, which was found based on the historical rainfall-runoff values)

Table 2.2 Renewable Groundwater data*

Aquifers	Salinity	Annual recharge	Groundwater reserves (MCM)			Groundwater reserves**
	mg/l	MCM	Proven	Probable	Possible	MCM
Khuff/Tawail	3800-6000	132	30 000	71 025	110 229	30 000
Aruma	1600-2000	80	71 000	168 094	260 876	85 000
Jauf/Sakaka	400-5000	95	100 000	236 752	367 431	100 000
Jilh	3800-5000	60	113 000	267 529	415 197	115 000
Total			314 000	743 400	1153 733	2185 000

* Data from El-Khatib (1974); Aburiziaza et al (1989); MAW, Water Atlas (1984).
** Dabbagh, Abdullah E (1997); MCM = million cubic meter.

of which only 1,800MCM, i.e., 30% of the total precipitation (El-Khatib, 1974) is utilized through dams for different purposes mostly for irrigation purpose.

The government has constructed 183 dams throughout the country to utilize the surface runoff water, with a total capacity of 450 MCM. While these dams store runoff water and increase infiltration for recharging ground water resources, they also prevent flash floods and irrigate adjacent agricultural lands. It is expected that efficient use of dams can provide a potential surface water supply up to 900 MCM/year for the Kingdom (MOP, 1985). The available surface water is an importance resource for the Kingdom due its good quality.

2.1.3 Desalinated Sea Water

The scarcity of surface water and the poor quality of groundwater resources have necessitated reliance on seawater desalination as an additional source of water supply for the Kingdom. Saudi Arabia is one of the largest users of desalinated seawater in the world. In 1970, the kingdom could produce only five million gallons a day of desalinated water, whereas in 1995 it produced 520 million gallons a day which represents 30% of the world's desalination capacity (MOP, 1995)

The Saline Water Conservation Corporation (SWCC), which is the authority in charge of desalination, presently operates 23 desalination plants, with a total production capacity of 1.9 million m^3 per day (MOP, 1995). Table 2.3 shows the main desalination plants in the Kingdom with their production capacities.

Seawater desalination plants requires a huge budget to construct, operate, and maintain. For example, the Saudi government has spent 33.5 billion riyals for operating

Table 2.3 Full capacities of the major desalination plants (SCER, 1997)

Year	Jeddah	Duba	Al Wajh	Al Khobar	Ummlajj	Farsan	Haql	Mad/Yam	Jubail	Rabigh	Al Barq	Mak/Taif	Asser	Total
1970	6.90	0.08	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.07
1974	6.90	0.08	0.08	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.58
1982	39.33	0.25	0.25	0.62	0.17	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	51.14
1983	122.13	0.25	0.25	0.62	0.48	0.18	0.17	34.50	331.20	0.33	0.69	0.00	0.00	570.15
1984	122.13	0.25	0.25	0.62	0.48	0.18	0.17	34.50	331.20	0.33	0.69	0.00	0.00	570.15
1985	122.13	0.25	0.25	8.83	1.93	0.18	2.21	34.50	331.20	0.33	0.69	0.00	0.00	581.85
1986	122.13	0.25	0.25	8.83	1.93	0.18	2.21	34.50	331.20	0.33	0.69	0.00	0.00	581.85
1987	122.13	0.25	0.25	8.83	1.93	0.18	2.21	34.50	331.20	0.33	0.69	0.00	0.00	581.85
1988	123.65	0.25	0.25	8.83	1.93	0.18	2.21	34.50	331.20	0.33	0.69	66.24	33.12	682.73
1989	140.48	1.48	0.94	8.83	1.93	0.18	2.21	34.50	331.20	0.33	0.69	66.24	33.12	701.48
1990	140.48	1.48	0.94	8.83	1.93	0.18	2.21	34.50	331.20	0.33	0.69	66.24	33.12	701.48
1991	140.48	1.48	0.94	8.83	1.93	0.18	2.21	34.50	331.20	0.33	0.69	66.24	33.12	701.48
1992	140.48	1.48	0.94	8.83	1.93	0.18	2.21	34.50	331.20	0.33	0.69	66.24	33.12	701.48
1993	140.48	1.48	0.94	8.83	1.93	0.18	2.21	34.50	331.20	0.33	0.69	66.24	33.12	701.48
1994	140.48	1.48	0.94	8.83	1.93	0.18	2.21	34.50	331.20	0.33	0.69	66.24	33.12	701.48
1995	145.89	1.48	0.94	8.83	1.93	0.18	2.21	34.50	331.20	0.33	0.69	66.24	33.12	706.89

All values in MCM

desalination projects between 1970 and 1985 alone (MOP, 1985). During the fifth five year plan (1990-95), the Saudi government allotted SR 16,798 million for the production of desalinated water, and expenditure for this purpose is targeted at more than SR 20,000 million during the coming development plan (MOP, 1995). The current five-year plan calls for the construction of 15 new plants and the expansion of the existing ones. The suggested 15 new desalination plants are expected to produce 496 million gallons a day, raising the Kingdom's production of desalinated seawater to 1.3 billion gallons a day.

Water quality in terms of TDS in both the Red Sea and the Arabian Gulf (which varies between 40,000 and 60,000 ppm) is much higher than that of other seas and oceans (Wojocit and Maadhah, 1981). For this reason, water desalination in Saudi Arabia is more expensive than in other countries that are using the same methods of desalination. Moreover, considering the fact that operational life of a desalination plant is in the range of 15-20 years, Saudi Arabia will require large amounts of expenditure to replace worn-out plants. This will impose a heavy burden on the country's financial resources, especially during a period of declining oil revenue.

2.1.4 Treated Wastewater

In an arid country where natural water resources are limited, treated wastewater can be an important potential source of water supply especially for agriculture, industrial and landscaping purposes. In addition, the treated wastewater has several advantages over other sources of water: it is cheaper than seawater desalination it minimizes pollution, and it is a good nutrient source for landscaping and farm irrigation.

The use of reclaimed wastewater in Saudi Arabia is in its early stages of development. Currently, around 150 MCM of reclaimed wastewater is being used for agricultural and industrial purposes. With rapid expansion of the potable water distribution system and sewage network, it is estimated that reclamation of wastewater could increase to 310 MCM/year by 2000. It is projected that around 1,000 MCM/year of treated wastewater will be available for reuse in the year 2010, which will amount to 5% of total resources (MOP, 1995).

2.2 Water Costs

In order to utilize the groundwater, we need to pump it. The cost of pumping depends on the depth of the water. The current data for the rate of water pumping is not readily available. The estimate given by Al-Layla et al. (1991) is in the range of 0.5 to 1.5 SR/m^3 depending on the depth of water. For this reason the production of water from renewable groundwater costs less than the non-renewable groundwater. Due to high TDS value in the groundwater, which varies between 500 and 10000 mg/l, the water is not directly potable. It requires treatment before use. According to Al-Layla et al. (1991), the treatment cost of groundwater is between 1.5 SR/ m^3 and 4 SR/ m^3. On the other hand the cost of treating wastewater by tertiary treatment method varies from 2 to 8 SR/m^3 (Al-Layla et al. 1991). The latest research regarding the treatment unit cost of tertiary treated wastewater is 1.1 SR/m^3 (Hussain and Ahmed, 1997). According to one of the studies on the production cost of desalination water in the Kingdom, it was found that the cost is 7 SR/m^3 (Anonymous, 1996).

2.3 Systems Analysis Approach to Water Resources Management

Saudi Arabia is facing an acute shortage of water resources. With ever-increasing demand for water, and continuous depletion of resources, it needs to be planned in a wise manner. Systems analysis allows the planner to plan the resources in the required mode.

Systems analysis may be defined as an analytical study that helps a decision-maker to identify and select a preferred course of action among several feasible alternatives. Systems analysis provides the answers by methods and techniques that are available to everyone for critical analysis and examination. The systems analysis technique makes use of all relevant information available and extracts the best solution(s) for the problem being investigated.

2.3.1 Systems Analysis and Water Resources

Basically, systems analysis is a problem solving technique wherein attempts are made to build a replica of a real world system or situation, with the objective of experimenting with the replica to gain some insight into the real world problem. However, since in most cases of water resources planning and management all the factors affecting the system are not known, or if known, often cannot be evaluated and quantified he resulting model does not exactly describe the real world situation, but may be fairly close to it for all practical purposes.

Broadly speaking, the analysis of a water resource system goes through five related stages (Biswas, 1976):

1. Identification and explicit statement of objectives.

2. Translation of objectives into measurable criteria.
3. Identification of alternatives and courses of action that will satisfy the criteria.
4. Determination of consequences that follow from each alternative.
5. Comparative evaluation of the consequences of the alternatives in terms of the criteria.

2.3.2 Water Resources Modeling

Model is the term usually used for a structure, which has been built purposely to exhibit features and characteristics of some other object. These models will usually be mathematical and hence are called mathematical models. The essential feature of a mathematical model is that it involves a set of mathematical relationships, such as equations, logical dependence, etc. (Williams, 1990).

The baseline model is the initial unified mathematical model of a problem. Base line model is the springboard by which we move into either a traditional, single objective linear programming model or to a multiple objective linear programming problem. Phases in the selection of a mathematical model are shown in Figure 2.1, which clearly exhibits the steps by which one can reach to either the traditional single objective type of model or he complex Multi-objective type of model.

Figure 2.2 shows the hierarchical structure and attributes of water resources planning as modeled by Changkong & Haimes (1983). It can be seen from the figure that the overall objective of this planning model is to improve the quality of life in the basin. In order to elaborate on this objective, the model is divided into two sub-objectives, namely to enhance regional economic development and to enhance quality of the

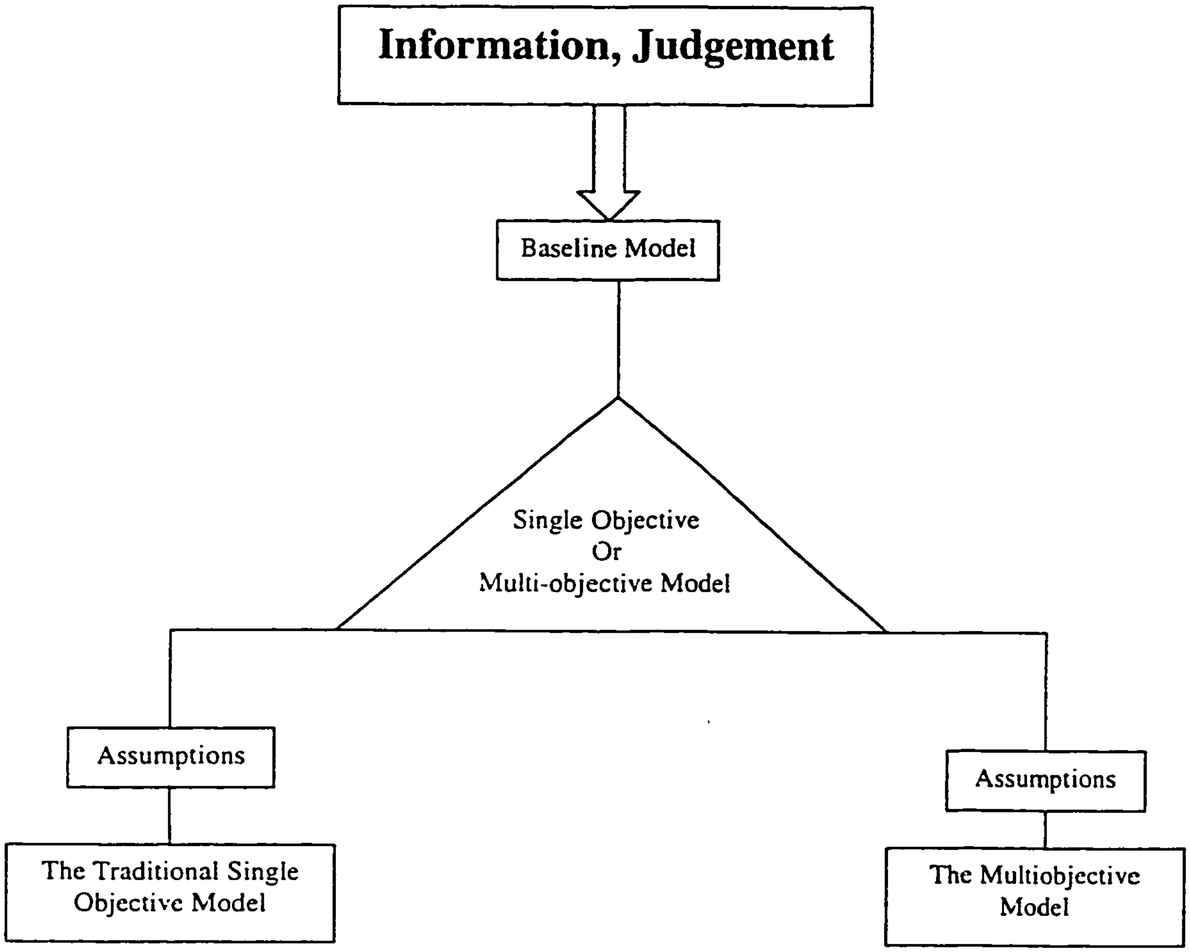

Figure 2.1 Phases in the Selection of the Mathematical Model (James, 1982).

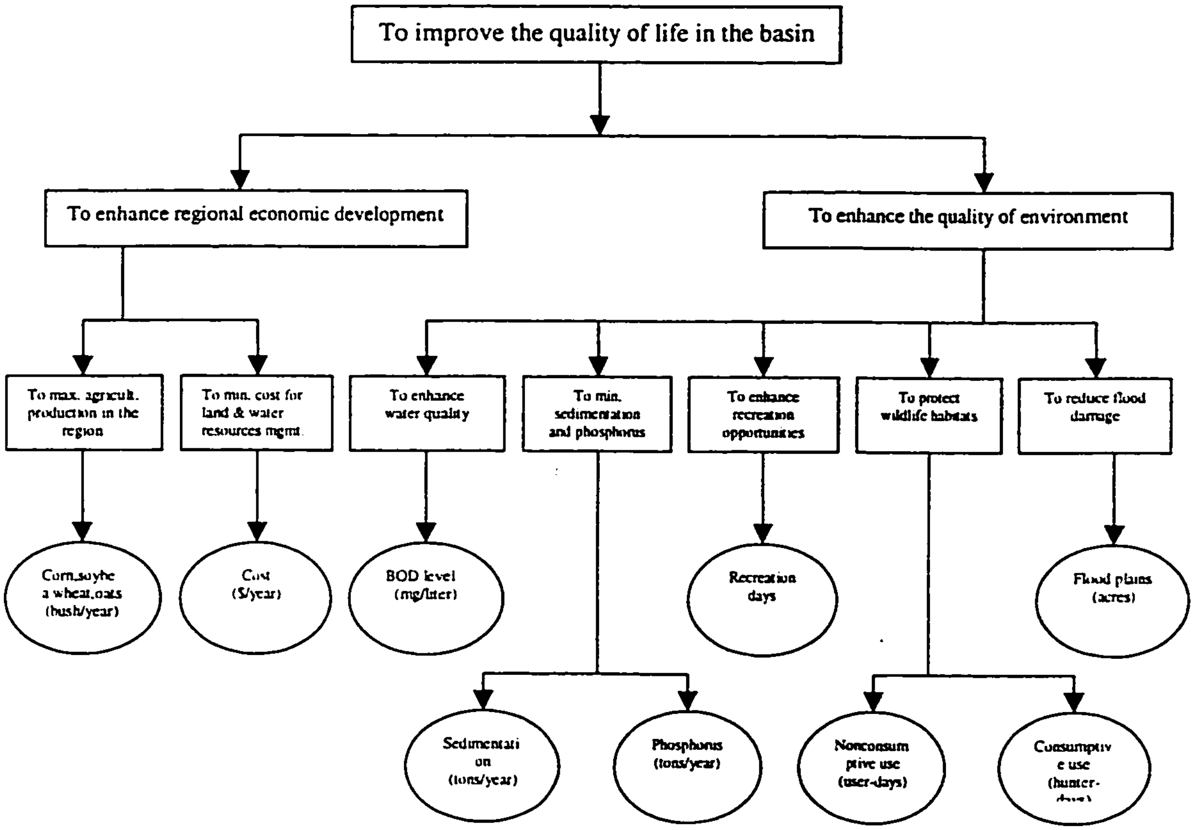

Figure 2.2 Hierarchical structure of a water resources planning model (Changkong & Haimes 1983)

environment. To fulfill the above two sub-objectives, specifically the model needs to consider the following:

- to enhance water quality;
- to reduce erosion, sedimentation, and phosphorus from nonpoint sources;
- to enhance recreational opportunities;
- to protect wild life habitats;
- to reduce flood damage;
- to protect agricultural land and increase agricultural production; and
- to minimize the cost of water and land resources management.

These phenomena is clearly shown in Figure 2.2.

2.3.3 Decision Making Techniques

Decision-making is an indispensable part of our every day life. Its application varies from individuals to the largest groups and societies. Nations and organizations at a global level also find decision-making an integral part of their responsibilities. The decision-making analysis considers situations ranging from simple like traditional single objective to complex Multi-objective model. Since the end of World War II, probably nore decision-making techniques have been developed in Operational Research (OR) than in any other field (Hipel, 1992).

2.3.3.1 Classification of Decision Making Techniques

Some of the deterministic optimization techniques developed in Operational Research (OR) include linear, many types of non-linear, integer, and dynamic programming. The set of probabilistic Operational Research (OR) methods contain

techniques such as queuing theory, inventory theory, Markov chains, decision theory simulation, as well as many kinds of time series and regression models. Other available Operation Research (OR) methods include multiple criteria decision making, classical game theory, conflict analysis, and network analysis (Hipel, 1992).

Operation Research (OR) methods can also be classified according to the number of decision-makers and objectives as shown in Figure 2.3. This figure describes, how Operation Research (OR) methods can be classified according to the number of decision-makers and objectives. We can observe from the figure that when there is one decision-maker who may represent one individual, a group of people such as an environmental agency etc., and the decision maker has only one objective, then most OR methods can be applied. The example of this type is Linear Programming. But if the decision-maker is one and objectives are many, a multicriteria decision technique is used. This technique is designed for finding a more preferred alternative solution to a problem in which discrete alternatives are evaluated against different criterion.

If there are many decision-makers and the objective is one, Team Theory is used. An example of this, is a sporting event where each team has the single objective of winning. If there are multiple decision makers with multiple objectives, Game Theory is used in which two or more decision makers, each of whom has multiple objectives, are in competition over some resource or issue.

A class of Operational Research (OR) techniques that is utilized widely in practice is the multicriteria decision-making method. In fact, various kinds of multicriteria

Objectives

Decision-maker		One	Multiple
	One	Most OR Methods	Multiple Criteria Decision Making
	Multiple	Team Theory	Game Theory

Figure 2.3 Classification of OR techniques (Hipel, 1992)

decision-making methods constitute the most widely employed family of decision-making techniques applied to water resources problems (Hipel 1992).

2.4 Multi-objective Water Resources Management

The origin of multiple objective decision-making (MODM) can be traced back to the work of Kuhn and Tucker (1951). However, the subject only recently has attracted the attention of researchers and practitioners. Hwang et al. (1980) have reported that the turning point in MODM occurred with the study of Johnson (1968) and the publication of Beneyoun et al (1971). The first conference devoted exclusively to multiple objective decision-making (MODM) was held at the University of South Carolina in 1972. The proceedings from that conference were published in Cochrane and Zeleny (1973). Gass and Saaty (1955) provided the first approach applicable to multi-objective programming problems.

The problem of decision making where there are many conflicting objectives is known as a multicriteria optimization (MCO) problem, and this forms the basis for most engineering designs. The term multi-objective decision making refers to the entire process of problem solving, as distinctly shown in Figure 2.4 (Changkong and Haimes, 1983). Figure 2.4 shows the five major steps in the multi-objective decision making process. The first step begins when the signals trigger for the need for change and diagnosis of the system. In the second step (Problem Formulation Step), we need to define the problem with the objectives and the attributes of the objectives; this step is executed using value judgment. In the third step (System Modeling Step), the model is constructed along with the model parameter estimation. In the fourth step (Analysis

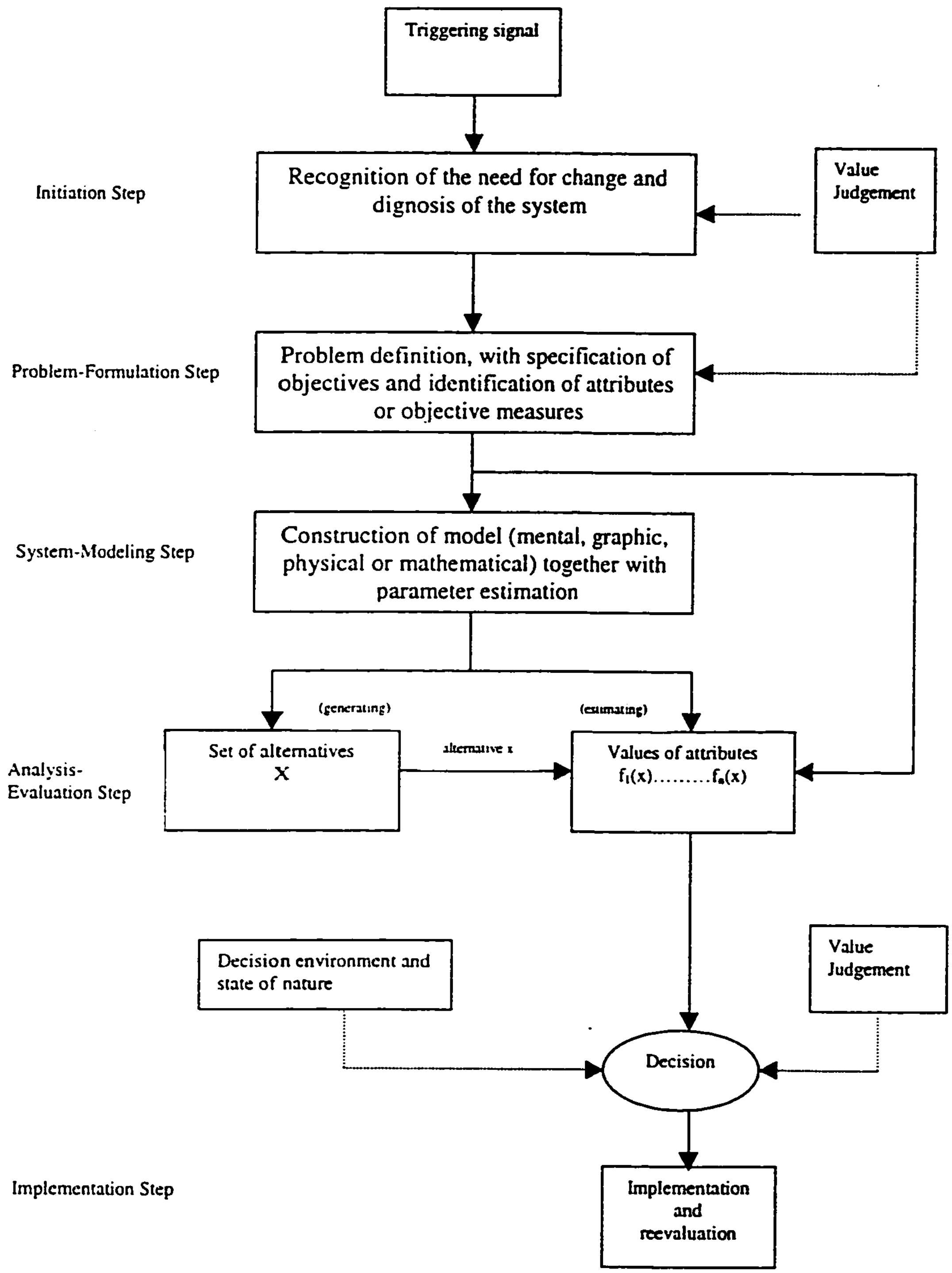

Figure 2.4 Typical multi-objective decision making

Evaluation Step), a set of alternatives are generated and then one alternative and the attributes are selected. Based on the value judgment and decision environment and nature, the decision is taken. In the final step (Implementation Step), the model is implemented and re-evaluated if required.

2.4.1 Value of Multi-objective Approaches

Multi-objective programming and planning represents a very useful generalization of more traditional single objective approaches to planning problems. The consideration of many objectives in the planning process accomplishes three major improvements in problem solving which are as follows (Cohon, 1978):

1. Multi-objective programming and planning promotes more appropriate roles for the participants in the planning and decision-making processes.
2. A wide range of alternatives is usually identified when a Multi-objective methodology is employed.
3. Models or the analyst's perception of a problem will be more realistic if many objectives are considered.

The application of the multi-objective approach to water resources planning is ustified as follows:

Demand for water resources increases as the population and economy grows, and as a result the problem will become larger and more complex over time. Consequently, the solutions to these problems become more difficult and significant. In order to mitigate this complexity of the problem, multi-objective water resources analysis can be adapted. Many of the recent advances in water resources planning have come in the field of multi-

objective analysis. Water resources planning will therefore continue to be effective, despite the increasing complexity of the problem that it seeks to solve (Deason, 1982).

2.4.2 Applications of Multi-objective Analysis in Water Resources: An Overview

Many techniques of multicriteria decision making (MCDM) have been developed and applied in water resources planning such as by Goicoechae et al. (1982), Haimes et al. (1975) and also an early review by Cohon and Marks (1975). The article by Stewart and Scott (1995) describes the evolution of a general group decision making or negotiation procedure for water resources planning at a strategic level, based on the principles of the multicriteria decision analysis. Nevertheless, the techniques are applied to water resources, but a number of difficulties are encountered in applying the standard multicriteria decision making (MCDM) method to broad policy issues in water resources planning, such as water resources development in contrast to simpler operational issues such as reservoir release rules. To overcome these difficulties, Phillips (1988) developed a new framework for multicriteria decision analysis and group negotiating support that incorporates many of the tools and concepts of multicriteria decision making (MCDM) and of decision conferring. The following sections discuss the application of multi-objective analysis in the various fields of water resources engineering.

2.4.2.1 Multi-objective technique applied in agriculture

Willis and Liu (1984) have used multi-objective analysis for a planning model to allocate groundwater to various agricultural demands for irrigation systems within a river basin.

2.4.2.2 Multi-objective technique applied in groundwater management

Multi-objective optimization methods have also been applied in groundwater management. Samir et al. (1994) presents a new approach to groundwater quality management incorporating multicriteria decision aid methodology. They consolidated a hydrodynamic groundwater flow simulation model with decision aid. To evaluate hydrodynamic behavior of the groundwater as well as to examine the management scenarios, multicriteria decision making was used.

We often face the difficulty of conflicting objectives in the analysis of multi-objective. For instance, in a multicriteria analysis of groundwater contamination management Nabil et al (1992) identified three conflicting objectives, namely, to maximize the fresh water supplies, to minimize the cost of contaminant removal and water restoration and to minimize the local draw-down effects cased by pumping. The groundwater management model was used to find a compromise strategy for trading off fresh water supply, containment of the waste, and the total pumping cost. A groundwater flow model was used to formulate the hydraulic constraints and the linear system model was used to describe the draw-down and velocity as functions of decision variables, which were pumping rates. In order to select a satisfactory alternative to the above mentioned multi-objective problem, three well known MCDM (Multicriteria Decision Making) techniques were used namely, Compromise Programming (CP), ELECTRE II, and MCQA II. From their analysis they observed that although the three techniques follow the different principles, the same preferred strategies were reached. In another study by Woldt et al. (1992), a multicriteria approach to groundwater quality monitoring

network design was developed. Composite programming that uses hierarchical structure was used for the MCDM component of the design methodology.

2.4.2.3 Multi-objective technique applied in water supply

Oscar et al (1996) has used multicriteria analysis for the design of water supply in southern France. The problem consisted of four actors (decision-makers), 13 criteria, and 38 alternatives. The methodology consisted of two steps, in the first step, preliminary overview of all possible alternatives was conducted. Using the ELECTRE III technique, the 38 alternatives were trimmed down to 8 to examine them thoroughly. In the second step all the decision-makers chose their preferences. Then using ELECTRE III, the model tested whether the reduced number of alternatives observed in the step 1 can be interpreted. But the methodology developed in this study lack the operational concepts for negotiations, such as possible tradeoffs between actors (decision-maker), asymmetry of information, or coalitions.

Using the technique of goal programming, Alidi and Al-Faraj (1994) developed a multi-objective model for optimal allocation of desalinated water to various water blending stations in Dammam city in Saudi Arabia. Multiple objectives of the model were to satisfy the demands for the blending water, control the salinity level, check the epletion of the local groundwater supplies, satisfy the demands for the brackish water at blending stations and to minimize the over production of desalinated water. The constraints for this included production capacity of the desalination plant, production rate of the groundwater wells, and the restricted salinity level. Various priority levels were given to the objectives and the model was applied to a local area.

Most of the research that has been done in the field of water resources planning considers the input parameters to be uncertain. This is not the case always, but generally planning for water resources use proceeds under the parameter of uncertainty. The following section highlights the research performed in this field.

2.5 Water Resources Planning and Management Under Uncertainty

Life is of full of uncertainty and this cannot even be avoided in water resources planning. Uncertainty is attributed mainly to our lack of perfect understanding with regard to phenomena and processes involved.

Uncertainty in water resources planning can arise because of many factors including demand and supply of water. For example we lack the understanding of the perfect behavior of the growth in population (important because population growth is related to water demand) and also supply uncertainties that exist due to limited availability of the resources.

Two types of uncertainties exist, one is an objective uncertainty associated with any random process or deductible from statistical samples, and another is subjective uncertainties for which no quantitative factual information are available (Yen and Ang '971). Other researchers such as Burges and Lattermair (1975), classify uncertainties in the mathematical models as type I error and type II error. The first one results from the use of an inadequate model with correct parameter values; if we use the perfect model with inadequate or uncertain parameters it is called type II error. In uncertainty analysis we are chiefly concerned with the assessment of statistical properties such as the probability density function PDF and statistical moments of a quantity subject to

uncertainty. Uncertainty analysis builds a formal and systematic framework to quantify the uncertainties associated with the model output.

The need to consider stochastic efforts actively or constructively in water resources management models has led to a large number of studies using stochastic optimization methods. One of the earlier approaches to the stochastic programming was by Sobel (1965), who proposed the use of stochastic linear programming to optimize the water quality. For a waste load allocation problem, Hall Carwell (1993), used stochastic dynamic programming. Stochastic dynamic programming method incorporates stochasticity solely in the transition matrix of the solution algorithm, making them relatively simple to be modified. We can add or modify the constraints easily. This model incorporates both model and parameter uncertainties.

However, stochastic dynamic programming is practically infeasible to solve the problem where there are many stated variables, especially multi-reservoir operation optimization problems. In order to overcome this difficulty Poonambalam and Adam (1995) proposed a new general algorithm called the multi-approximate dynamic programming (MAM-DP) model which solves, especially multi-reservoir operation optimization problems for the cases of deterministic and stochastic flows. This approach was solved satisfactorily using heuristic an algorithm by Kumaraswamy et al. (1996), and applied to the Parambikulam-Aiyer project as the case study. It has the advantage that it can take account of the complex configuration of real world reservoir systems, but the derived policy is sub-optimal.

Donna et al. (1993) developed a stochastic model of river water quality. This is concerned with the stochastic variable flow, surface water quality model for water quality (salinity) considerations. This model was developed by modifying a series of differential equations representing the large-scale hydrological model. It was applied to the Colorado river; however, the shortcoming of this model was that the linear hydrology parameters were not estimated but were directly assumed to be one. Rather than using the traditional statistical parameters for solving the uncertain water resource systems, Aris et al. (1993), introduced an alternative approach based on the set characterization of uncertainty. This procedure calls for finding a set of admissible actions that ensures the system stays within its bounds for the duration of its operational horizon. This method was applied to three reservoir systems in the US successfully.

The preceding sections, discuss the multi-objective approach in the field of water resources planning and show that it has been applied successfully by several researchers. Different scientists used different techniques for the development and solution of the multi-objective model. In this study, because we are dealing with many goals and objectives, a multi-objective model has been developed that adapts the goal programming technique. Moreover, the parameters involved in the model will be considered as uncertain parameters. More detailed discussion will be presented in the next section

3. METHODOLOGY

As shown in the preceding chapters, the problem at hand includes multiple objectives and constraints. Multi-objective analysis is a methodical and systematic approach or process where tradeoff is made on non-commensurate objectives (often in conflict and or competition). There are a number of approaches to solve the multi-objective problems. The method adopted for this research is the goal programming approach.

3.1 Reasons for the selection of goal programming

In recent years, plans and public policy statements related to water resources have emphasized the need for multi-objective analysis because such planning inherently involves numerous competing and conflicting goals and objectives.

We often face difficulty in selecting a suitable technique for the solution of a multi-objective problem in the area of water resources planning, and such selection itself involves the use of multi-objective analysis (Ducstein, 1982). Goal programming has been chosen for the formulation and solution of the multi-objective model in this research. The reasons for the selection of goal programming are discussed as follows:

1. Water resources planning is better represented by mathematical equations in terms of its quantity and quality aspects. As the goal programming method deals with the mathematical equations for both objectives and constraints, it is preferred in this research.

2. The problem at hand should consider both quantitative as well as qualitative nature of the resource. As goal programming can take care of any mathematical equation, we can incorporate the quantity as well as quality of water in the model.

3. The technique should be capable of accommodating prior articulation of a preference structure taking care of actual or hypothetical policy guidelines.

4. The technique selected should be flexible in the sense that the decision-maker should be able to compare the outcomes of different strategies.

5. The selected technique should be capable of incorporating uncertainties of demand and supplies.

The points discussed above necessitate the use of goal programming technique, and hence it has been selected for the model development and analysis.

3.2 Goal Programming

Goal programming is one of the commonly used multicriteria optimization echniques. It was originally developed by Charnes and Cooper (1961). Furthering their research in goal programming, the same authors facilitated the incorporation of environmental, organizational, subjective and other considerations to the model through the determination of the targeted levels and their priorities.

In contemporary research, goal programming finds many applications in managing and planning water resources systems. Mohan and Jayant (1991) used goal programming

in reservoir system operation and also discussed its application to a multipurpose reservoir project in India. Two goal-programming models were developed and applied to the Bhadra reservoir system as irrigation and hydropower system as the dual purposes in India. First, the model had the objectives of minimizing the deviations from the storage targets and the other variables with the conflicting objective of minimizing the deviations from the release targets. Their model proved that the model with released targets was preferable over the other for determining the operational policies for multipurpose reservoir system. Dandy and Crawly (1992) examined the development of an operating policy of a multiple reservoir system taking water quality into consideration. In their study which was particularly designed to consider the operation of headwork system for Adelaide, Australia an optimization model was used to consider water quality. Can and Houch (1984) used goal programming for real time reservoir operation.

Discussing the alternative strategies in water resources development for the Kingdom of Saudi Arabia, Al-Layla et al. (1991), used the goal programming methodology for model development. Making a brief survey of the available water resources (groundwater, surface water, and desalinated water) and the water use of Saudi Arabia (domestic, agricultural, industrial, and landscaping and gardening), the model was ɔrmulated. The model had the objectives of satisfying the demand requirements, minimization of groundwater consumption, and minimization of the total cost of production of water. The constraint of the model includes the total quantity and also the demand requirements for various purposes of water. The assumption of the model is that it considers the input parameters of demand and supply as certain.

Goal programming technique tries to minimize the deviations of actual achievements from targets or goals. In complex situations where there are multiple objectives and constraints, it is usually infeasable to reach an optimum solution with all constraints being satisfied. This technique, i.e., goal programming, provides the decision maker with an option to specify priorities and sub-priorities (weights) in order to identify thereby a preference structure according to which goal programming will attempt to arrive at an optimum solution (Lee, 1981).

3.3 Model Development

Before discussing the model development, it is imperative to discuss the problem to be solved. The problem here is to form those mathematical equations which represent the actual scenario as closely as possible. In our problem we have six objectives and four sets of main constraints. These were transformed into mathematical equations. There were two cases considered for the model development and solution. Both cases have the same objective functions but different sets of priorities. These shall be discussed in detail in ensuing sections

The general form and specific form of the multi-objective model is explained as follows:

Objectives

P1(...........)

P2(...........)

P3(...........)

P4(...........)

.

.

.

.

Pn(..........)

P1..........Pn represents priorities.

Specifically, the model has the following objectives.

1.To satisfy the domestic demand.

2. Meet the required domestic quality in terms of TDS.

3. Satisfy the agricultural demand.

4. Satisfy the agricultural water quality.

5. Satisfy the industrial demand.

6. Satisfy the landscaping demand.

Constraints

Quantity constraint

Quality constraints

Demand constraints

Cost constraints

'hese constraints are discussed as follows:

A. Quantity Constraints: The quantity constraints of the model are the finite amount of groundwater, surface water, desalinated water, and treated wastewater.

B. Demand Constraints: The demand constraints are the quantities of the demands to be satisfied such as domestic demand, landscaping and gardening demand, industrial demand, and agricultural demand.

C. Quality Constraints: The quality constraint includes the available quality of the resources such as the quality of groundwater in terms of TDS and also the quality of the surface water as well as the desalinated water source. Certain quality criteria apply for the various demands. This is also a quality constraint in the model.

D. Cost Constraint: Cost of production of water for the different resources are not equivalent. For example the cost of production of groundwater, desalinated water, and treated wastewater all vary. These factors become the cost constraints.

The general form of the modeling framework is shown in Figure 3.1

The model has been solved for the following two cases.

Case 1: When the desalination water is unlimited, i.e., there is no constraint on the availability of the desalination water.

Case 2: When the desalination water is limited.

The mathematical form of the objective function with constraints, deviation variables, and priority functions are explained as below.

'riorities: We would like to achieve the following goals with priorities signified by the order in which they are stated.

P_1 : To satisfy the domestic demand requirements of the water i.e., we minimize the negative deviation d^-_1 . This is the "achieve equal to" case.

Table 3.1 Modeling Framework

Demand (I) / Source (J)	I_1	I_2	I_3	I_4
J_1	q_{11}	q_{12}	q_{13}	q_{14}
J_2	q_{21}	q_{22}	q_{23}	q_{24}
J_3	q_{31}	q_{32}	q_{33}	q_{34}
J_4	q_{41}	q_{42}	q_{43}	q_{44}

P_2 : To satisfy the quality of water for domestic use, i.e., we desire to achieve the required TDS value for the domestic water. Hence, we are interested in the "achieve equal to goal" (we should meet the required TDS).

P_3 : To satisfy the demand for the agricultural use. We desire to meet the "achieve equal to goal case" (meet the demand, i.e., equal to the set requirement).

P_4: To satisfy the quality of water for agricultural use, i.e., we desire to achieve the required TDS value for the agricultural water. Hence we are interested in the "achieve equal to goal" (we should meet the required TDS).

P_5 : To satisfy the demand for the industrial use. We target the "achieve equal to goal case" (meet the demand i.e., equal to the set requirement).

P_6: To satisfy the demand for the landscaping use. We target the "achieve equal to goal case" (meet the demand i.e., equal to the set requirement).

Goals:

1) For demand satisfaction:

In this goal we try to minimize the negative deviation variable d_1^- in the equation as shown below.

Domestic Consumption $q_{11} + q_{21} + q_{41} + d^-_5 - d^+_5 = D_D$

Vhere d^-_5 is the under achievement of the satisfaction of the domestic demand.

And d^+_5 is the over achievement of the satisfaction of the domestic demand. The other terms are explained in Appendix II.

2) For the satisfaction of quality of the domestic water:

Quality of the water (TDS) is satisfied according to the following equation.

Total dissolved solids (TDS)

$q_{11}(T_g-T_x) + q_{21}(T_s-T_x) + q_{41}(T_d-T_x) + d^-_9 - d^+_9 = 0$

d^-_9 is the under achievement of the quality parameter.

d^+_9 is the over achievement of the quality parameter.

3)For the satisfaction agricultural demand.

Agricultural Usage $q_{14} + q_{24} + q_{34} + q_{54} + d^-_8 - d^+_8 = D_A$

d^-_8 is the under achievement of the satisfaction of the agricultural demand.

d^+_8 is the over achievement of the satisfaction of the agricultural demand.

4) For the satisfaction agricultural quality of water:

$q_{14}(T_{ng}-T_a) + q_{24}(T_{rg}-T_a) + q_{34}(T_s-T_a) + q_{54}(T_w-T_a) + d^-_{12} - d^+_{12} = D_A$

d^-_{12} is the under achievement of the satisfaction of the agricultural water quality demand.

d^+_{12} is the over achievement of the satisfaction of the agricultural water quality demand

5) For the satisfaction industrial demand:

Industrial demand $q_{13} + q_{23} + q_{53} + d^-_7 - d^+_7 = D_I$

d^-_7 is the under achievement of the satisfaction of the industrial demand.

d^+_7 is the over achievement of the satisfaction of the industrial demand.

5) For the satisfaction landscaping demand.

.andscaping and Gardening $q_{22} + q_{32} + q_{52} + d^-_6 - d^+_6 = D_L$

d^-_6 is the under achievement of the satisfaction of the landscaping & gardening demand.

d^+_6 is the over achievement of the satisfaction of the landscaping & gardening

3.4 Statistical Distributions

In order to evaluate the uncertainty of a parameter in the model, it is essential to simulate the process using random numbers. To generate to the random numbers we need to study the statistical characteristics of the parameters and hence have the necessity to examine the candidate statistical distributions. Before we proceed, let us define the following terms.

Random Variable: Random variable is a parameter that cannot be predicted with certainty; that is, a random variable is the outcome of a random or uncertain process. Such a variable can be treated in statistics as either discrete or continuous.

Discrete Random Variable: Discrete random variables arise when we deal with the quantities that are finitely many or countable infinite.

Continuous Random Variable: Continuous random variables arise when we deal with the quantities that are measured on a continuous scale, for example, all points in a plane etc. The behavior of either demand-input parameter or supply input parameter, in this study, can be assumed to be continuous as the data points lie on the same plane.

Many probability distributions for continuous variables are available in statistics nd each distribution has particular characteristics. The most widely used probability distributions are the following: normal, lognormal, uniform, exponential, beta, extreme value (gumbel), weibull, and triangular distributions

3.4.1 Normal Distribution

The normal distribution is also known as the Gaussian distribution or normal error curve and is fundamental to the entire realm of probability and statistics. One reason is that the central theorem states that under very general conditions, as the number of variables in the sum becomes large, the distribution of the sum of a large number of random variables will approach the normal distribution regardless of the underlying distribution (Benjamin and Cornell, 1970). Normal distribution is generally used when the results have many variables and none of them are predominant. The statistical characters such as cumulative density function (CDF), mean, and standard deviation of a normal distribution are given in Table 3.2

3.4.2 Lognormal Distribution

The lognormal distribution occurs in practice whenever we encounter a random variable, which is such that its logarithmic form has a normal distribution. This distribution is used generally when there is large uncertainty within the data. The characteristic parameters of this distribution are median (mean of the log) and standard deviation of log of quantity. The statistical characteristic CDF, mean and variance is :iven in Table 3.2.

3.4.3 Uniform Distribution

The uniform distribution with the parameters α and β is defined by the equation.

Table 3.2 Characteristics of Candidate Statistical Distributions

Distribution	CDF	Mean, μ	Variance, σ^2
Normal (x, μ)	$(x-\mu)/\sigma$	μ	σ^2
Lognormal (y_0,s)	$[(l/s)Ln(y/y_o)]$	$y_o \exp(s^2/2)$	$y_o^2 \exp(s^2)[\exp(s^2-1]$
Uniform (α, β)	$(x-a)/(b-a)$	$(a+b)/2$	$(b-a)^2/12$
Weibull (θ, m)	$1-\exp[-(y_m/\theta)^m]$	$\theta\Gamma(1+1/m)$	$\theta^2\{\Gamma(1+2/m)-\Gamma+1/m)]^2\}$
Exponential	$1-\exp[-(y-\theta)]$	θ	θ
Gumbel (Type III)	$\exp\{-y_m-y/\theta)^m\}$	$y_m-\theta\Gamma(1+1/m)$	$\theta^2\{\Gamma(1+2/m)[\Gamma(1+1/m]^2\}$
Triangular	0 if $x<a$ $(x-a)^2/(b-a)(c-a)$ if $a\leq x\leq c$ $1-\{(b-a)^2/[(b-a)(b-c)]\}$ if $c\leq x\leq b$ 1 if $b<x$	$(a+b+c)/3$	$(a^2+b^2+c^2-ab-ac-bc)/18$

y_m = maximum value of variable y
θ = scale factor of distribution
m = shape factor of distribution
s = Lognormal scatter factor
y_o = median value
a = lower limit of Uniform distribution
b = upper limit of Uniform distribution
a, b, c are the location of sides of the triangle in the Triangular distribution

$$f(x) = \begin{cases} 1/(a-b) & for\, a<x<b \\ 0 & elsewhere \end{cases}$$

Note that all values of x from a to b are equally likely in the sense that the probability that x lies in an interval of Δx entirely contained in the interval from a to b is equal to Δx/(a-b), regardless of exactness of the location of the interval. mean and standard deviation of the uniform distribution are given in Table 3.2.

3.4.4 Weibull Distribution

Closely related to the exponential distribution, Weibull distribution is one of the most widely used distributions in statistics. When the shape factor (m) of Weibull distribution becomes 1 it becomes an exponential distribution. The CDF, mean, and standard deviations of a Weibull distribution are also given in Table 3.2.

3.4.5 Exponential Distribution

As discussed earlier, if the shape factor in the Weibull Distribution is '1', it becomes the exponential distribution. This distribution has the interesting property that its nean equals its standard deviation or C.V. is 1, where C.V. is the coefficient of variation. The CDF, mean, and standard deviation of exponential distribution are also given in Table 3.2.

3.4.6 Extreme Value (Gumbel) Distribution

If normal or lognormal distribution cannot explain the extreme behavior of the data, an extreme value distribution is used. The PDF arises from the theory of extremes and has an appropriate shape, but is unbounded in both lower and upper ends. The CDF has a peculiar double exponential form.

Extreme Value Type I: When the random value can take any value between $-\infty$ and $+\infty$.

Extreme Value Type II: When the random value can take any value between 0 and $-\infty$.

Extreme Value Type III is the three-parameter model. It arises from the parent distribution in which the tails fall off about some finite value. The CDF, mean and variance of the type III distribution are shown in Table 3.2.

3.4.7 Triangular Distribution

When we do not have any data on the random variables of interest, the techniques discussed above are not applicable to the problem of selecting corresponding probability distributions. Triangular distribution can be a rough estimate of the data in this case. However, we require the values of minimum and maximum data points (a, b and h). The characteristic of this distribution are shown in Table 3.2.

'.5 Selection of Appropriate Distribution

For all the input variables in the model, i.e., the demand and supply parameters, it is necessary to know the type of distribution each parameter follows, so that we can deal with them as random variables and generate the appropriate number of realizations.

Numbers of tests are available to test the data for the type of distribution. The Kolmogrov-Smirnov test (K-S test) is one of the best techniques to check the distribution of the data.

3.5.1 Kolmogrov-Smirnov Test

The Kolmogrov-Smirnov test is a non-parametric test for differences between the cumulative distributions. It is concerned with the agreement between the observed cumulative distribution of sample values and a specified continuous distribution function; thus it is a test of goodness of fit.

The Kolmogrov-Smirnov one sample test is generally more efficient than the Chi square test for small samples, and it can be used for very small samples where the Chi square test does not apply (Irwin and John, 1985).

In this test we calculate the maximum absolute difference, D, between the values of cumulative distribution of random samples of size n and a specified theoretical distribution. Using the value of n and a level of significance, α, we calculate the D_α value from the K-S table. If D_α value is more than D value then the assumed distribution is true. The K-S test is exact for all samples (Benjamin and Cornell, 1970).

'.6 Forecasting Methodology

The basic step in water resources planning is determining an accurate forecast of the demand and supply of water. This forecast is then used as a basis for optimum allocation of water to various sectors of demand and supply. Forecasting is a time series process; that is, forecasting models provide us with a forecasted value at a given interval

of time. The accuracy of forecasting depends on the accuracy of the data, the stability of the data generating process, the length of forecasting periods and the forecasting method used. The idea behind any forecasting method is to use the past data to predict future values. Forecasting techniques can be classified as follows.

Short Range Forecasting: A typical period for short range forecasting is from hours to 1 year. Therefore, hourly, daily, weekly and monthly forecasts are considered to be short term forecasting. It is more accurate than medium or long range forecasting. In water demand or supply forecasting, this type of forecasting is seldom used.

Medium Range Forecasting: The time period of medium range forecasting is 1 to 5 years. The 1-year period is most accurate while the 5-year is the least accurate; this is due to the increase in the uncertainty in the period of forecasting. Sometimes medium range forecasting is used in water resources planning, for example for 5-year plans.

Long Range Forecasting: The time period of long range forecasting is more than 5 years. Telephone companies generally use long range forecasting to determine future demand for telephone services to allow for a reasonable and cost effective expansion of the network. Similarly, water planners also use long range forecasting of 15-20 years in order o plan the development of resources to meet the forecasted demand. In this research we se long range forecasting techniques to predict the future demands of water.

In the following section some of the forecasting techniques are presented and their limitations are discussed.

3.6.1 Gregory-Newton Interpolation Formulas

The Gregory-Newton interpolation formulas are used for interpolation and also for extrapolation (forecasting) of a data series when the function f(t) is known at discrete, evenly spaced points. The last point is used as base line. Following are the two formulas for interpolation and extrapolation.

Gregory-Newton Forward-difference Formula

$$f(t) = f_0 + t\Delta f_0 + t(t-1)/2!\ \Delta^2 f_0 + t(t-1)(t-2)/3!\ \Delta^3 f_0 + \ldots.. \quad (3.1)$$

$$f(t) = f_0 + t\nabla f_0 + t(t-1)/2!\ \nabla^{\tau} f_0 + t(t-1)(t-2)/3!\ \nabla^{\tau} f_0 + \ldots.. \quad (3.2)$$

Where f(t) = value of the function at time t

$\Delta f_i = f_{i+1} - f_i$ { the forward difference of f(t) at a period I}

$\Delta^2 f_i$ = the second forward difference

∇f_i = is backward difference of f(t) at i.

Equations 3.1 and 3.2 describe two polynomials that pass through every data point. These equations are poor methods for forecasting when the underlying data generation process contains randomness or noise. Therefore this study must have the forecasting method that accounts for randomness.

_.6.2 Regression Methods

If we assume the existence of the randomness in the observed data that we are evaluating, a smooth function, such as line, a logarithmic function, or a second-order polynomial, may be more a reasonable approximation of the average trend in the data. The problem we face in fitting such a function to the data is to determine the best

criterion to use in judging the goodness of the fit. The method of least squares in regression models is known to be an efficient and unbiased criterion for fitting such functions. The method of least squares defines the best fit as that which minimizes the sum of square errors between the observed data and the function. Regression models can be Simple Linear Regression or Multiple Linear Regression.

The regression method assumes that a relationship exists between the independent variables and the dependent variable and that relationship is stable over the time considered however, it would be naive to expect the dependent variable in the model to only depend on the independent variable; it could be a function of other variables also. A class of much easier to use tracking models that does not require an exogenous independent variable is the moving average method which is discussed as follows.

3.6.3 Moving Average Method (MA)

The moving average model tracks the changing movement of the variable of interest as a function of its prior levels. There are two types of moving average methods the simple moving average and moving average with trend methods.

3.6.3.1 Simple Moving Average

The simple moving average forecasting model assumes that the data generating rocess is constant but contains some random noise, as follows:

$$x_t = a_0 + \varepsilon_t , \qquad t = 1,2,3 \ldots\ldots. n$$

where a_0 = level that is assumed to be constant,

ε_t = random variable that represents the random noise in the data,

$E(\varepsilon_t) = 0$, $Var(\varepsilon_t) = \sigma_e^2$, and

n = number of periods for which data are available,

The moving average forecasting model should be written as

$$x_{t,\tau} = a_{0,}$$

where $x_{t,\tau}$ = forecast for period τ made at the end of period t, and

a_0 = estimate of a_0 at the end of period t , as calculated using the sum of square errors.

3.6.3.2 Moving Average with Trend

When a trend occurs in the data generating process, the appropriate description is

$$x_\tau = a_{0,t} + a_{1,t}\,\tau + \varepsilon_t$$

where $a_{0,t}$ = level at time t, assumed to be changing with the trend

$a_{1,t}$ = slope at time t, and

τ = number of periods into the future for which the forecast is to apply

To forecast future values of x_t, we need to estimate the parameters of the model:

$$x_{1,t} = a_{0,t} + a_{1,t}\,\tau$$

Developing expression for $a_{0,t}$ and $a_{1,t}$ can be done by observing the time series data. If a simple moving average of the trend is taken it will lag the actual data according to the equation

$$x_t - MA_t^{[1]} = [(n-1)/2]\, a_{1,t}$$

where $MA_t^{[1]}$ is a notation for the simple moving average taken at time t, and n is the number of observations in $MA^{[1]}$.

The double moving average is defined as

$$MA_t^{[2]} = 1/n \sum MA_t^{[1]}$$

In effect, the double moving average is an average of the simple moving average. Double moving average lags the simple moving average by the same amount as the simple moving average lags the actual level of the data. Hence we get the estimated values of $a_{0,t}$ and $a_{1,t}$ as follows.

$$a_{0,t} = MA_t^{[1]} + [MA_t^{[1]} - MA_t^{[2]}]$$

$$= 2\,MA_t^{[1]} - MA_t^{[2]}$$

In other words, we forecast the level of the data generating by adding to the simple moving average the difference between the simple and double moving average.

To find an expression for $a_{1,t}$,

$$MA_t^{[1]} = x_t - (n-1)/2\; a_{1,t}$$

$$a_{1,t} = 2/(n-1)(\,x_t - MA_t^{[1]}\,)$$

since $$x_t = a_{0,t} = 2MA_t^{[1]} - MA_t^{[2]}\,,$$

$$a_{1,t} = 2/(n-1)(MA_t^{[1]} - MA_t^{[2]}\,)$$

Hence, this equation does compute the forecast of the demand

$$\bar{x}_{1,t} = \bar{a}_{0,t} + \bar{a}_{1,t}\tau$$

where $$a_{0,t} = 2\,MA_t^{[1]} - MA_t^{[2]}$$

$$a_{1,t} = 2/(n-1)(MA_t^{[1]} - MA_t^{[2]}\,)$$

For the case of forecasting water demand, this methodology has been chosen. We can choose to use a three-point average or five-point average. The best method will be that which minimizes the sum of square errors between the forecasted level and actual level. Obviously the sum of squared errors will be lesser for a five point moving average (Box and Jenkins, 1976).

3.6.4 Exponential Smoothing

Exponential smoothing is a mathematical technique that utilizes the same principle of an N period moving average; however, it requires fewer calculations than does the moving average method. There are two types of exponential smoothing techniques 1. simple exponential smoothing and 2. double exponential smoothing techniques. Exponential smoothing is generally used for short term forecasting (Montgomery, D. C., 1968). Since we are planning for the long term we will not consider this technique of forecasting.

There are two more techniques for forecasting, the Winter's method and Box Jenkins methods. These are also short time series forecasting techniques and we will not consider them in our case.

From the above discussion, it can be inferred that for long term forecasting, there are two most suitable techniques, one is regression line fitting and the other moving average models. To forecast the demand of water (domestic, industrial, landscaping, and agricultural) the suitable technique is the moving average technique. Since there exist trend in our data, the moving average technique with trend was selected for forecasting. ts calculations are shown in the next chapter of Data Analysis.

3.7 Reliability Analysis

After calculating the model for uncertainty, the model should incorporate the reliability concepts. Basic concepts of reliability engineering are discussed in the following paragraphs.

The reliability study is concerned with random occurrences of undesirable events. It is defined as follows: The reliability of a system is the probability that, when operating under stated environmental conditions, the system will perform its intended function adequately for a specified interval of time.

3.7.1 The Reliability function

The probability of failure as a function of time can be defined by

$$P(\mathbf{t} \leq t) = F(t), \; t \geq 0$$

where **t** is a random variable denoting the failure time. Then F(t) is the probability that the system will fail by time t. In other words, F(t) is the failure distribution function (also called the unreliability function). If we define the reliability as the probability of success, or the probability that the system will perform its intended function at a certain time t, we can write

$$R(t) = 1 - F(t) = P(\mathbf{t} > t)$$

Where R(t) is the reliability function.

3.7.2 Normal reliability function

In this study, it is proved (discussed in section 4.2) that most of the data follows ɔrmal a distribution. Consequently, incorporation of reliability shall also be based on the normal distribution.

The normal distribution takes the well-known bell shape. The cumulative distribution for this is

$$F(t) = P[t \le t] = \int_{-\infty}^{t} 1/(\sigma\sqrt{2\pi})\, exp\left[-1/2(\left[(\tau - \mu)/\sigma\right]\right]$$

and

$$R(t) = 1 - F(t)$$

The integral cannot be evaluated in a closed form; however, tables for the standard normal density function is readily available and can be used to find probabilities for any normal distribution (Kapur and Lamberson, 1977).

The probability density function (p.d.f) for any normal distribution is given by

$$\phi(z) = \frac{1}{\sqrt{2\pi}} exp(-z^2/2), \quad -\infty < z < \infty$$

Then the standardized cumulative distribution function (c.d.f) is

$$\phi(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} exp(\tau^2/2)\, d\tau$$

Then, for a normally distributed random variable **t**, with mean, μ and standard deviation, σ, is equal to

$$P(t \le t) = P\left(z \le \frac{t-\mu}{\sigma}\right) = \phi\left(\frac{t-\mu}{\sigma}\right)$$

'he 95% quantile line is defined as equal to mean + standard deviation (μ + σ) and 5% quantile line is equal to mean - standard deviation ((μ - σ).

3.8 Model Solution Procedure

Model solution involves the following steps.

3.8.1 Step1 (Aspiration Levels)

The baseline model was formed in the previous section with the deviation variables in it. Next the model should specify the aspiration levels for each and every objective. Following are the components whose aspiration levels are to be specified.

1. Quantity and quality (TDS) of available groundwater Q_G ($10^6 m^3$/year)

2. Quantity and quality (TDS) of available surface water Q_S ($10^6 m^3$/year)

3. Quantity and quality (TDS) and quality (TDS) of available desalinated water Q_D ($10^6 m^3$/year)

4. Quantity and quality (TDS) of available treated wastewater Q_W ($10^6 m^3$/year)

5. Domestic demand D_D ($10^6 m^3$/year)

6. Landscaping demand D_L ($10^6 m^3$/year)

7. Agricultural demand D_A ($10^6 m^3$/year)

8. Industrial demand D_I ($10^6 m^3$/year)

9. TDS required for each category of demands i.e., T_d, T_l, T_a, T_i.

The quality aspect of the aspiration level in the model is shown in the Table 3.3. The reference KFUPM/RI (1997) establishes that the TDS required for landscaping and ıgricultural usage is 20 and 10 TSS, the values of 1,500 and 3,500 PPM for the said usage assumed according to this reference. The value of 3000 PPM for the industrial water has been assumed.

Table 3.3 Quality Parameters in the model

Parameter	TDS (PPM)
Non Renewable GW(T_{ng})	3500
Renewable GW (T_{rg})	2500
Surface Water (T_s)	1500
Desalinated Water (T_d)	50
Wastewater (T_w)	1000(10*)
Domestic Demand (T_x)	500
Landscaping Demand (T_l)	1500(20*)
Industrial Demand (T_i)	3000
Agricultural Demand (T_a)	3500(10*)

* Total suspended solids

3.8.2 Step2 (Prioritization)

In this step the goals are ranked according to their importance. Priority 1 is given to the constraint of satisfying the domestic consumption. Other priorities are shown in the mathematical model formulation section.

3.8.3 Step3 (Computer solution)

In the third step we solve the model using an appropriate computer package. We make use of the goal programming procedure in Statistical Analysis Systems (SAS) to solve this problem. The solution gives the values of the objective functions, the decision variables (q_{11} ...... q_{54}), and the deviational variables (d^-_1.....d^-_{13} and d^+_1 ..... d^+_{13}). The zero values for the objective function indicate that the objective is achieved. The negative deviation (d^-_1.....d^-_{13}) indicates that there is excess amount of that constraint available. The positive deviation (d^+_1 ..... d^+_{13}) indicates how much quantity of the constraint we need to supply to satisfy the conditions of the objectives and the constraints.

3.8.4 Step4 (Incorporating the Uncertainty in the model)

It has been discussed in the earlier sections that the input parameters in the model (supply demand and quality) behave with a high degree of uncertainty. To incorporate the parameter uncertainty, appropriate random numbers (realizations) are generated based on the statistical distribution and characterization of the parameters. Then the developed model is run according to the generated realizations. More detail is presented in the next chapter.

3.8.5 Step5 Reliability analysis

Notions of risk and reliability are incorporated to the results after running the model for uncertainty, as discussed in section 3.7.

4. DATA ANALYSIS

4.1 Data Description

The multi-objective model formulated in the previous chapter is applied to the Kingdom of Saudi Arabia. The data collected is described in the following section.

4.1.1 Water Supply

The data for the surface water, groundwater, desalinated water, and treated wastewater is shown in the Tables 4.1, 4.2, 4.3, and 4.4 respectively.

4.1.2 Water Demand

The data for the domestic demand, landscaping and gardening demand, industrial demand, and agricultural demand are shown in Tables 4.5, 4.6, 4.7 and 4.8, respectively.

The domestic demand data was collected from the Ministry of Finance and National Economy (MFNE) Statistical Yearbooks of Saudi Arabia. The industrial demand data are assumed as 85% of the domestic demand and the landscaping demand is assumed as 15% of the domestic demand (KFUPM/RI, Water Resources And Environmental Division, 1997). Along with the domestic demand data in Table 4.5, the data for the population of Saudi Arabia are also shown.

Table 4.1 Surface Water Data (MFNE, Statistical Year Book)

Year	Total rainfall (mm)	Runoff (MCM)*
1976	1777.77	533.33
1977	1435.90	430.77
1978	1402.30	420.69
1979	1832.50	549.75
1980	1289.10	386.73
1981	1523.00	456.90
1982	3056.00	916.80
1983	1487.80	446.34
1984	1678.60	503.58
1985	2804.90	841.47
1987	1922.77	576.81
1988	1723.90	517.17
1989	2537.60	761.28
1990	1766.40	529.92
1991	2000.10	600.03
1992	3703.50	1111.05
1993	3275.20	982.56
1995	3344.70	1003.41

* amount utilized by dams

Table 4.2 **Groundwater Data (MOP, 1995)**

Year	**Non Renewable GW (MCM)**	**Renewable GW (MCM)**
1980	2460	660
1985	8830	950
1990	13840	1100
1992	28110*	1570*
1995	14836	1500
2000**	13040**	1750**,

* Abdullah E Dabbagh (1997)
** Predicted By MOP (1995)

Table 4.3 Desalinated Water Data (MFNE, 1985-1995)

Year	Total (MCM)
1985	432.16
1986	485.73
1987	509.33
1988	568.66
1989	635.17
1990	653.29
1991	673.1
1992	691.17
1993	714.28
1994	715.6
1995	840
2000*	1150

* Predicted by MOP(1995)

Table 4.4 Treated Wastewater Data (MOP, 1995)

Year	Treated Wastewater(MCM)
1985	100
1990	110
1992	185
1995	150
2000	310*

* Predicted value

Table 4.5 Domestic Demand Data (MFNE, 1971-95)

Year	Domestic Demand(MCM)	Population(10^6)
1971	59.9	NA
1972	85.2	NA
1973	87.1	NA
1974	92.84	2.612+
1975	110	2.704+
1976	152.07	2.799+
1977	158.9	2.898+
1978	210.95	3.000+
1979	224.05	3.105+
1980	231.98	3.215+
1981	279.24	NA
1982	373.99	NA
1983	418.9	NA
1984	518	NA
1985	637	NA
1986	521.77	NA
1987	555.28	NA
1988	619.32	14.016++
1989	669.52	14.435++
1990	677.96	14.870++
1991	771.33	15.771++
1992	855.43	16.929++
1993	877.09	17.564**
1994	931.79	18.224**
1995*	946.92	18.906**
2000*	1746	22.60**

* Predicted by MOP (1995) : NA = Not Available
** Population growth rate of 3.75% (SCER, 1995)
+ UN estimates (UN World Population, 1992)
++ The Middle East and Africa (1996)

Table 4.6 Landscaping and Gardening Demand Data (MFNE, 1971-95)

Year	Landscaping Demand (MCM)
1971	8.98
1972	12.78
1973	13.06
1974	13.92
1975	16.5
1976	22.81
1977	23.83
1978	31.64
1979	33.60
1980	34.79
1981	41.88
1982	56.09
1983	62.83
1984	77.7
1985	95.55
1986	78.26
1987	83.29
1988	104.89
1990	101.69
1991	115.69
1992	128.31
1993	131.56
1994	139.76
1995*	142.03
2000*	261.9

* Predicted by MOP(1995)

Table 4.7 Industrial Demand Data (MFNE, 1971-95)

Year	Industrial Demand (MCM)
1971	47.92
1972	68.16
1973	69.68
1974	74.27
1975	88
1976	121.65
1977	127.12
1978	168.76
1979	179.24
1980	185.58
1981	223.39
1982	299.19
1983	335.12
1984	414.4
1985	509.6
1986	417.41
1987	444.22
1988	559.45
1990	542.36
1991	617.06
1992	684.34
1993	701.67
1994	745.43
1995*	757.53
2000*	1396.8

* Predicted by MOP(1995)

Table 4.8 Agricultural Demand Data (MOP 1985, 1990, 1995)

Year	Agricultural Demand(MCM)
1975	1900
1980	1850
1985	7400
1987	11784
1990	14580
1992	15308
1995	16400
2000*	14700
2010*	16900

* predicted by MOP (1995)

4.1.3 Groundwater Quality

Groundwater quality is an uncertain parameter, as there are number of aquifers in the Kingdom and there is a large variability of water in terms of quality. The quality of water is chiefly indicated by the presence of Total Dissolved Solids (TDS) in the water. The value of TDS varies largely for different aquifers. The three values of TDS are chosen for the quality indication of the water. The average of the minimum TDS of all the aquifers, the average of the maximum TDS of all the aquifers and the average of the average of the minimum and maximum TDS of all the aquifers, for both the non renewable and renewable groundwater are shown in Table 4.9.

4.2 Type of distributions

The demands (domestic, landscaping and industrial) are assumed to follow the normal distribution. For the case of non-renewable groundwater, we do not have enough data. As shown in Table 2.1, there are three types of non-renewable groundwater, the probable, proven, and possible. Triangular distribution is the most appropriate type of distribution for this. Figure 4.1 shows the triangular distribution of the possible, proven and probable resource.

Similar to the non-renewable groundwater, the renewable groundwater resources have the same three parameters i.e., proven, possible and probable reserves. Since we have these three parameters known for the quantification of this resource, triangular distribution is most appropriate to predict the availability of this resource. This distribution is shown in Figure 4.2.

Table 4.9 Groundwater Quality

TDS (PPM)	Non-renewable GW	Renewable GW
Minimum (a)	1750	2400
Maximum (b)	4866	4500
Average (c)	3308	3450

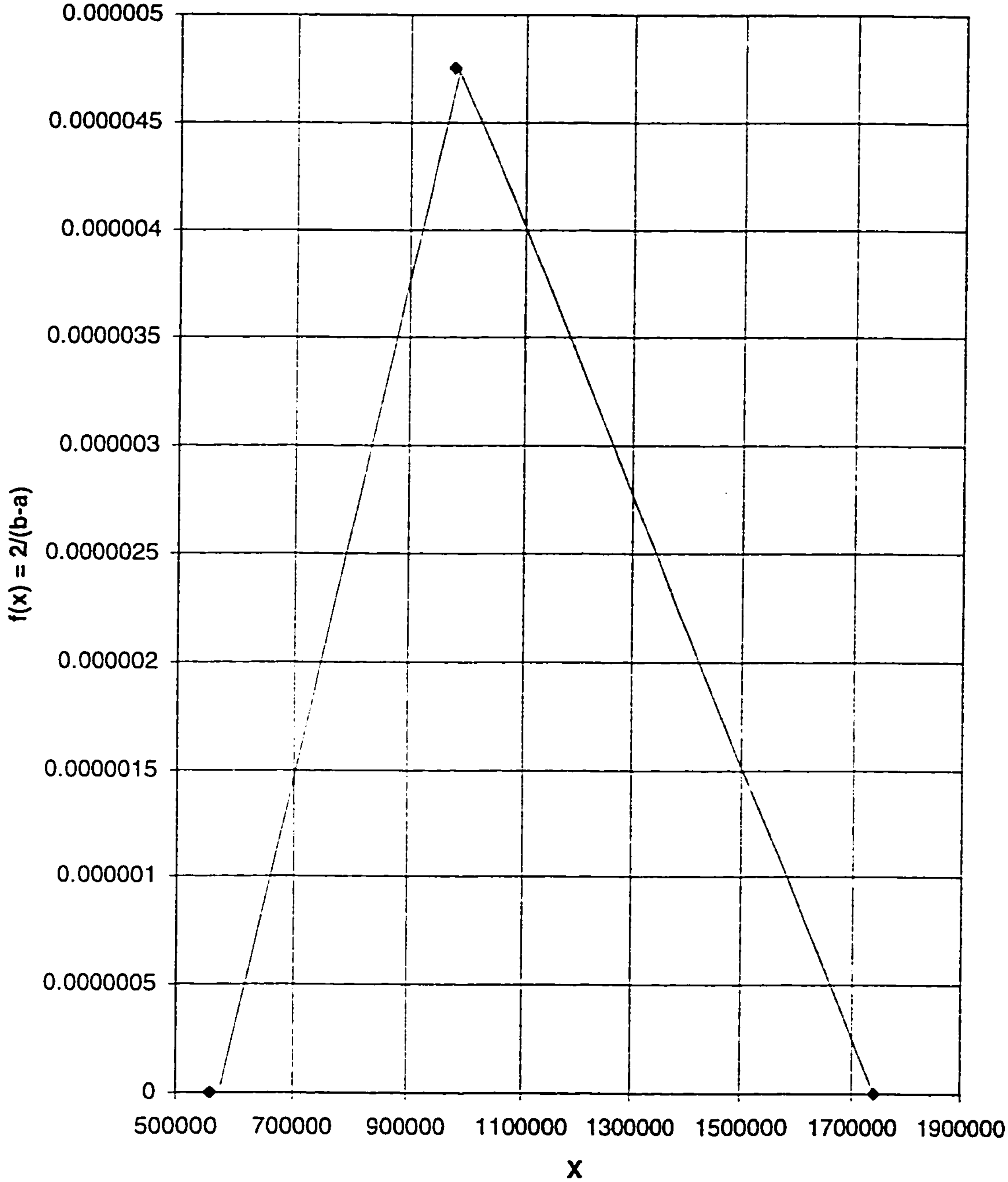

Figure 4.1 Triangular(a,b,c) density function for Non renewable GW for the year 1997

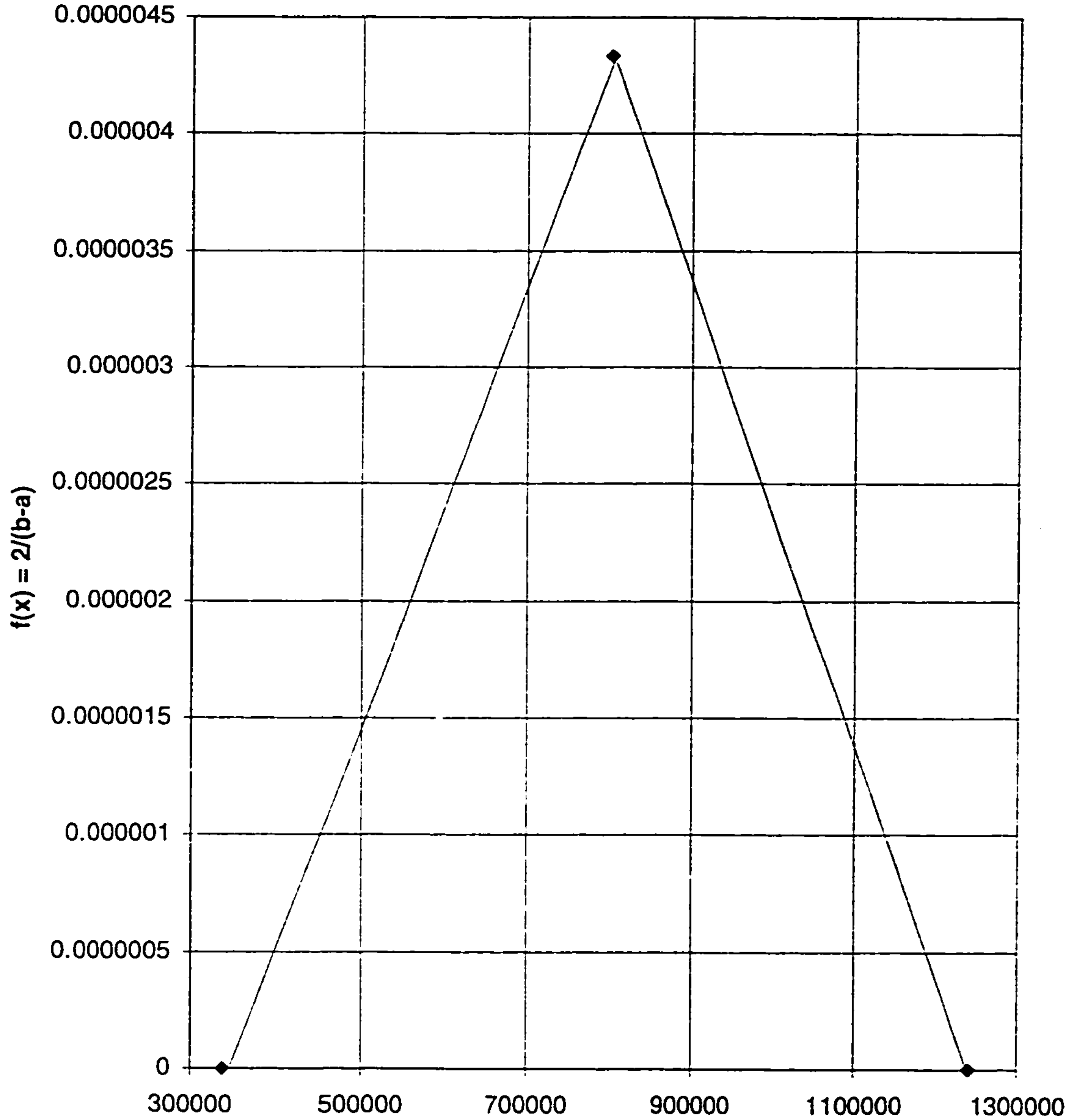

Figure 4.2 Triangular density function for Renewable GW for the year 1997

There are three parameters for the case of groundwater quality, i.e., minimum, maximum and average of the TDS values. Hence this can also be assumed to be triangular distribution as shown in Figure 4.3. The three parameter of the triangular distribution i.e., a, b and c are shown in Table 4.9.

Table 4.10 shows the statistical characteristics of all the parameters, taking the mean of the data upto the year 1995.

4.3 Data Forecasting

In the previous chapter, we have discussed various forecasting methods. The Moving Average with trend method has been used to forecast the data for the water resources demand (domestic, agricultural, industrial and landscaping) and supply (surface water and wastewater) parameters.

4.3.1 Domestic demand forecasting

The forecasted values of the domestic demand are shown in Figure 4.4. Black dots indicated the actual values and the other two lines are the forecasted values one by using moment average method and the other by the growth rate of 9.2% per annum predicted by ΛOP, 1995. The method of moment average seems to be reasonable as the 9.2% growth ırve rises steeply, which is highly unlikely to occur especially for long planning period. The moment average forecasted values would be used for the model run.

Table 4.10 Statistical characteristics of the parameters

S.no	Parameter	Type of Distribution	Mean(MCM)*	SD
1	Non-renewable GW	Triangular	-	-
2	Renewable GW	Triangular	-	-
3	Surface Water	Normal	642.69	230.22
4	Desalinated Water	Normal	607.85	102.18
5	Wastewater	Normal	171	84.73
6	Domestic Demand	Normal	585.11	625.48
7	Landscaping Demand	Normal	87.76	93.82
8	Industrial Demand	Normal	468.09	500.38
9	Agricultural Demand	Normal	11203.11	6008.7

* Data upto the year 1995

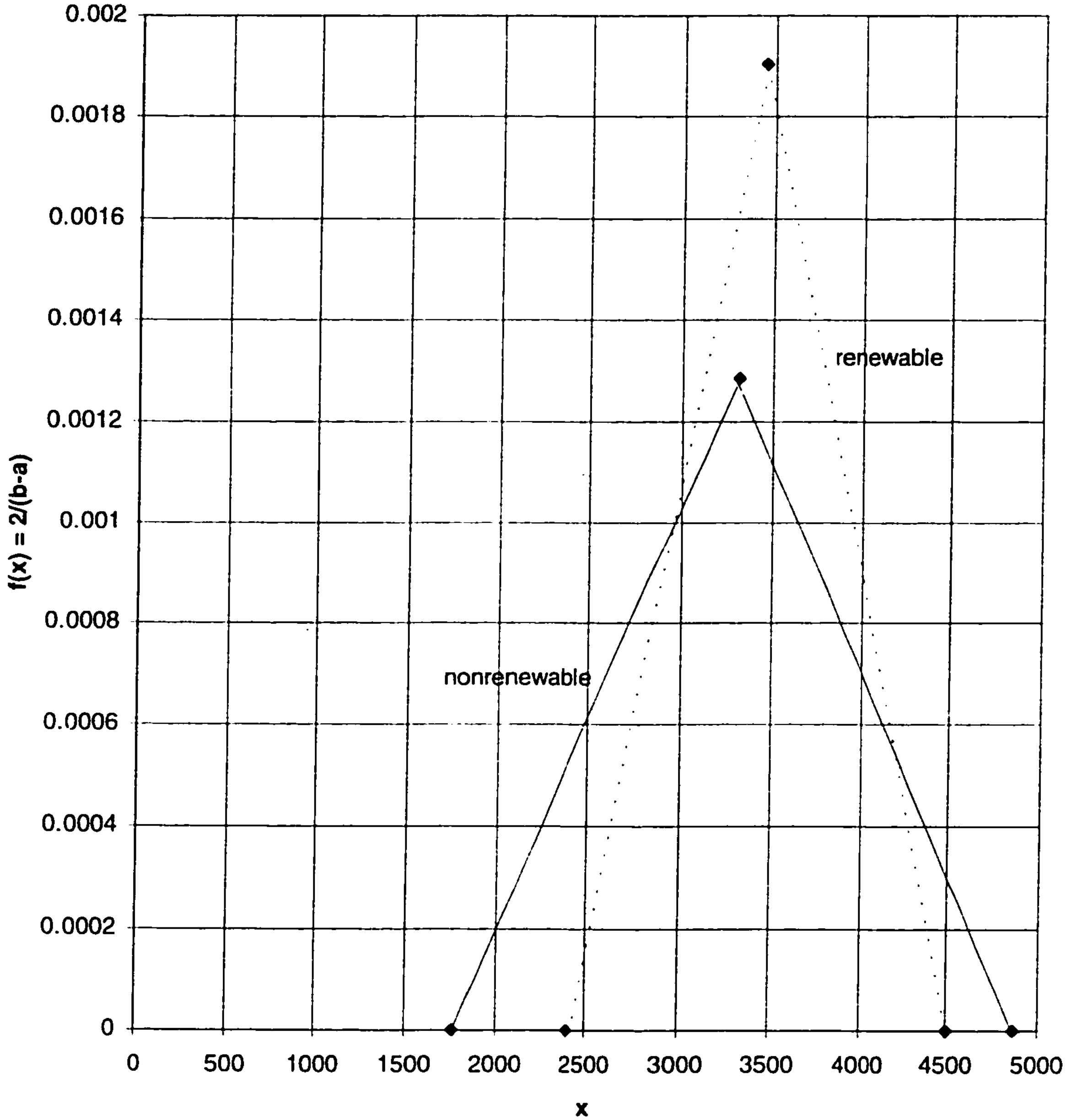

Fig 4.3 GW quality distribution for the year 1997

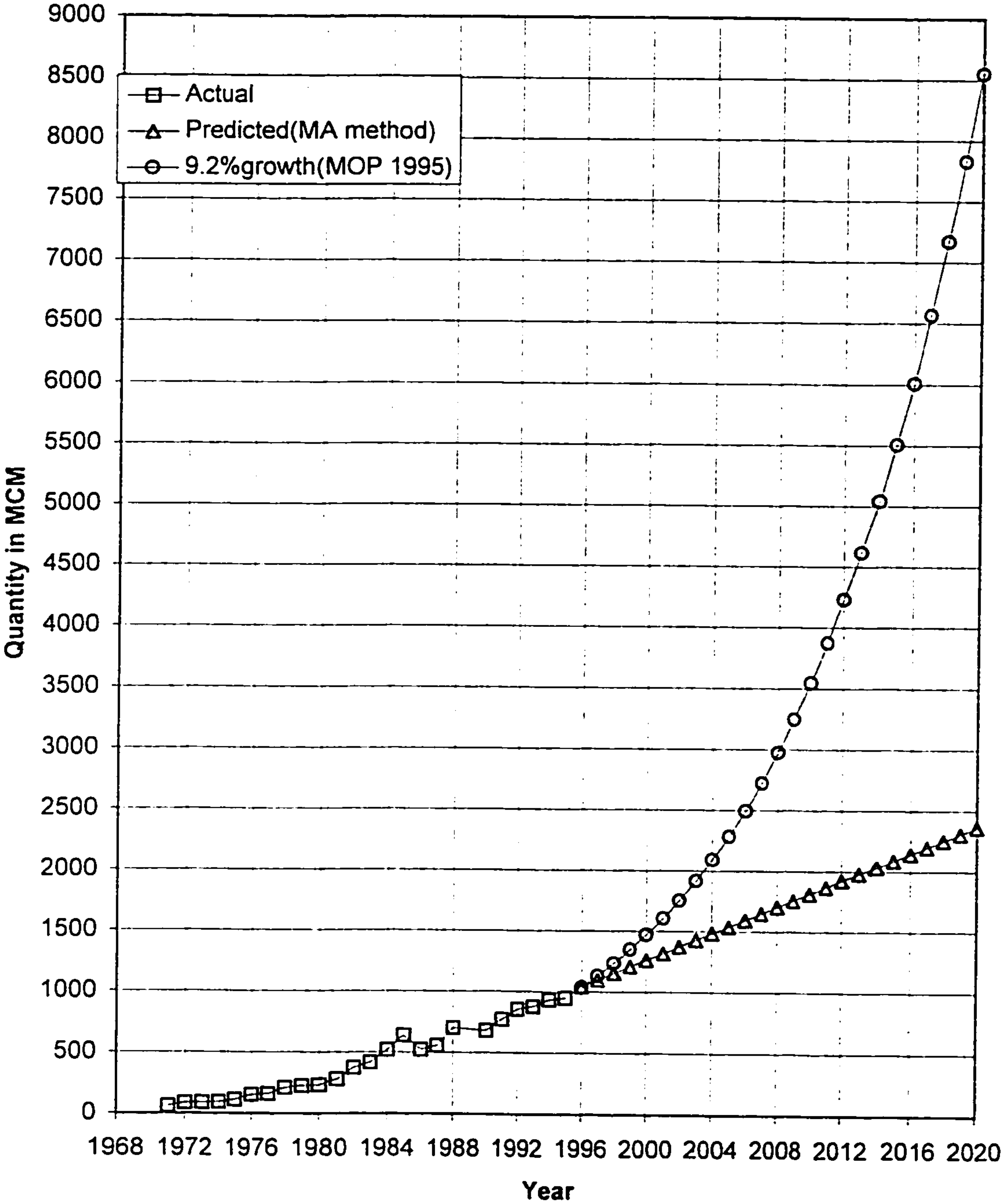

Figure 4.4 Historical and forecasted values of Domestic Demand

4.3.2 Landscaping demand forecasting

The forecasted values of the landscaping demand are shown in Figure 4.5. Black dots indicate the actual values and the other two lines are the forecasted values one obtained by using moment average method and the other by the growth rate of 9.2% per annum predicted by MOP, 1995. The method of moment average seems to be reasonable as the 9.2% growth curve rises steeply, which is highly unlikely to occur. The moment average forecasted values will be used for the model run.

4.3.3 Industrial demand forecasting

The forecasted values of the industrial demand are shown in Figure 4.6. Black dots indicated the actual values and the other two lines are the forecasted values, one obtained by using the moment average method and the other by the growth rate of 9.2% per annum predicted by MOP, 1995. Similar to the domestic and landscaping demand behavior, in this case also the method of moment average seems to be reasonable as the 9.2% growth curve rises steeply, which is highly unlikely to occur. The moment average forecasted values would be used for the model run.

3.4 Agricultural demand forecasting

The forecasted values of the agricultural demand are shown in Figure 4.7. Black dots indicate the actual values and the other two lines are the forecasted values one obtained by using moment average method and the other by the reduction rate of 2.5% per annum predicted by MOP, 1995. If we observe the actual value dots we can infer that there was a steep rise in the agricultural demand initially. Later it remains constant. The

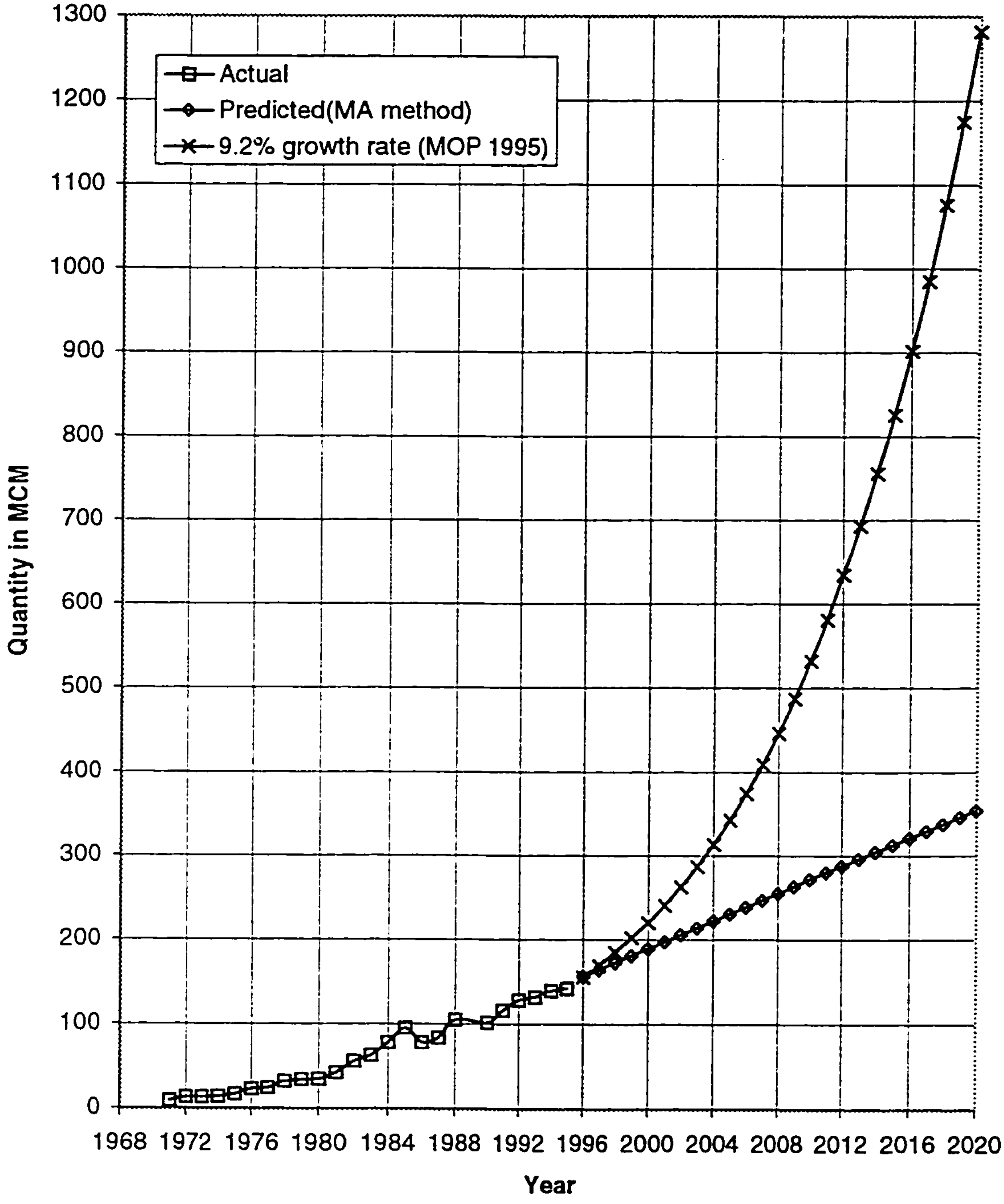

Figure 4.5 Historical and forecasted values of Landscaping Demand

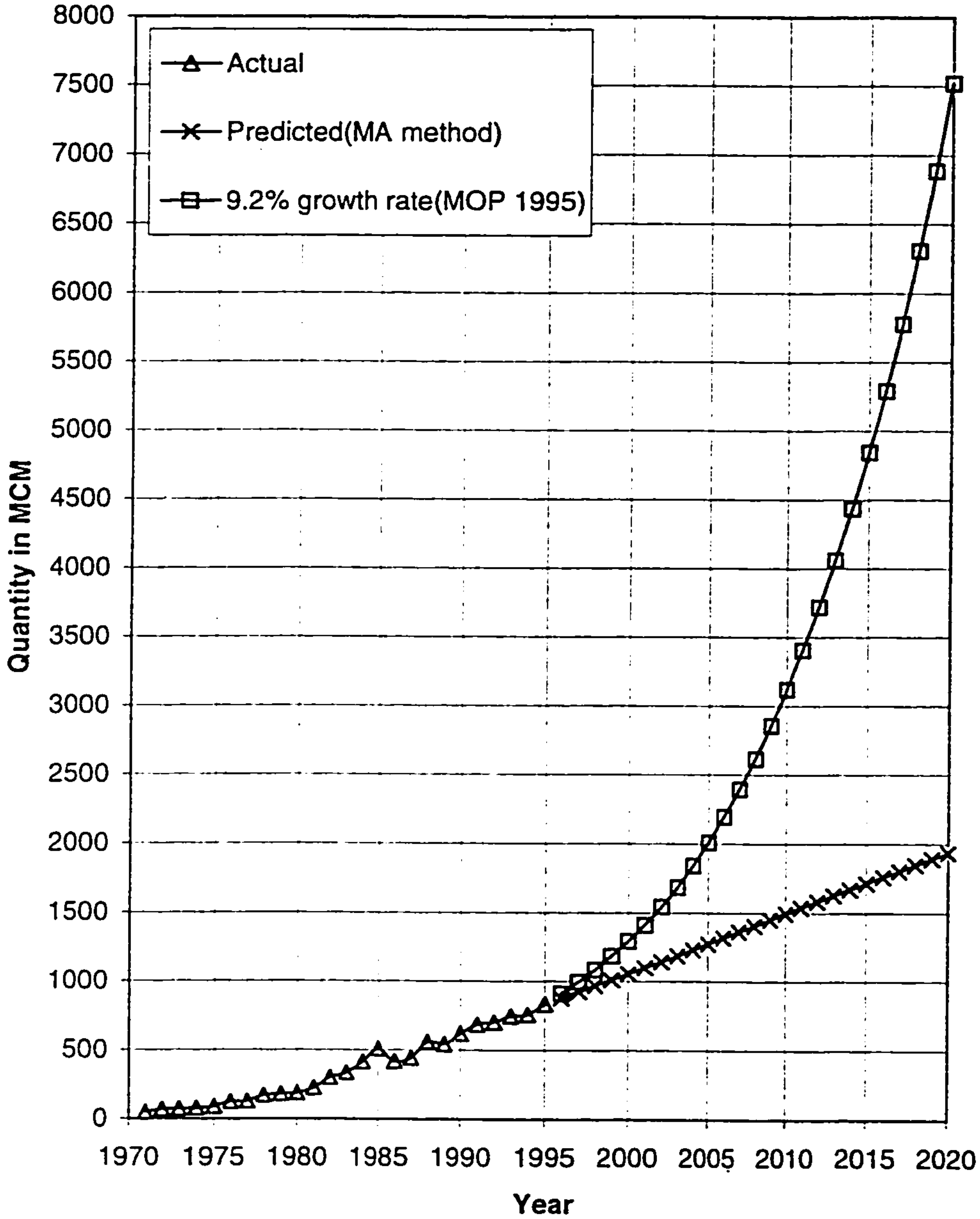

Figure 4.6 Historical and forecasted values of Industrial Demand

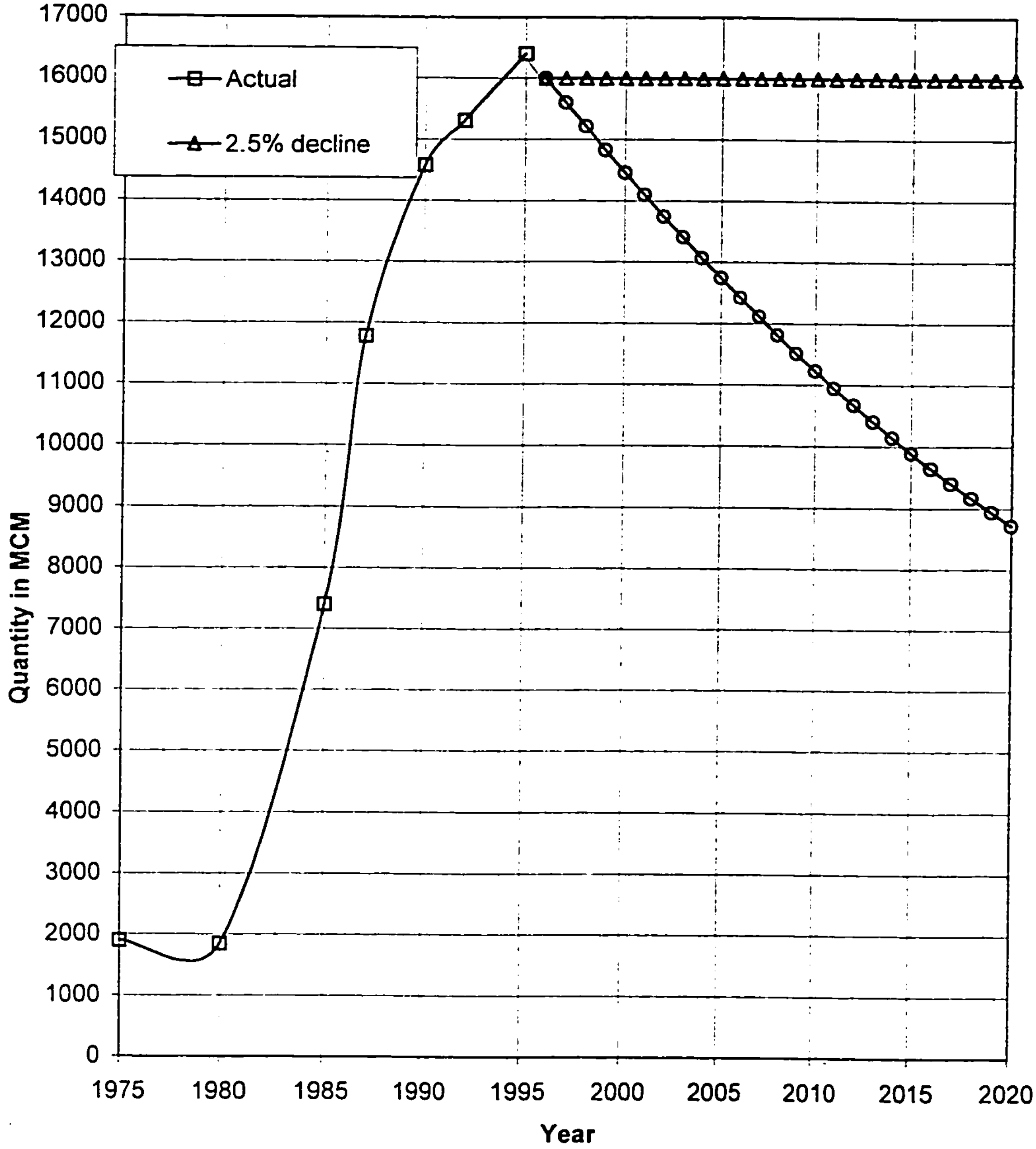

Figure 4.7 Historical and forecasted values Agricultural Demand

development plan of Saudi Arabia (MOP, 1995) emphasizes the reduction of agricultural water use by 2.5% per annum. Since it is difficult to cut short the developed infrastructure, at least we can say that the agricultural demand remains constant assuming there is no growth in the agricultural production in future. So we have to either use a constant straight line or the reduction rate curve of 2.5% as shown in Figure 4.7. We will use the straight line for the model run.

4.3.5 Surface Water

The previous data of the surface water is shown in Figure 4.8. We will use an average value of the historical data for the future surface water prediction as shown by the straight line in the Figure 4.8.

4.3.6 Desalinated Water

The forecasted values of the desalinated water are shown in Figure 4.9. The forecast is done using the value of the 10% given by MOP, 1995.

4.3.7 Wastewater

The previous (actual) data and the predicted data of the wastewater is shown in igure 4.10. The curves, one by moment average and the second by 15.6% growth (MOP, 1995) are shown in the graph. Since our aim is to use the wastewater as much as possible, we will use the steep rise curve (MOP, 1995 prediction) for the model run.

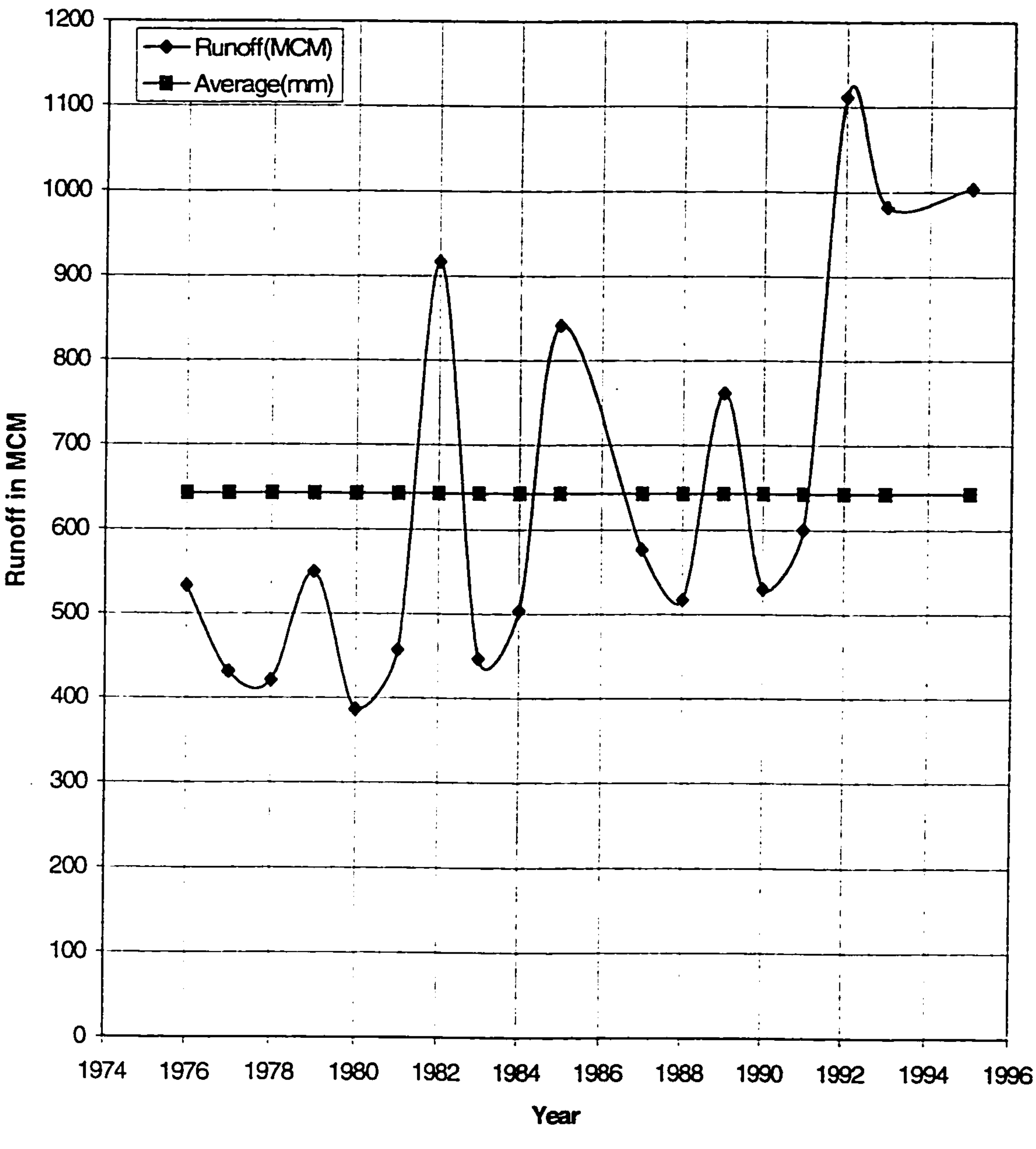

Figure 4.8 Historical Surface Water

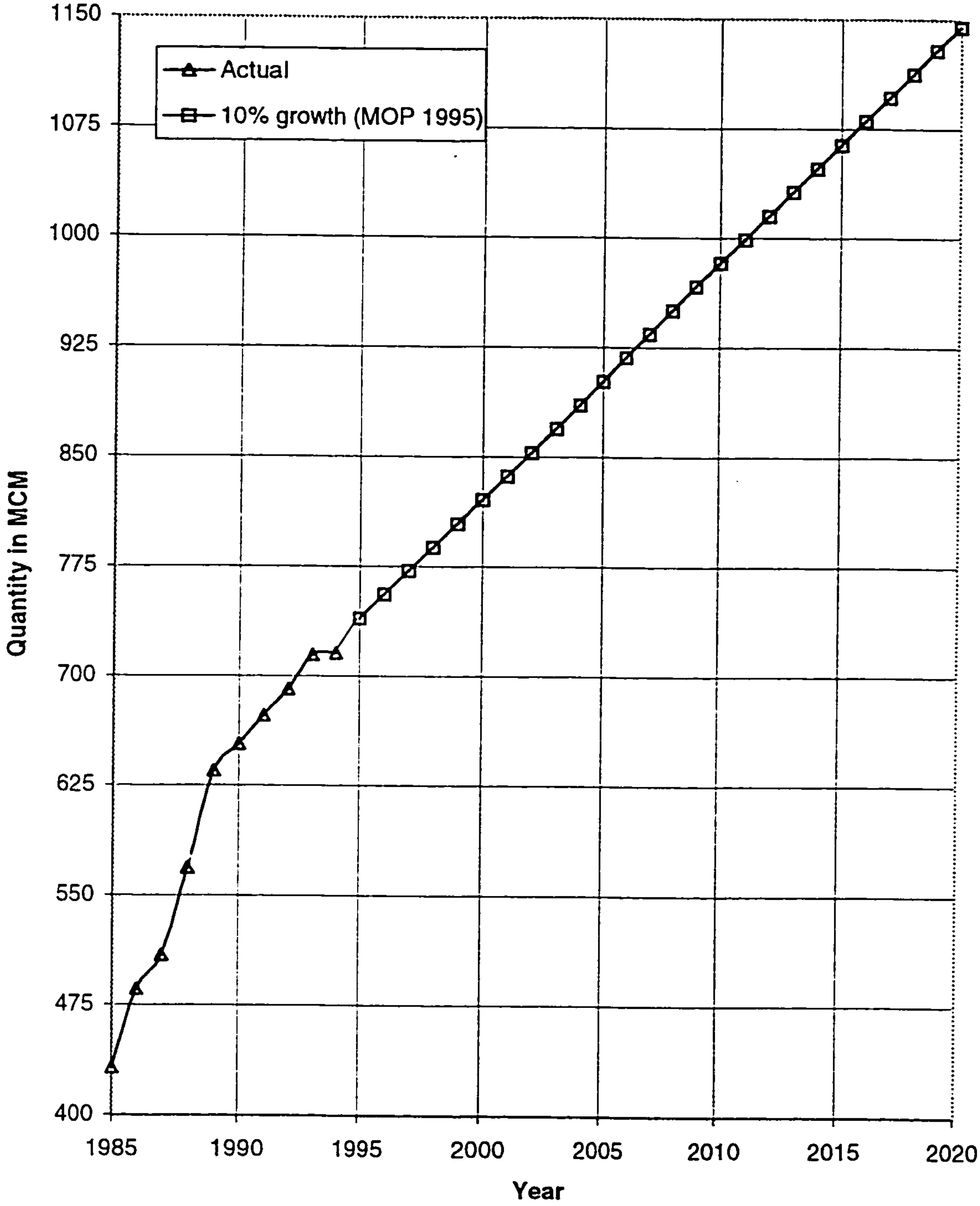

Figure 4.9 Historical and forecasted values of Desalinated Water

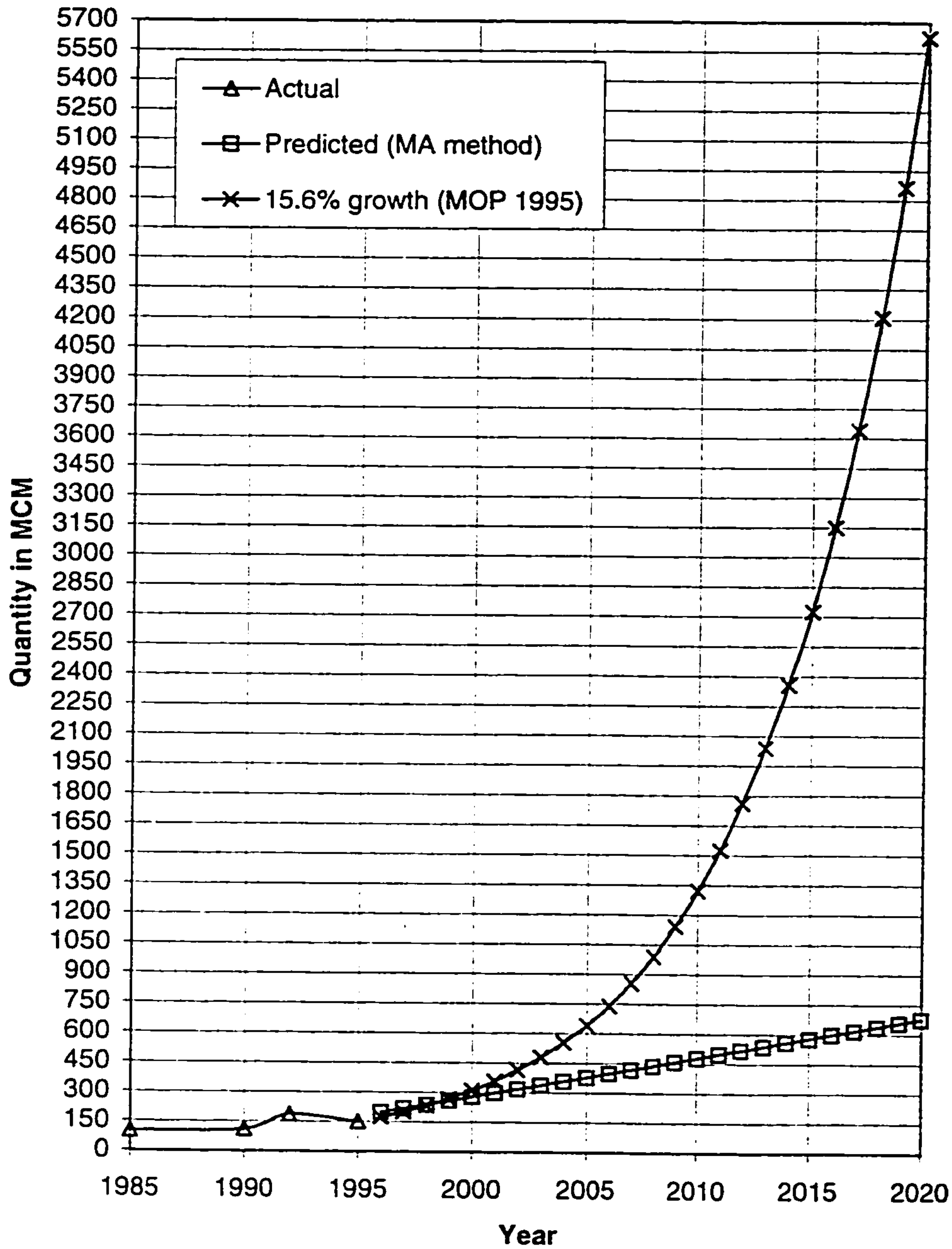

Figure 4.10 Historical and forecasted values of Wastewater

4.3.8 Non-renewable groundwater

Figure 4.11 shows the total picture of this resource. The three categories, i.e., proven, probable, and possible resources are shown in the figure. The forecast is done using the criteria given in MOP, 1995. The ministry of planning proposes a reduction in the consumption of this resource by an amount equal to 2.6% per annum of the current consumption. This is reflected in Figure 4.11.

4.3.9 Renewable groundwater

Figure 4.12 shows the total picture of this resource. The three categories i.e., proven, probable, and possible resources are shown in the figure. The forecasted values are calculated by taking the value of 2.0% increase in the current consumption (1995) of the resource as given by MOP, 1995.

4.3.10 Groundwater Quality Forecast

The main indicator of the groundwater quality is the total dissolved solids content (TDS). It is seen that the quality of groundwater deteriorates as we extract the water. It 'as been proved that in general the quality of groundwater deteriorates by 1.8% of TDS :r annum (i.e., the TDS of the groundwater increases by 1.8% every year), for the Dammam aquifer as researched by Zubari et al. 1997. The quality forecast is shown in Figure 4.13

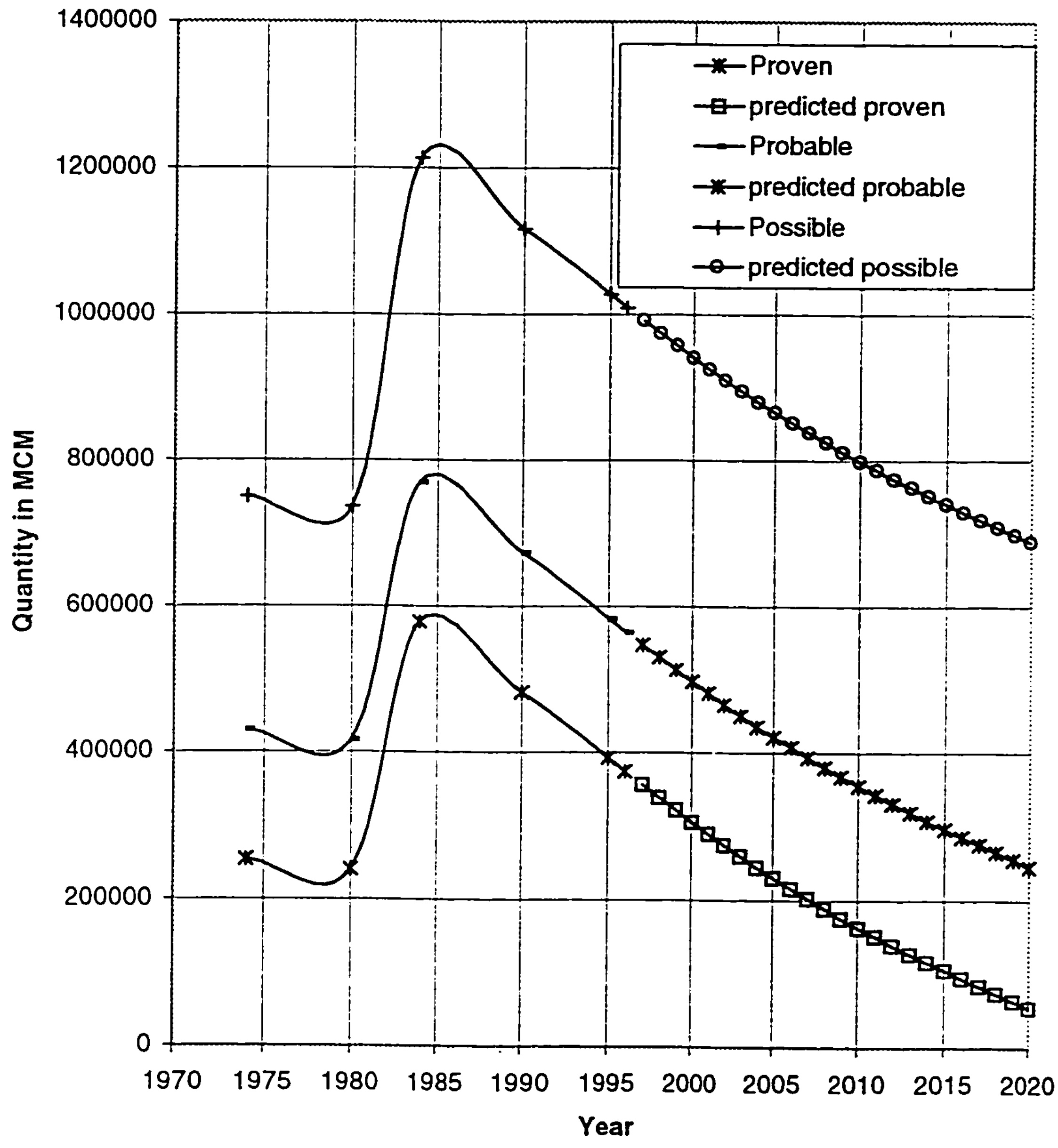

Figure 4.11 Nonrenewable GW depletion as forecasted by MOP, 1995

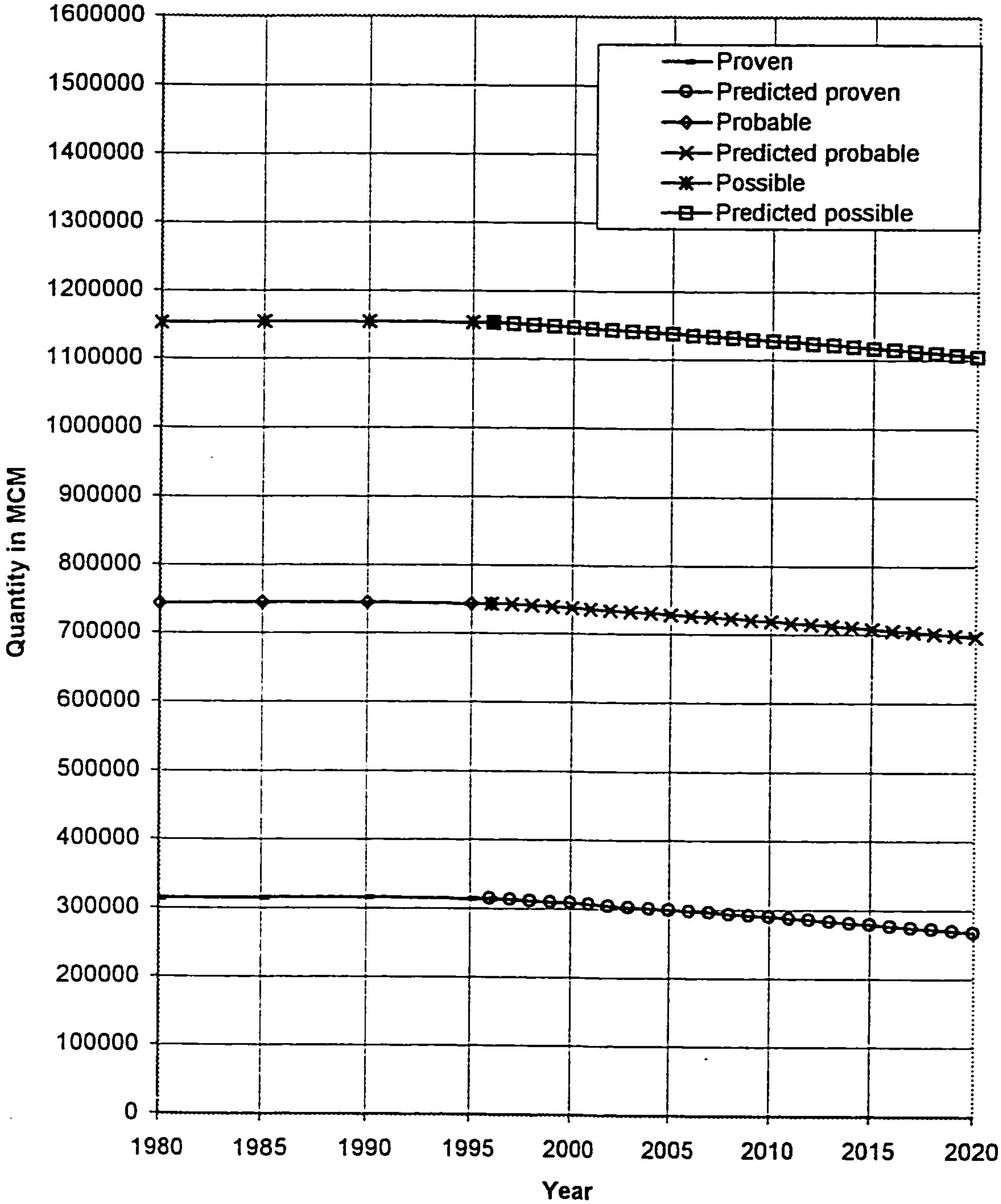

Figure 4.12 Renewable GW depletion as forecasted by MOP, 1995

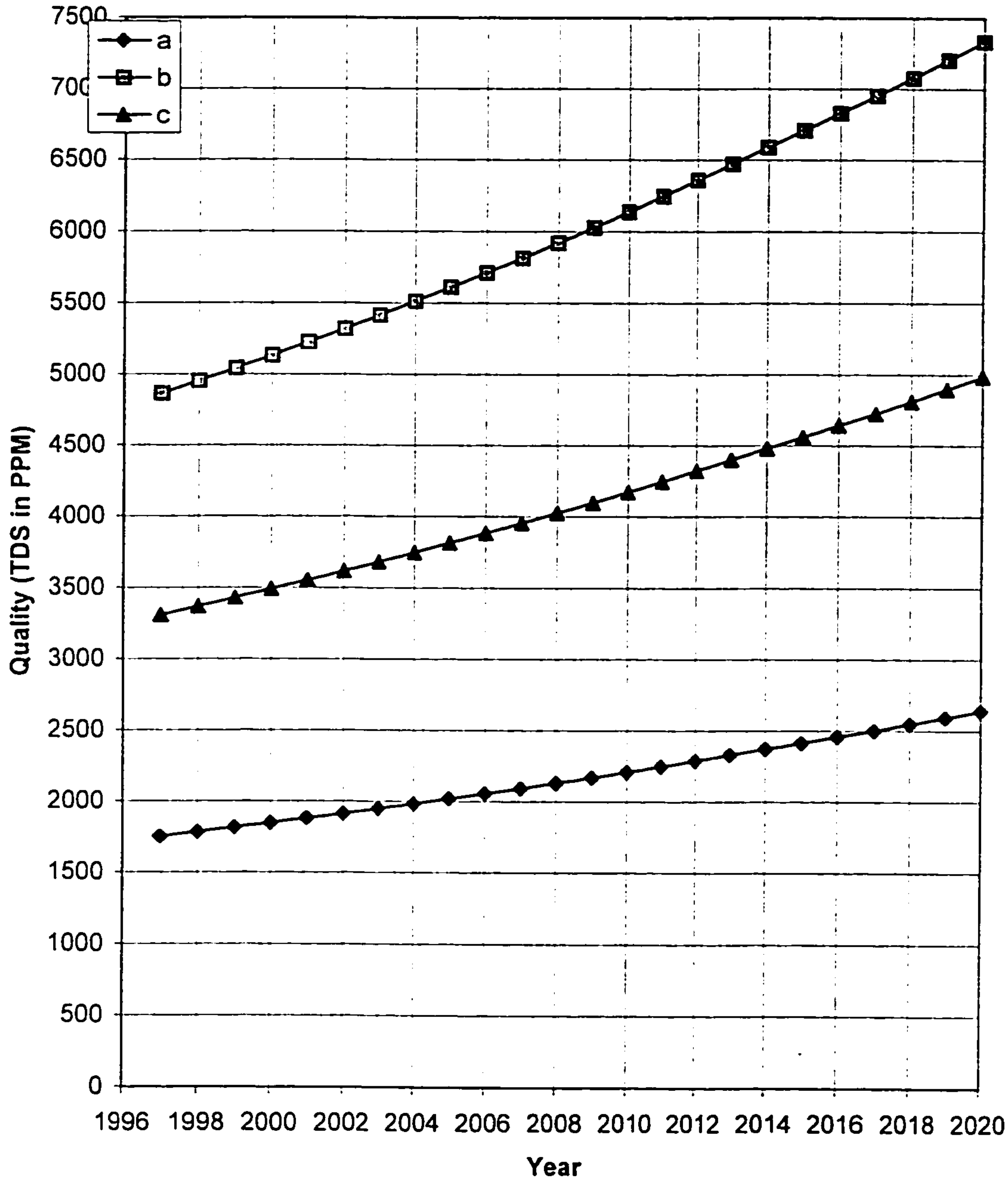

Figure 4.12 Groundwater Quality Change

4.4 Certain and Uncertain input parameters

There are two types of parameters, which are to be entered in the model for the model solution, i.e., the parameters that are certain and the parameters that are uncertain. The certain parameters are those that are constant for the particular year. They do not change for conditions of the model. For example, the supplies of surface water, desalinated water etc., are known.

The uncertain input parameters are defined as those which are not known with certainty, for instance the groundwater resource (proven, probable, possible), the groundwater quality (TDS), and the demands on the water supplies (domestic, agricultural etc,.). These are discussed in detail as follows.

4.4.1 Certain parameters

The parameters which will be considered as certain parameters in the model include the following:

(I) Surface water: Surface water is related to rainfall. In our case we shall assume an average value of surface water for future forecast using the historical values. Hence this is ·onsidered to be a certain parameter.

I) Desalinated water: Since the total capacity of all desalinating plants within the Kingdom is known, desalinated water will be dealt with as certain parameter.

(III) Wastewater: The wastewater is a certain parameter, because it assumed to be known before the model run. Its quantity (known quantity) is gradually increased with the increase of time.

(III) Desalinated and wastewater qualities: The qualities of desalinated water and the wastewater are also known with certainty, hence these parameters are also certain in the model.

(IV) Agricultural Demand: Agricultural water usage in Saudi Arabia has increased considerably in the recent years, which puts a burden on the groundwater reserves. The concerned authorities have recommended the reduction of agricultural water uses, however it is impracticable to reduce the developed infrastructure. But there is a possibility of maintaining a constant consumption, which has been considered in this research, The quantity used in this study is constant and equal to the current consumption.

4.4.2 Uncertain parameters

The parameters that will be considered as uncertain when running the model are as follows:

(I) Groundwater: The groundwater (renewable as well as non-renewable) is uncertain because we have proven probable and possible reserves of this resource. Since it is not known with certainty, it will be considered as an uncertain parameter.

II) Demands: The demands on water supplies (domestic, landscaping, and industrial) are ›nsidered to be uncertain as these depend on the population and the population is highly unpredictable. Hence these parameters are considered as uncertain in the model.

(III) Groundwater quality: There are number of aquifers in the Kingdom that provide the water requirements of the Kingdom, and these aquifers have variable quality. Hence we consider the groundwater quality to be an uncertain parameter in terms of TDS in the model.

4.5 Random number generation

A stochastic event is the event whose outcome is uncertain (e.g., the domestic demand of water). To describe a stochastic event, we specify the probability distribution that governs the outcomes. Using this probability distribution, we can simulate a stochastic event without actually waiting for it to occur. Simulation of this stochastic event is called the random number generation, a process in which each number in a specified interval has an equal probability of occurring.

In the preceding section we have discussed the behavior of the input variables, i.e., its statistical characteristics and the appropriate probability distributions. In order to run the model under uncertainty we need to generate the random numbers or what are called the realizations.

4.5.1 Number of Realizations

The random numbers were generated using the package MS Excel, in which there is built-in menu for the random number generation. This menu contains the random number generation for various distributions (including the normal distribution) but does ιot have the option for the triangular distribution. In order to generate the random ımbers following triangular distribution (for example the behavior of non-renewable groundwater, or the groundwater quality), a program was written in MATLAB and this was package used for the generation of the realization (for triangular distribution). A copy of this program is shown in Appendix I.

The model must ascertain how many random numbers will reasonably simulate the process. In order to find this a trial generation of different sets of 20, 30, 40, and 50

random numbers for a particular year (1997) was tested. Then, the mean and standard deviation were calculated and compared with the actual mean and standard deviation. The comparison is shown in Tables 4.11 and 4.12. From observing the table it was decided that a value of 40 numbers of realization is fairly reasonable for simulating the process.

Table 4.11 Comparison of Statistical Characteristics of Various Numbers of Realization for a Normal Distribution

	Mean	Std Dev	Variance
Actual*	1096.55	625.48	391233
20 Random Numbers	1056.65	699.32	489060
Standard Error(%)	***3.64***	***-11.81***	***-25.00***
30 Random Numbers	1186.6	683.27	466865
Standard Error(%)	***-8.21***	***-9.24***	***-19.33***
40 Random Numbers	1172.49	577.94	334016.8
Standard Error(%)	***-6.93***	***7.60***	***14.62***
50 Random Numbers	1041.54	553.67	305891.4
Standard Error(%)	***5.02***	***11.48***	***21.81***

* Domestic demand data of the year 1997

Table 4.12 Comparison of Statistical Characteristics of Various Numbers of Realization for a Triangular Distribution

	a	**b**	**mean**
Actual*	530331.3	1148599	839465
20 Random Numbers	604300	1015900	783610
Standard Error(%)	***-13.95***	***11.55***	***6.65***
30 Random Numbers	620300	1051700	765486.7
Standard Error(%)	***-16.96***	***8.44***	***8.81***
40 Random Numbers	599060	948830	763950.7
Standard Error(%)	***-12.96***	***17.39***	***9.00***
50 Random Numbers	553900	1011600	773242
Standard Error(%)	***-4.44***	***11.93***	***7.89***

* Non renewable GW data for the year 1997

5. MODEL APPLICATION & RESULT ANALYSIS

As we have discussed in section 3.3 the general multi-objective model was run for two cases; these two cases are discussed in the following sections.

5.1 Case 1

This case considers the desalinated water quantity (Q_D) as an unlimited source. It means that the model is allowed to utilize as much desalinated water as it requires along with the other source (groundwater), in order to satisfy the domestic water quantity and quality. The mathematical equations of the objective function and the constraints of the model are shown in the appendix VIII, and Table 5.1 shows the framework of the model.

5.1.1 Model Execution

The multi-objective water resources model was coded using the SAS program as shown in the appendix IX, then the developed model was applied to Saudi Arabia as a case study. The water supply and demand data for Saudi Arabia have already been discussed in the previous chapters. A sample of the input variables for the year 2000 is shown in appendix X.

Table 5.1 Modeling Framework

Demand (i) / Source (j)	Domestic (1) D_D	Landscaping &Gardening (2) D_L	Industrial (3) D_I	Agricultural (4) D_a
Nonrenewable (1) Groundwater(Q_{NG})	q_{11}	-	q_{13}	q_{14}
Renewable (2) Groundwater(Q_{RG})	q_{21}	q_{22}	q_{23}	q_{24}
Surface (3) water(Q_S)	-	q_{32}	-	q_{34}
Desalinated (4) water(Q_D)	q_{41}	-	-	-
Treated (5) Wastewater(Q_W)	-	q_{52}	q_{53}	q_{54}

5.1.2 Input parameters

There are two types of parameters that are needed to run the model. They can be classified as certain and uncertain parameters, which have been discussed previously in sections 4.4.1 and 4.4.2.

5.1.3 Model Run Procedure

The procedure of running the developed multi-objective model is as follows.

Step1: We transcribe the values of the input variables (for both certain and uncertain) classified for a particular year of model run. For uncertain classification the variable is considered as the mean value. From the past data we calculate the standard deviation of the uncertain input variable.

Step2: Using the calculated values of mean and standard deviation of the uncertain input variables, we generate 40 realizations.

Step3: Using these realizations, we run the developed multi-objective model the number of times equal to the number of realizations generated in step 2, keeping the certain parameter the same for each individual run.

1.4 Model Output

The output of the developed multi-objective model comprises, the values of the decision variables ($q_1 ...... q_{13}$), negative deviational variables ($n_1 ...... n_{13}$) and positive deviational variables ($p_1 ...... p_{13}$). A sample output is shown in appendix for V the year 2005.

The model has been run for the years 2000, 2003, 2005, 2007, 2010, 2012, 2015, and 2020. These years were selected randomly in order to avoid making the complex calculations for every year in the range. Ideally, one should run the model for uncertainty for each year.

5.2 Result Analysis

The results of the multi-objective model are discussed as follows:

5.2.1 Demands

For the stochastic run of the model for the years tested (2000, 2003, 2005, 2007, 2010, 2012, 2015, 2020), the percentage of times not fulfilling the desired objective (when we run the multi-objective model each year for 40 times, always we may not achieve the priority, i.e., P_1, P_2 etc. shown in appendix VIII, and thus is what failure rate means). Results are shown in Table 5.2. The number of runs for each year is 40.

From the table the following is concluded:

For each year, 0% (0 out of 40) is the failure rate for domestic demand and quality (failure to achieve the priorities). That is with 100% confidence it can be stated that the 'omestic demand and quality has been satisfied.

With a risk ranging from 0 to 12.5%, the other demands (landscaping, industrial, and agricultural) have also have been met.

The domestic demand and quality, being the first objective has always been achieved. These are the first and second priorities of the model. In the 40 random runs 100% of the time we get it as zero, which means these priorities have been achieved.

Table 5.2 Percentage Times of not fulfilling the desired objective for Case 1

Year	DD	LD	ID	AD	DQ	LQ
2000	0	7.5	0	0	0	0
2003	0	10	0	0	0	12.5
2005	0	12.5	0	0	0	20
2007	0	2.5	0	0	0	0
2010	0	7.5	0	0	0	0
2012	0	7.5	0	0	0	7.7
2015	0	0	0	0	0	7.7
2020	0	0	0	0	0	0

5.2.2 Quality

Table 5.2 also shows the quality failure rate of the domestic (DQ) and landscaping demand (LQ). From the table we infer that there is 0% risk of not meeting the prescribed domestic water quality (in terms of TDS=600 mg/l), the same for the landscaping water (TDS=2000 mg/l). Since the achievement of the domestic demand water quality is the second priority in the model it has been achieved 100% of the times. Moreover, this quality is dependent on the desalinated water whose quality is constant and its quantity has no constraint. The landscaping water quality is achieved since its demand is low compared to other demands.

Industrial and agricultural water quality is dependent mainly on groundwater resources whose quality and quantity are uncertain, and there is a wide variation in the quality of these water sources. Figures 5.1 and 5.2 show the variation of the output water quality of this resource. If we wish to incorporate the notions of risk and reliability, we have to build a 95% reliability line (mean + standard deviation) and 5% reliability line (mean - standard deviation) as shown in the figures. A procedure for incorporating the oncepts of risks and reliability has been discussed in the section 3.7.5. We observe the llowing from the figures.

5.2.2.1 Industrial water quality

The 95q line is built as shown in Figure 5.1. This line indicates the quality achievement of the industrial water (in TDS) with a risk of 5%. For example, in the year 2010 there is a risk of 5% to get the industrial water quality of 3650 mg/l approximately.

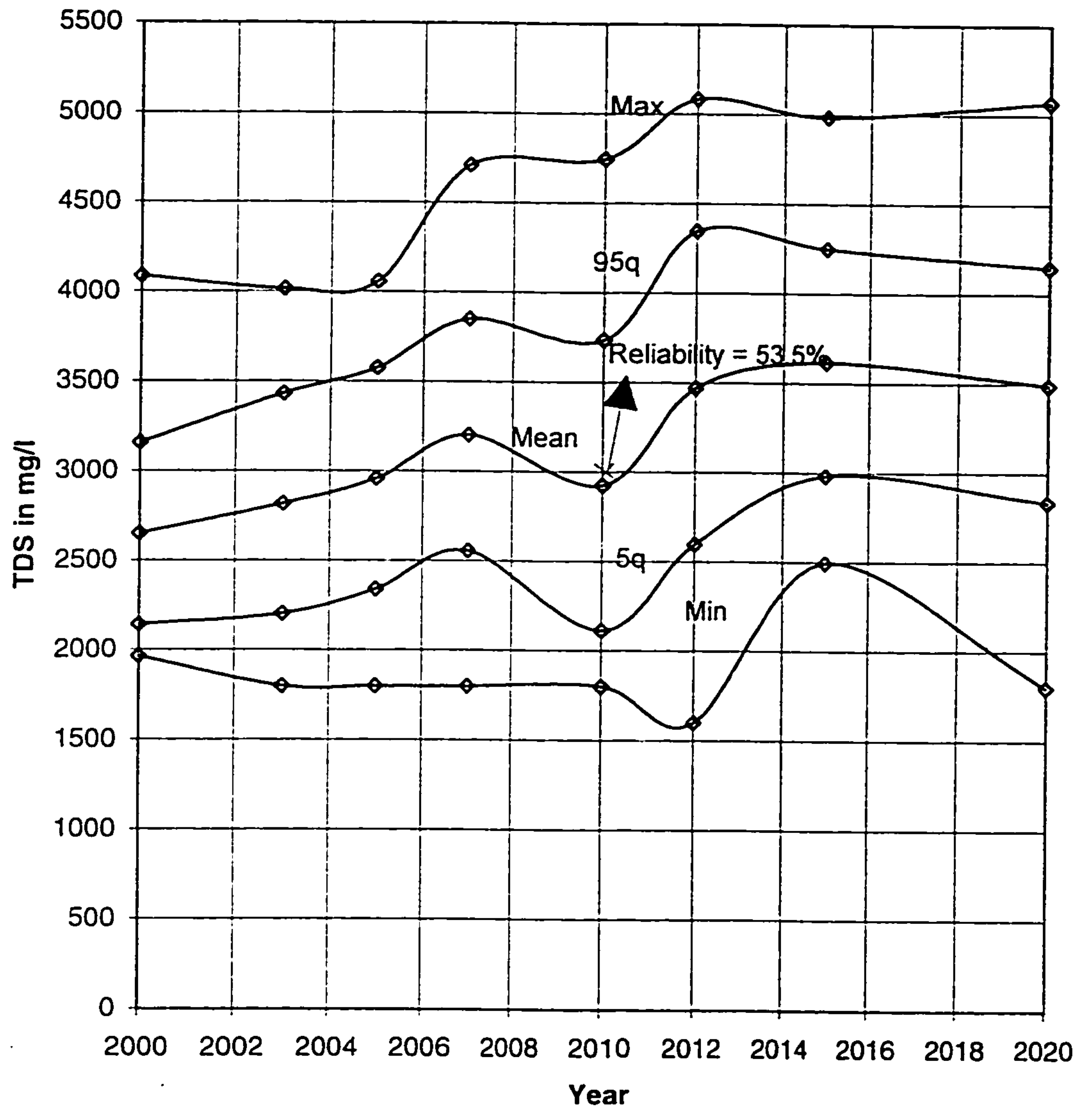

Figure 5.1 Industrial water quality variation for Case 1

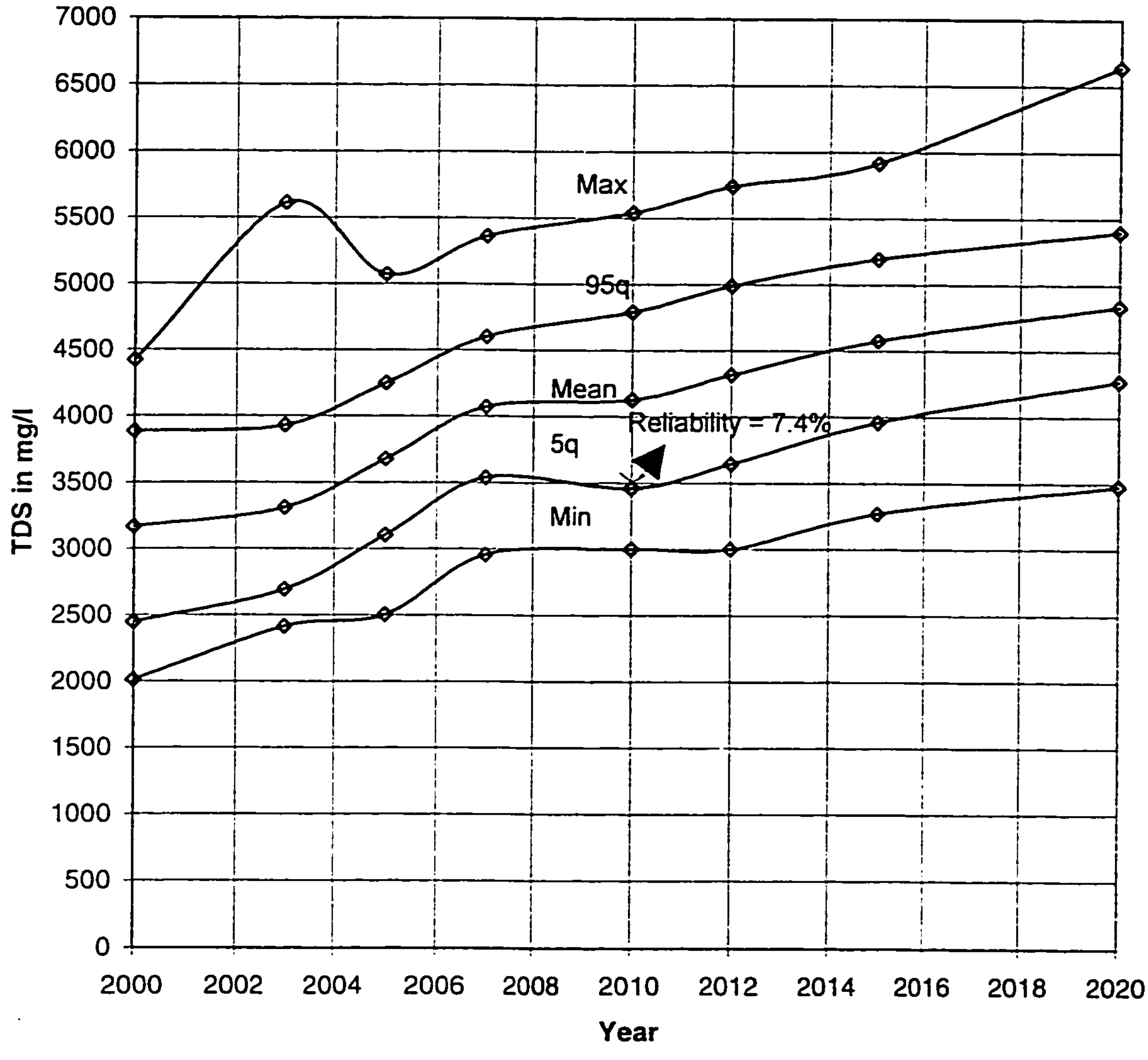

Figure 5.2 Agricultural water quality variation for Case 1

On the other hand, the risk of achieving a quality of 3000 mg/l in the year 2010 can be calculated as follows:

μ_{2010} = 2924 mg/l ; σ_{2010} = 810.67 mg/l, as discussed in the section 3.7.5, the formula for the reliability function (assuming normal distribution) to get the reliability for 3000 mg/l is

R(1800) = P[z> (3000-2924)/810.67)] = φ(0.093)from the normal distribution table we get a value of 0.5359, that means the reliability is 53.59% i.e., a risk of failure of about 46%. Such calculated values of reliability and risk are shown in Table 5.3.

Table 5.3 shows the risk and reliability of achieving the prescribed quality (TDS≤ 3000 pm), for all the years for which the model has been run. We observe from the Table that as the time increases the reliability of achieving the assumed quality decreases.

For example, with 75.1% confidence we can state that the quality of industrial water will be achieved in the year 2000, and for the year 2020 there is only a 23% confidence.

Similar interpretations can be made from Figure 5.1 and Table 5.3.

5.2.2.2 Agricultural water quality

As described for the industrial water quality figure, a 95q line was constructed as own in Figure 5.2. To quote an example from this figure, there is a 95% reliability (or 5% risk) when we say that in the year 2010 the agricultural water has a quality of approximately 4600 mg/l. Table 5.4 shows the risk and reliability of achieving the prescribed quality (TDS≤3500 mg/l), for all the years for which the model has been run.

Table 5.3 Reliability of the TDS of the Industrial water of case 1

Year	Max	Min	Mean	Stdev	Risk	Reliability
2000	4086	1965	2650	507.80	0.249	0.751
2003	4016	1800	2818	613.20	0.386	0.614
2005	4058	1800	2959	616.56	0.477	0.523
2007	4709	1800	3203	646.19	0.621	0.379
2010	4746	1800	2924	810.67	0.465	0.535
2012	5083	1600	3471	874.84	0.700	0.300
2015	4984	2494	3616	633.53	0.834	0.166
2020	5069	1800	3491	655.97	0.77	0.230

Table 5.4 Reliability of the TDS of the Agricultural water of case 1

Year	Max	Min	Mean	Stdev	Risk	Reliability
2000	4423	2015	3167	717.84	0.323	0.677
2003	5612	2417	3312	617.88	0.367	0.633
2005	5072	2504	3677	571.87	0.617	0.383
2007	5363	2958	4071	531.42	0.857	0.143
2010	5542	3000	4126	665.74	0.826	0.174
2012	5742	3000	4317	674.52	0.886	0.114
2015	5918	3270	4577	619.35	0.958	0.042
2020	6638	3477	4836	564.45	0.966	0.034

We observe from this table that as the time increases the reliability of achieving the said quality decreases (i.e., the risk increases).

For example, as shown in Figure 5.2, in the year 2010 the reliability of achieving the quality of agricultural water (equal to 3500 mg/l) is 7.4%.

Also, with 67.7% confidence we can state that the prescribed quality of agricultural water will be achieved in the year 2000, and in the year 2020, there is only 3.4% confidence. Similar interpretations can be made from Figure 5.2 and Table 5.4.We observe from the figures that there is a trend toward deterioration of these qualities as the time advances. This is because of the depletion of the groundwater reserves, which in turn deteriorates the groundwater quality.

5.2.3 Resources

In this section the groundwater (non-renewable and renewable), desalinated and wastewater resources are discussed.

5.2.3.1 Non-renewable groundwater

There is uncertainty associated with this resource, since we have proven, probable, and possible reserves, that we have assumed to follow a triangular distribution. The values of these reserves have been chosen based on the current values (1997). When the model is run for the year 2000, the predicted consumption of the year 1998 and 1999 have been subtracted to get the values of proven, probable and possible resources for the year 2000. Again, after running the model for the year 2000 (40 runs), an average value has been taken as the consumption for the year 2000 and this value has been used to subtract from the year 2000 to

obtain the values for the subsequent years. After running the model for the years (2000, 2003, 2005, 2007, 2010, 2012, 2015, and 2020), the residue of this resource is shown in Figure 5.3. The following conclusions are made after incorporating the concepts of risk and reliability.

In general, there is a downward trend of the reserve with respect to time. This is quite natural because as the time increases, there is an increase in demand and hence more burden on the groundwater resource.

Figure 5.3 shows the 95% reliability line. This line shows the amount of non-renewable groundwater that exists with a risk of 5%.For example, there is a risk of 5% or with 95% confidence we say that the non-renewable groundwater that remains in the year 2020 is approximately 920,000 MCM. Similar interpretations can be made from the figure for the other years.

There is an unusual rise of this resource between the years 2010 and 2014. Although there is no reason that this resource shall increase at any time (as there is no recharge), this can be incorporated to the unusual values of the random numbers that were generated for the model run. In general there is downward trend, which is quite logical.

5.2.3.2 Renewable groundwater

For the case of renewable groundwater, shown in Figure 5.4, following are the conclusions.

It is found that the depletion pattern of this resource is somewhat like a straight line with slight inclination. This is because this resource is rechargeable and hence complete depletion does not occur. Moreover, this resource is less uncertain than the previous one (non-

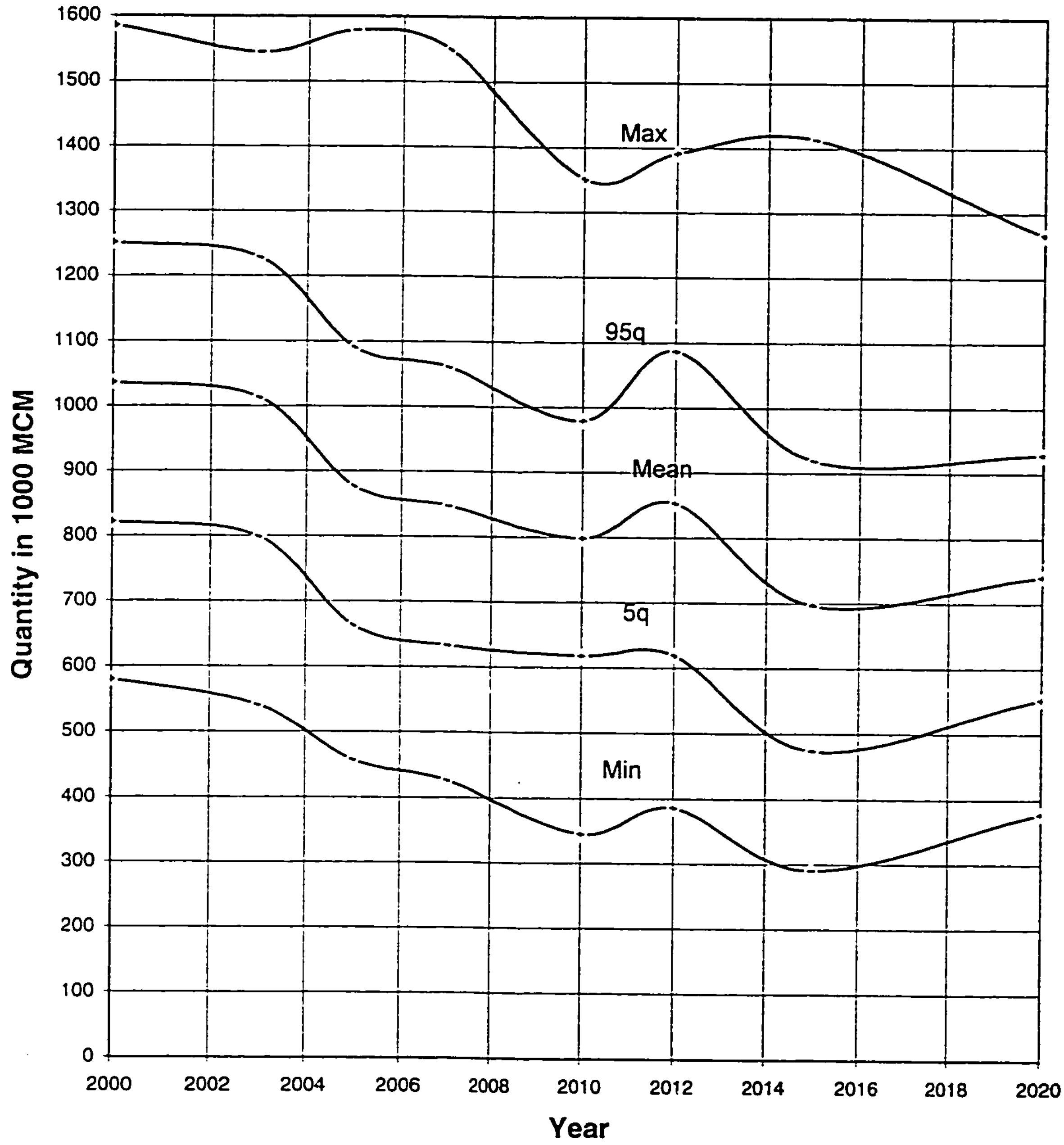

Figure 5.3 Non-renewable GW depletion for Case 1

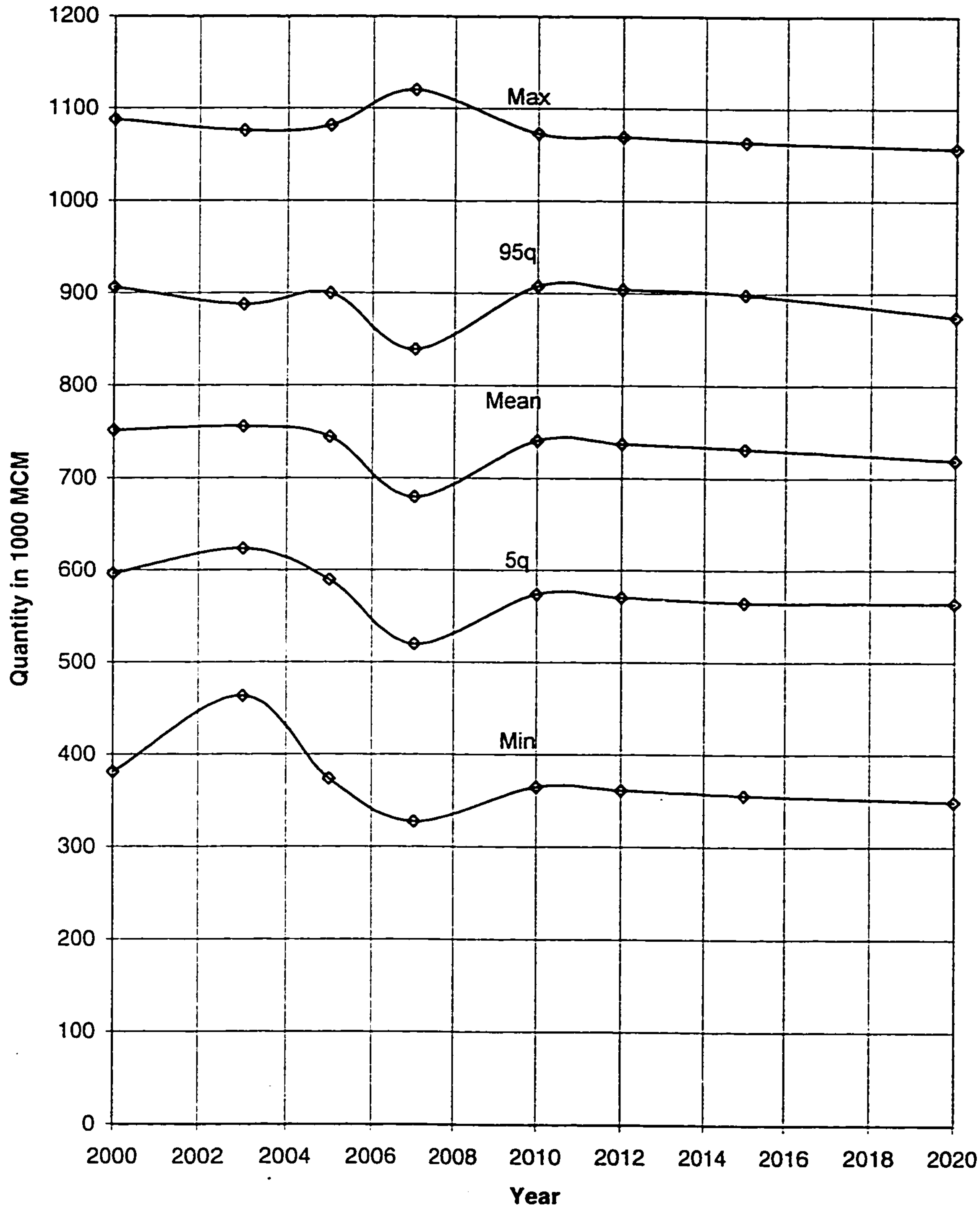

Figure 5.4 Renewable GW depletion for Case 1

renewable). As can be revealed from the Figure there is sudden draw- down between years 2006 and agricultural, industrial and landscaping purpose) in the consequent years, the load on this resource abates.

The 95% quantile line is shown in Figure 5.4, to give an example from this figure, in the year 2020, the renewable groundwater that remains with 95% confidence (or 5% risk) is approximately 880,000 MCM. Similar interpretation can be inferred from the figure.

5.2.3.3 Desalinated water

Since in this case i.e., case 1 there is no restriction on the utilization of the desalinated water, the consumption pattern of this water is shown in Figure 5.5. Following are the inferences from the figure.

Obviously, there is an increasing trend in the desalinated water consumption, thus reflecting the increase in the demand, hence the necessity to produce more water.

With 95% confidence it can be stated that an amount of 2100 MCM of desalinated water will suffice for the domestic demand and quality in 2020. Similar interpretations can be made from the figure with the help of the 95% confidence line. Suppose the amount of desalinated water available in the year 2000 is 1500 MCM; then the risk to satisfy the domestic water quantity and quality is found as 18% (calculated using the procedure shown in section 5.2.2.1) which is marked in Figure 5.5.

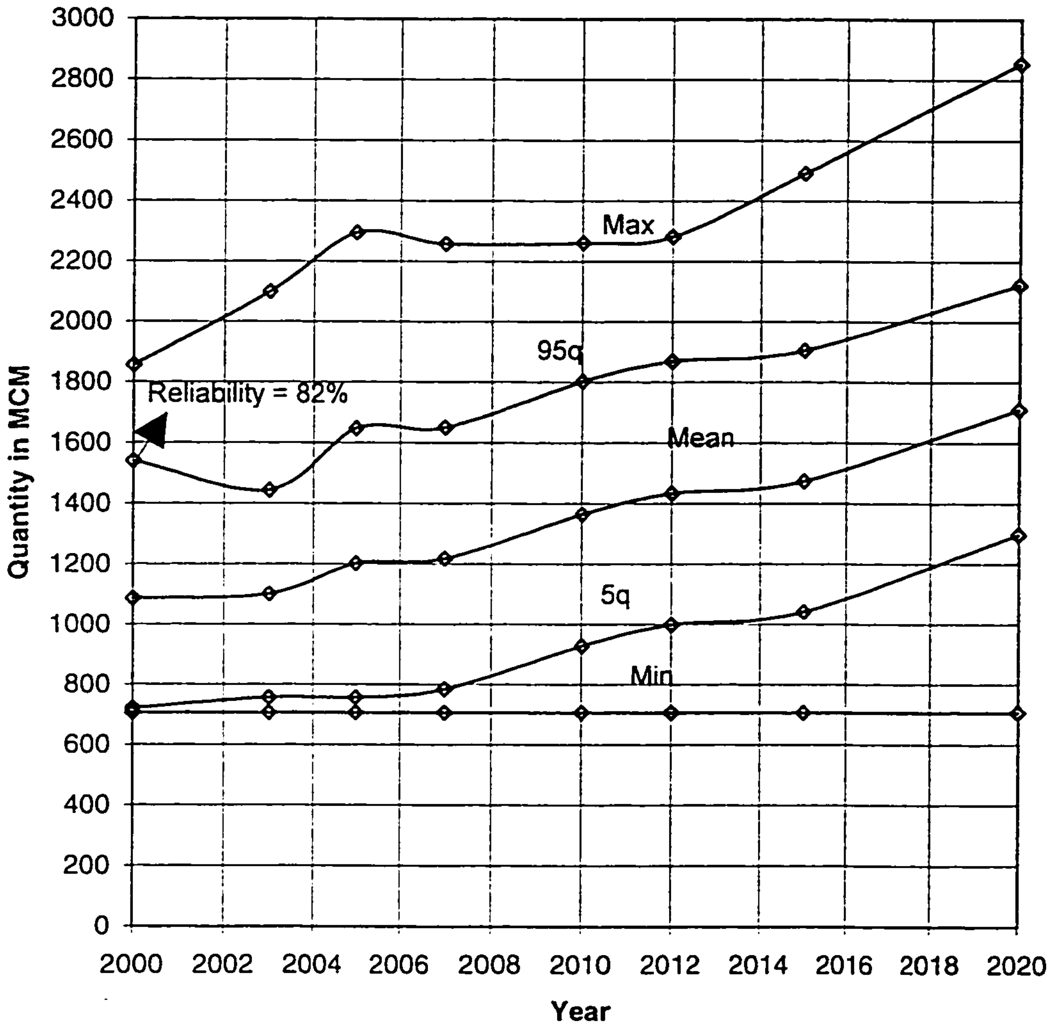

Figure 5.5 Desalinated water consumption for Case 1

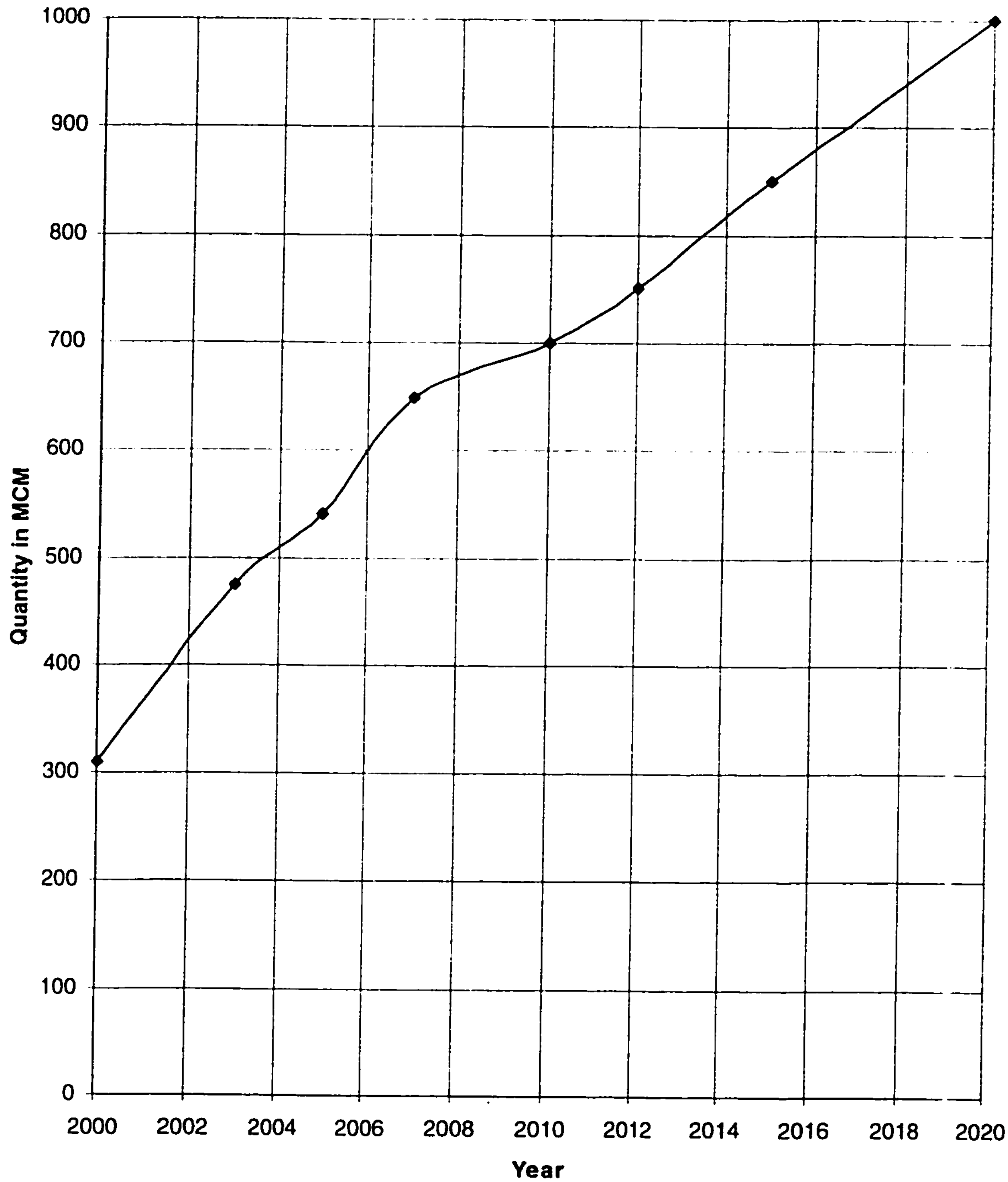

Figure 5.6 Wastewater utilization in the model

5.2.3.4 Wastewater

Wastewater utilization is shown in Figure 5.6. This is not uncertain and hence we cannot incorporate the concepts of risk and reliability. This is the amount of wastewater which we need to provide in

5.2.4 Cost

The graph for the total cost of water is shown in Figure 5.7. Following are the observations from this figure.

The cost increases as the time increases, which is due to the fact that there is an increase in the water consumption.

From the 95% confidence line it can be concluded that the sum of approximately 54,000 million SR is required as the water budget in the year 2020, i.e., we say this with a

5.3 CASE 2:

The hypothetical situation, case 2, assumes the same objective function and constraints as that of case 1, except for the constraint number 4 (shown in the Appendix III), where the value of p3 becomes zero. Because in this case there is a strict restriction on the quantity of the desalinated water, this constraint is made a rigid constraint, resulting in the right hand side of this equation (amount of desalinated water) remaining constant.

The procedure of the model run and its output format is similar to what has been discussed in sections 5.2.1 to 5.2.3.

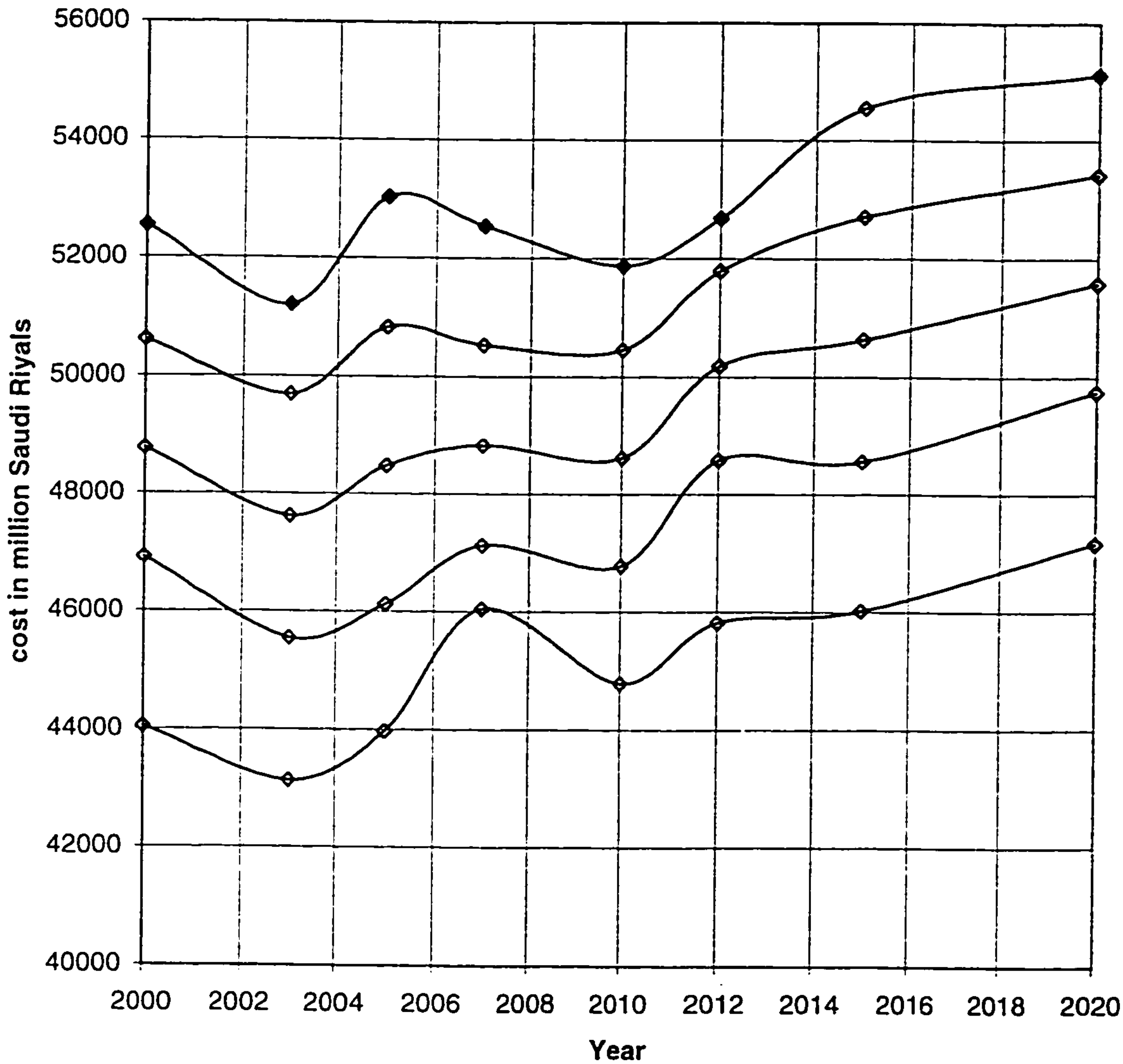

Figure 5.7 Cost variation for Case 1

5.4 Result Analysis

Similar to that of case 1, the results of the model run for this case are discussed as follows:

5.4.1 Demands

For the stochastic run of the model for the years tested (2000, 2003, 2005, 2007, 2010, 2012, 2015, and 2020), the failure rate to achieve the various priorities (percentage times of not fulfilling the desired objective) are shown in Table 5.5. The number of runs for each year is 40.

After observing the table, it can be said, for example that for the year 2000, 0% of the time (or 0 out of 40 times) did we fail to achieve the priority of the domestic demand. And similarly 2% (1 out of 40 times) was the failure rate for the industrial demand for the year 2000. On the Basis of this table the following points are concluded:

Reliability of having a domestic water quality with in the target, given the limited amount of desalinated water as a condition is, much lower than in the case of unlimited desalination capacity. From observing Table 5.6, it can be said with 46.9% confidence that the domestic quality (TDS≤1000 ppm) is met, in the year 2000. The reliability decreases with the year and in the year 2020, this reliability value is 2.4%.

The reason for the non-achievement of the prescribed domestic water quality is the limited amount of desalinated water and the poor quality of groundwater employed for the domestic water requirements.

Table 5.5 % Times of not fulfilling the desired objective for Case 2

Year	DD	LD	ID	AD	LQ
2000	0	7.5	0	0	0
2003	0	10	0	0	2.5
2005	0	17.5	0	0	5
2007	0	2.5	0	0	0
2010	0	7.5	0	0	0
2012	0	2.5	0	0	5
2015	0	0	0	0	2.5
2020	0	0	0	0	0

Table 5.6 Reliability of domestic water quality

Year	Max	Min	Mean	Stdev	Risk	Reliability
2000	1681	600	971	353.08	0.531	0.469
2003	1892	600	1092	386.68	0.594	0.406
2005	1568	600	1075	326.59	0.591	0.409
2007	1602	600	1088	306.41	0.610	0.390
2010	1522	600	1101	377.50	0.602	0.398
2012	1562	600	1191	392.32	0.742	0.258
2015	1566	600	1275	227.12	0.886	0.114
2020	1752	885	1384	192.88	0.976	0.024

5.4.2 Quality

In this case, since the amount of desalinated water is restricted, which is the major source of water for the domestic water, there is a direct effect on the quality of the domestic water. The model puts a burden on groundwater resource in order to satisfy this demand; however, because the quality of the groundwater is poor and uncertain, there is a wide variation in the quality of the output domestic demand water as shown in Figure 5.8. Table 5.6 shows the risk and reliability values for the domestic water quality. The minimum value of TDS for domestic water quality is TDS=1000 ppm, as prescribed by WHO standards (KFUPM/RI, 1997). In Table 5.6, the reliability column indicates achievement of domestic water TDS less than or equal to 1000 ppm. Following are the observations from Figure 5.8 and Table 5.6.

Figure 5.8 shows the 95% quartile line, for example in the year 2010, there is risk of 5% to have a TDS of domestic water quality less than or equal to approximately 1475 mg/l.

To have a quality of less than or equal to 1000 mg/l in the year 2010, the risk associated is 60.26% (or the reliability is 39.74%), which is shown in the figure.

Figures 5.9 and 5.10 shows the variation of the water quality of the industrial and agricultural demands. We observe the following from the figures.

5.4.2.1 Industrial water quality

The 95q line is shown in Figure 5.9. An example from this figure is that with 95% confidence it can be stated that in the year 2010, the industrial water quality achieved is 4200 mg/l.

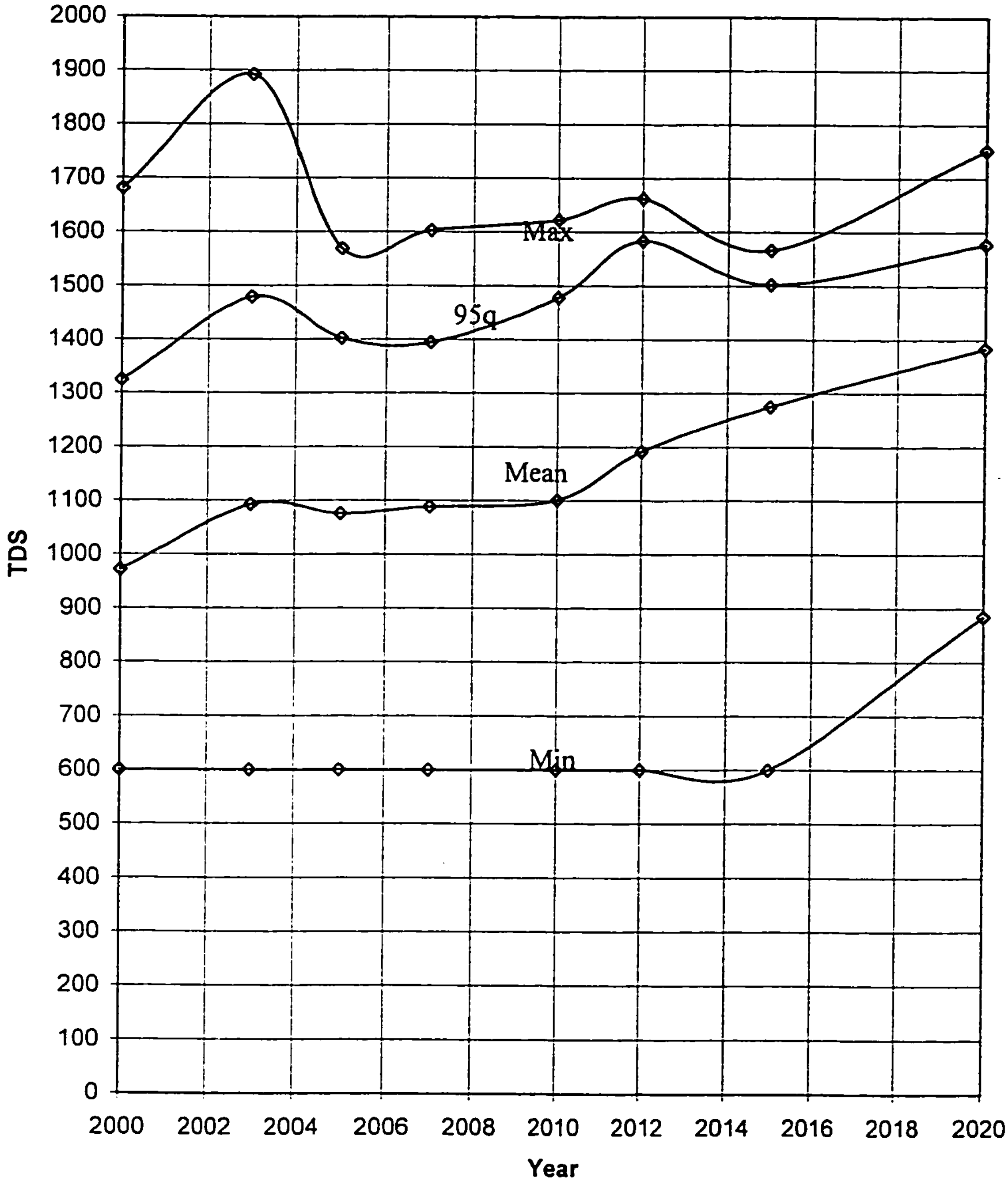

Figure 5.8 Domestic water quality variation

Table 5.7 Reliability of the TDS of the Industrial water of case 2

Max	Min	Mean	Stdev	Risk	Reliability
4892	1800	2636	942.50	0.352	0.648
5711	1800	2892	847.73	0.453	0.547
4058	1800	2946	641.93	0.465	0.535
4709	1800	3203	646.19	0.621	0.379
4746	1800	3402	728.77	0.708	0.292
5083	2203	3523	593.64	0.810	0.190
4984	2494	3518	581.43	0.813	0.187
5069	1800	3582	584.36	0.838	0.162

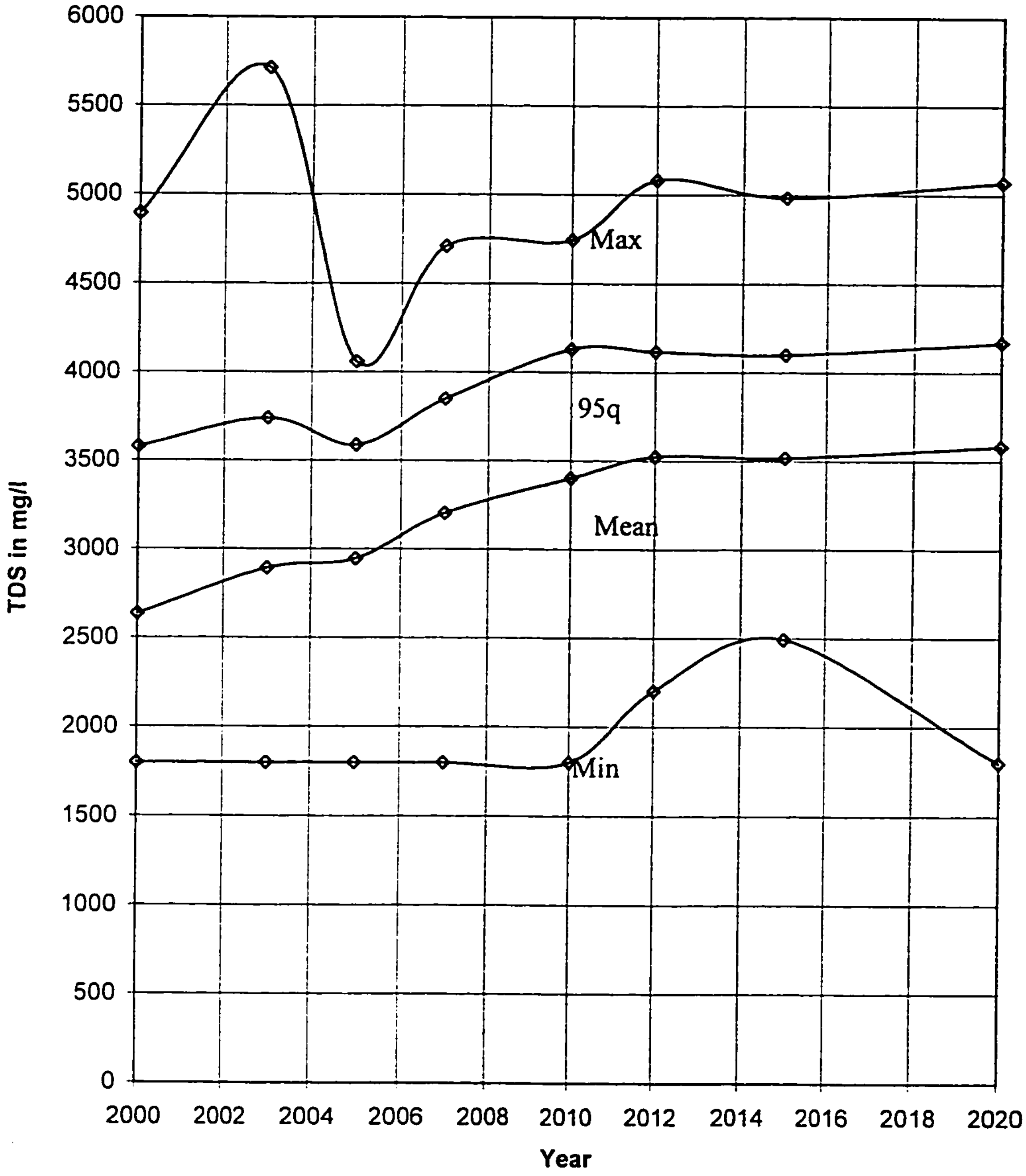

Figure 5.9 Industrial water quality variation for Case 2

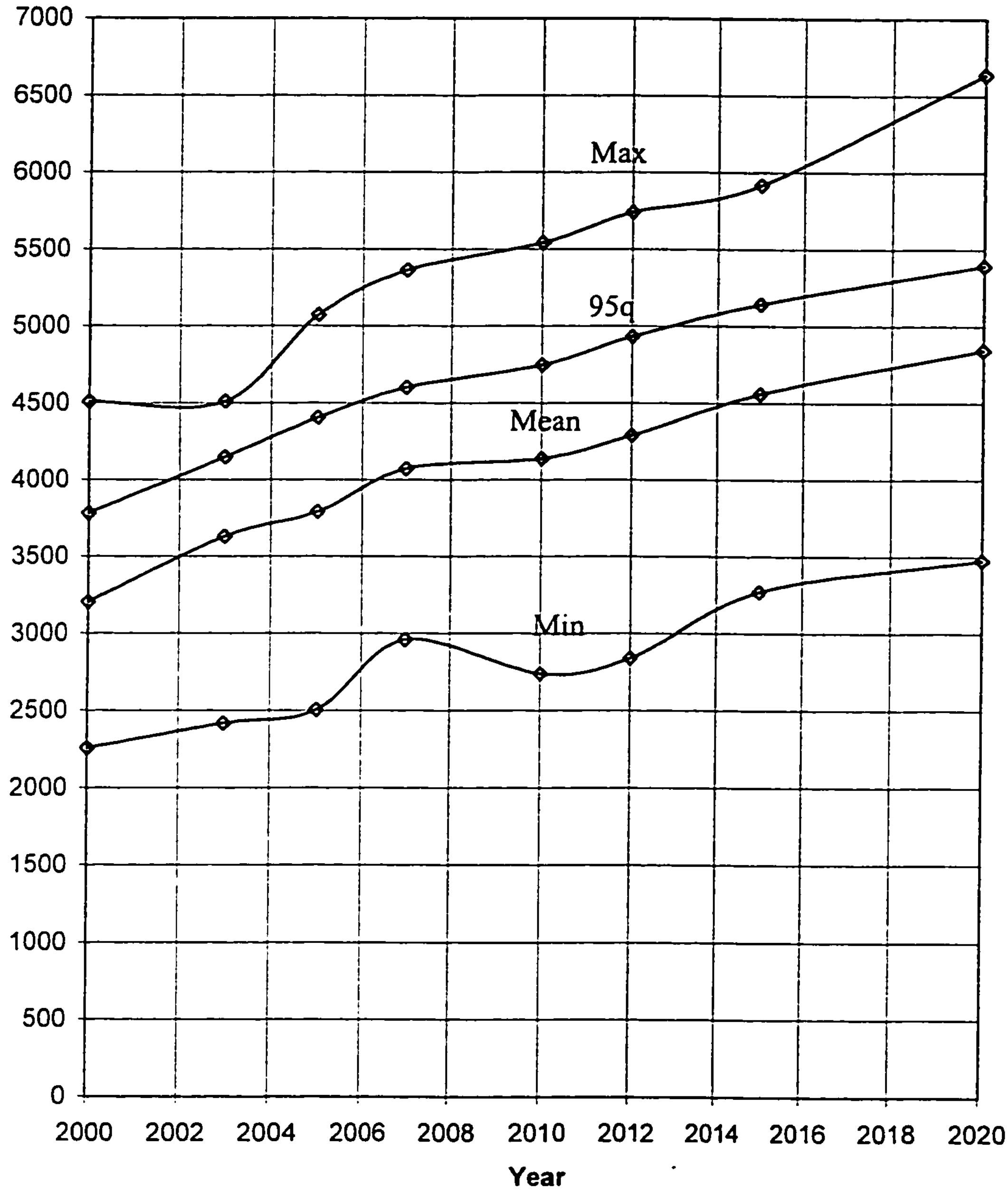

Figure 5.10 Agriculture water quality variation

Table 5.7 shows the risk and reliability of achieving the prescribed quality (TDS=3000 mg/l), for all the years for which the model has been run. We observe from the table that as the time increases the reliability of achieving the said quality decreases.

For example, with 64.8% confidence it can be stated that the prescribed quality of industrial water will be achieved in the year 2000, and in the year 2020, there is only 1.62% confidence.

There is an unexplained sudden decrease in the maximum value between the years 2003 and 2005, which can be attributed to the generated random numbers.

5.4.2.2 Agriculture water quality

As has been done in earlier sections, a 95q line is constructed for this case also, which is shown in Figure 5.10. The meaning of this line is that, in the year 2010, there is a 95% confidence in stating that the agricultural water has a quality of approximately 4200 mg/l. Similar renditions can be made for different years, using the 95q line.

Table 5.8 shows the risk and reliability of achieving the prescribed quality (TDS≤3500 mg/l), for all the years for which the model has been run. We observe from the table that as the time increases the reliability of achieving the said quality decreases (i.e., the risk increases) which is obvious because the groundwater quality is deteriorating.

For example, with 69.5% confidence we can state that the quality of industrial water will be achieved in the year 2000, and in the year 2020, there is only 1.2% confidence. Similar interpretations can be made from Figure 5.10 and Table 5.8.

Table 5.8 Reliability of the TDS of the agricultural water of case 2

Year	Max	Min	Mean	Stdev	Risk	Reliability
2000	4511	2258	3205	577.91	0.305	0.695
2003	4512	2417	3631	516.42	0.598	0.402
2005	5072	2504	3792	612.94	0.680	0.320
2007	5363	2958	4071	531.43	0.857	0.143
2010	5542	2739	4139	610.00	0.850	0.150
2012	5742	2838	4288	642.77	0.888	0.112
2015	5918	3270	4561	581.00	0.965	0.035
2020	6638	3477	4844	547.30	0.988	0.012

5.4.3 Resources

In this section the groundwater (non-renewable and renewable), desalinated and wastewater resources shall be discussed.

5.4.3.1 Non-renewable groundwater

There is uncertainty associated with this resource, since we have proven, probable and possible reserves, that we have assumed to follow a triangular distribution. After running the model for the years tested (2000, 2003, 2005, 2007, 2010, 2012, 2015, and 2020), the residuum of this resource was plotted as shown in Figure 5.11. The following conclusions are made after incorporating the concepts of risk and reliability.

In general, there is a downward trend of the reserve with respect to the time. This is quite natural as the time increases, there is an increase in demand and hence more burden on the groundwater supplies.

The 95q line is constructed as shown in Figure 5.11. After observing this line it can be seen, for instance that in the year 2010, there is a risk equal to 5% that the quantity of nonrenewable groundwater is approximately 1000,000 MCM.

Also it can be stated there is an error risk of 5%, or that with 95% confidence, the non-renewable groundwater that remains in the year 2020 is 860,000 MCM. Similar interpretations can be made from the figure for the other years.

5.4.3.2 Renewable groundwater

For the case of renewable groundwater shown in Figure 5.12 the following conclusions can be made.

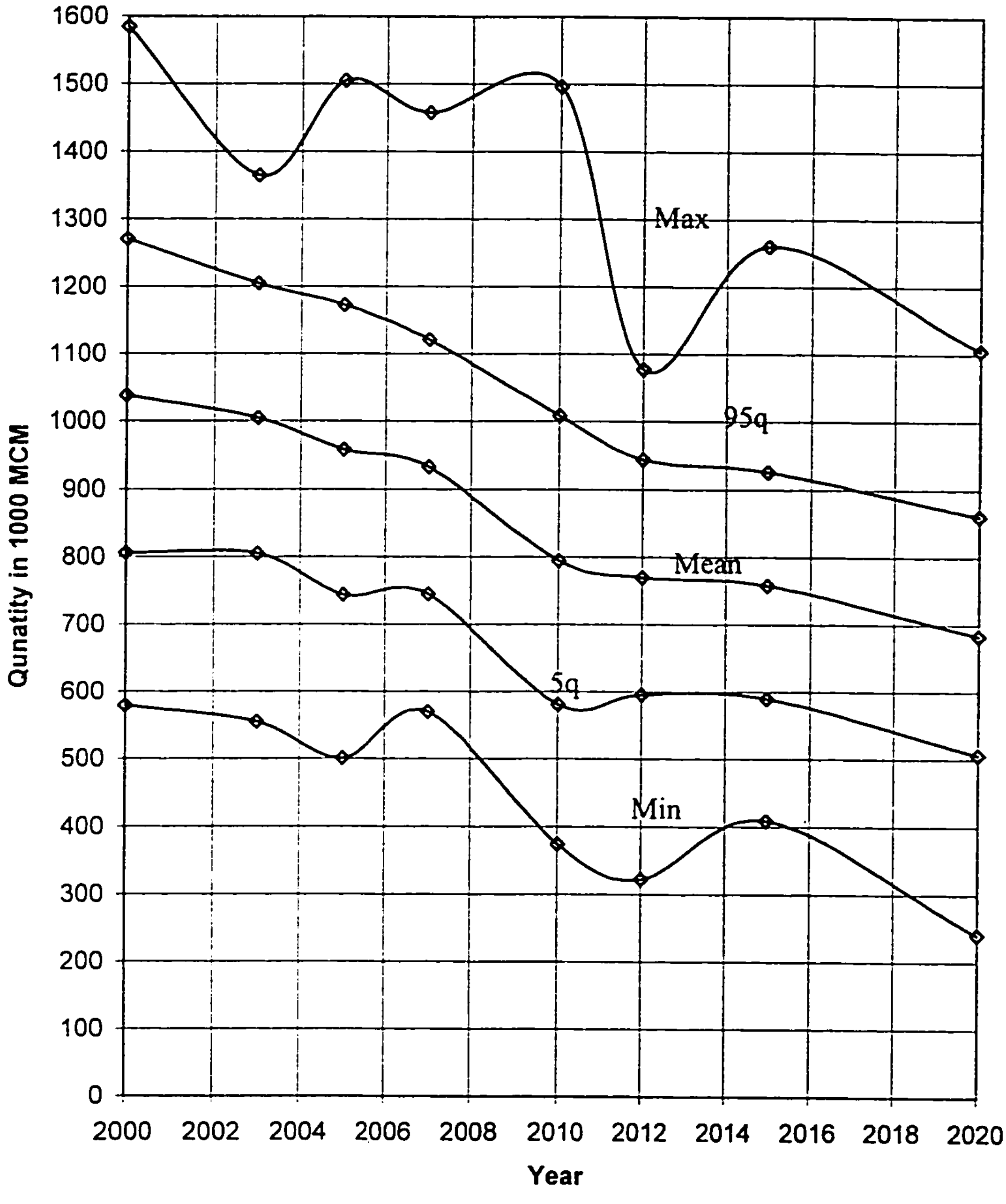

Figure 5.11 Non renewable GW depletion for Case 2

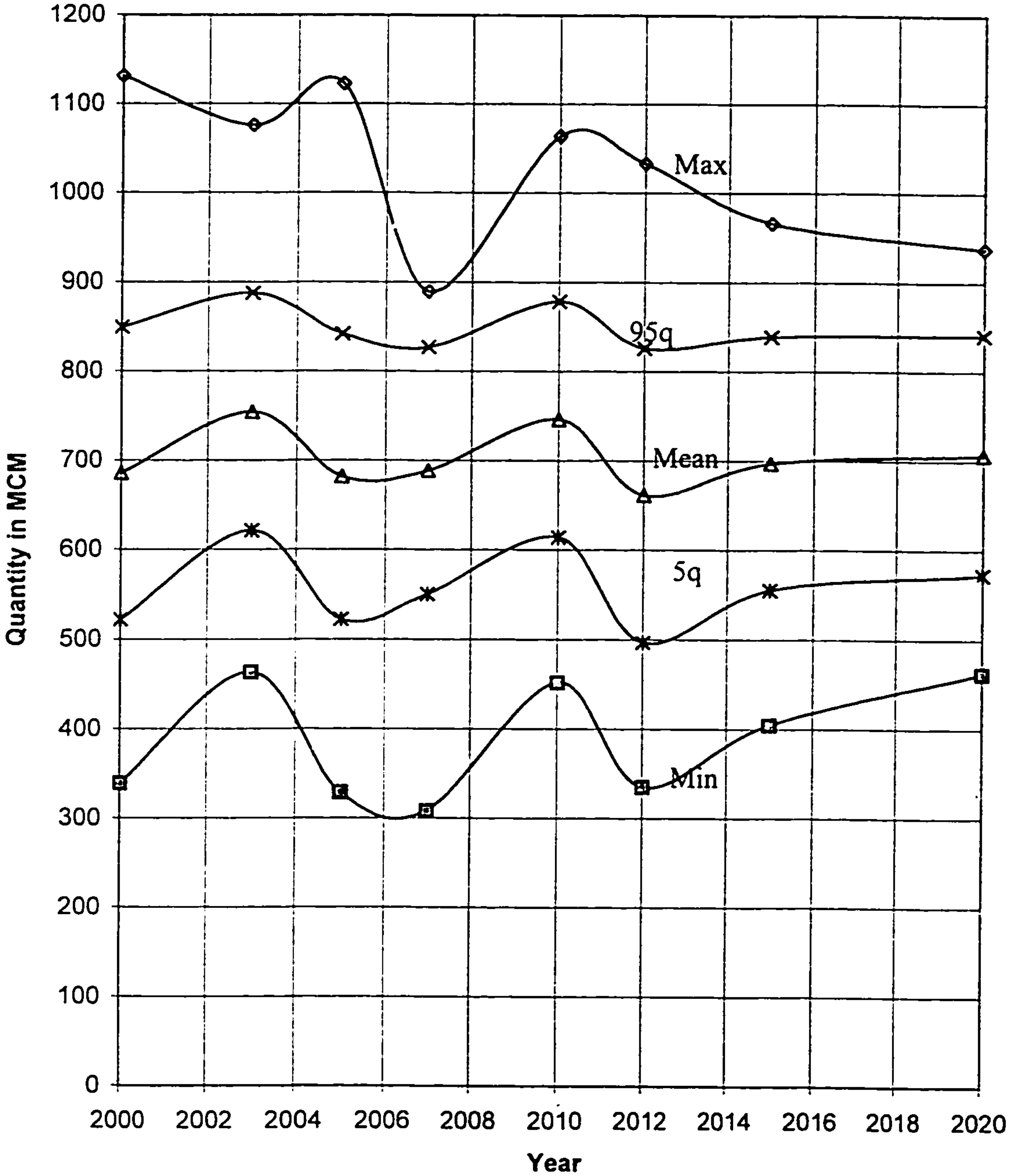

Figure 5.12 Renewable GW Depletion for Case2

It is found that the depletion pattern of this resource follows somewhat a straight line with slight inclination. This is because this resource is rechargeable and hence experiences lower depletion than the consumption level. Moreover, this resource is less uncertain than the previous one (non-renewable). As can be seen from the figure there is sudden draw-down between years 2006 and 2010. This draw-down is due to the normal increase in the demands, but as the utilization of wastewater increases in the consequent years, the load on this resource lessens.

The 95% quartile line is shown in Figure 5.12. With 95% confidence it can be stated that the amount of this resource that exists in the year 2020 is approximately 850,000 MCM.

5.4.3.3 Desalinated water

In this case the desalinated water is assumed to be fixed, i.e., the total capacities of the desalination plants (705.89 MCM/year as given in SCER, 1997). So there is no variation of this resource.

5.4.3.4 Wastewater

Wastewater utilization is shown in Figure 5.6. In this case, it has the same trend as case 1 that was described previously.

5.4.4 Cost

The graph for the total cost of water is shown in Figure 5.13. Following conclusions are made from the figure.

The cost increases as the time increase, which is due to the fact that there is an increase in the water consumption.

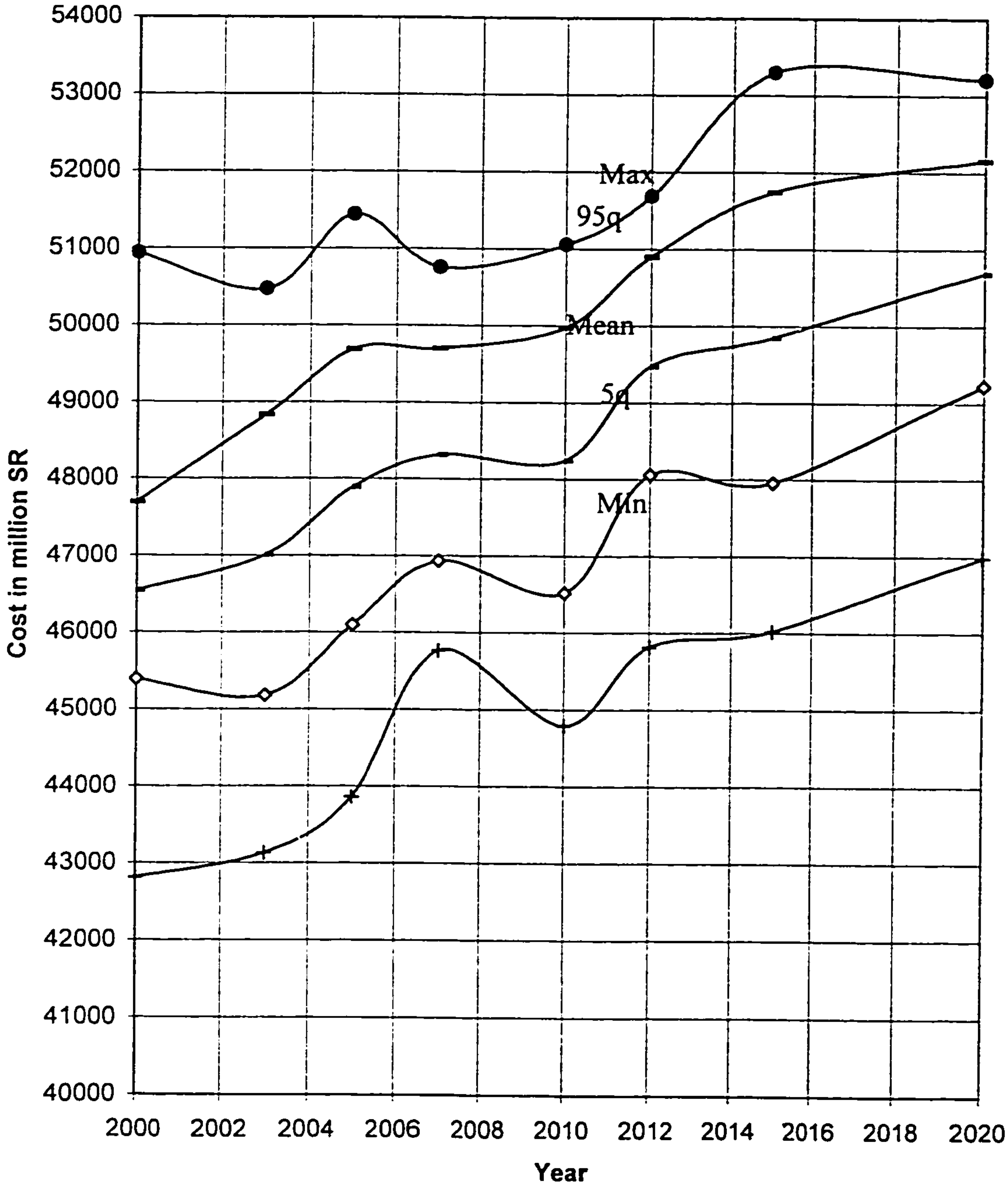

Figure 5.13 Cost variation for Case 2

From the 95% confidence line it can be concluded approximately 52,000 million SR is required in the year 2020, i.e., it is stated with a risk of 5%. Another way of interpreting this figure is to suppose there is a budget constraint of 50,000 million SR for the year 2020, then the risk associated with the satisfaction of water demand and quality is 32%.

5.5 Comparison of case 1 & 2

We observe the following when the two cases, i.e., the cases of limited and unlimited desalinated water are compared.

5.5.1 Demands

There is no major difference between the two cases in fulfilling all demands. These demands have been achieved 100% of times out of 40 runs in both cases, i.e., there is 100% reliability of achieving this priority. The exception is landscaping demand for which the reliability is about 94%.

5.5.2 Quality

If we compare the quality of industrial and agriculture water for case 1 and case 2, the reliability for achievement is more in case 1 than in case 2 as shown in Tables 5.3, 5.4, 5.7 and 5.8. The reason for this can be explained as follows.

In case 1, there is an unlimited supply of desalinated water, which helps in reducing the burden on groundwater, which in turn reduces the burden on the quality parameter of the groundwater (less strain on the groundwater quantity means lower deterioration of

Table 5.9 Demand and quality comparison of the Case 1 & 2

Parameter	Case 1	Case 2
Demands*		
Domestic demand	100	100
Landscaping demand	94	93
Industrial demand	100	100
Agricultural demand	100	100
Quality**		
Domestic quality	100	2.4
Landscaping quality	93	91
Industrial quality	23	16
Agricultural quality	3.4	1.2
Cost[+] (million SR)	53500	52500

* % Reliability of achieving the demands.

** % Reliability of achieving the prescribed quality

\+ Water cost in the year 2020 with 95% reliability.

groundwater quality) and hence there is more reliability to achieve the desired quality water in case 1.

The domestic water quality has not been achieved in case 2. The variation of its quality is shown in Figure 5.8. The reason the scenarios does not meet the objective is the limited quantity of desalinated water. This limitation forces the model to extract water from groundwater, whose water quality is poor. The comparison of demand and quality achievement for case 1 and 2 is shown in Table 5.9.

5.5.3 Resources

There is more depletion in case 2 for both non renewable and renewable groundwater, for obvious reasons of limited desalinated water supplies, which puts more pressure on the groundwater supplies and leads to more depletion. This comparison is shown in Table 5.10.

5.5.4 Cost

The cost in case 1 is greater than that of case 2. In case 1 the model uses the desalinated water freely which adds cost, as shown in Table 5.9.

5.6 Comparison with other studies

The current study conducted is unique in terms of its methodology and inputs. Thus it is difficult to compare with other studies. For instance, there are quite a few studies done in the area of water resources planning for Saudi Arabia ignoring the parameter uncertainty, which has been considered extensively in this research. Also, hitherto the quality

Table 5.10 Resource comparison of case 1 and 2

Variable	Case 1						Case 2					
	Max	Min	Aver	St.dev	95q	5q	Max	Min	Aver	St.dev	95q	5q
Non-renewable GW	1266.38	378.39	741.03	187.99	929.03	553.03	1105.3 4	240.56	683.56	177.35	861	506
Renewable GW	1056.46	348.84	719.06	155.28	874.35	563.77	937.49	462.19	706.73	133.98	841	573
Desalinated water	2852.61	706.89	1709.51	412.60	2122.11	1296.91	-	-	-	-	-	-
Treated wastewater	1000	-	-	-	-		1000	-	-	-	-	-

* Data in MCM of the year 2020

aspects of the parameters have not been considered. Yet two studies in proximity to our area of research can be compared to this work.

The first one is by Aburiziaza and Allam, 1989 (hereafter called study 1). This study examines the water supply-demand balance of the Kingdom, and compares the water supply-demand conditions for the current and future conditions.

The second significant study in this area is by Al-Layla et al. 1991 (hereafter called study 2). In this study, goal programming methodology is used to develop a multi-objective model. Five different scenarios were formed and run using the goal programming. The outcomes were studied thoroughly.

The common feature of the above two studies with the current study is the depletion of the groundwater resource. Study 1 considers the groundwater as proven probable, and possible reserves. According to this study, the depletion of these reserves is as follows:

Proven in the year 2005, probable in the year 2012 and possible in the year 2030.

Study 2 does not consider these reserves (proven, probable, and possible) as separate, but considers only fossil groundwater. This study has five different strategies (scenarios). The most optimistic strategy predicts the total depletion of fossil groundwater around the year 2030, and the most pessimistic strategy predicts the total depletion of this resource in the year 2002.

The current study considers the groundwater as two resources, i.e., non-renewable and renewable, and studies their depletion separately. While running the model as uncertain, the parameters used are the proven, probable and possible reserve for both non-renewable and

renewable groundwater, but the output has one value. This study does not consider the complete depletion of these resources (for example, it does not estimate in what year these reserves vanish). After running the model upto 2020, it was found that there exists about 920,000 MCM and 850,000 MCM of the non-renewable and 875,000 MCM and 800,000 MCM of the renewable groundwater (for case 1 and case 2 stating this with 95% confidence). The most optimistic scenario of the study 2 suggests that there exists groundwater in the year 2020 and similarly the possible reserve exists in the year 2020 as shown by the study 1. The current study is in agreement with the above two studies, i.e., there exists groundwater in the year 2020. A step ahead of the above two studies, the current study calculates the reliability of the amount that exists any particular year.

6. SUMMARY CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

The following paragraphs comprise a summary of the current research.

The main aim of this study was to develop an appropriate water resources model, that satisfies the various water supply demands (domestic, landscaping, industrial, and agricultural) and water quality demands and then study the resulting effect on the resources (groundwater, desalinated, wastewater etc.) in general for a large region and particularly apply it to the Kingdom of Saudi Arabia using the historical data. A thorough literature review on water resources planning revealed that a multi-objective model for water resources planning is most appropriate. A goal programming methodology is used for the solution of the multi-objective model. Historical water demand and supply data for the Kingdom were collected and analyzed. The behavior of demand is assumed to follow a normal distribution and the supply especially the supply of groundwater to follow triangular distribution (proven, probable, and possible reserves). This study also considers the quality parameter uncertainty.

To incorporate the parameter uncertainty in the model, the uncertain parameters (demand, supply and quality) were simulated using random numbers.

The model was run and analyzed for two cases, first by assuming the quantity of desalinated water to be unlimited and the second the opposite, i.e., assuming the quantity of desalinated water to be limited.

The conclusions and recommendations of the model are as follow:

6.2 Conclusions

1. From the model output we conclude that all the demands have been fully achieved.

2. Industrial water quality has been met for both cases with a risk ranging from 0.751 in 2000 to 0.016 in 2020 and the agricultural water quality from 0.695 to 0.012 in 2000 and 2020 respectively. This indicates the rapid deterioration of groundwater quality over time. The remedy lies in employing preliminary water treatment methods to the groundwater before supplying it for these purposes.

3. In case 2 domestic water quality is severely affected. The reliability is poor for achieving the minimum quality (TDS=1000 ppm) which is 0.419 in 2000 and becomes 0.024 in 2020. Hence it is imperative to increase the quantity of the desalinated water (above the current annual production of 705 MCM). The best indication of amount of water to produced is as shown by the 95q line in Figure 5.5. With 95% confidence we state that we shall be in position produce 2100 MCM of desalinated water by 2020.

4. One of the objectives of the study was to study the depletion pattern of the groundwater resource (non-renewable and renewable). Formulation and running of this model was

based on the current pattern of utilization of various resources as given in development plans of the Ministry of Planning. From the model run we conclude the following:

(i) There is more depletion of non-renewable groundwater, when compared to renewable groundwater, reflecting the current pattern of consumption of more non-renewable groundwater than renewable.

(ii) With 95% confidence we conclude that neither of the resources (non-renewable and renewable) will deplete to zero by the year 2020. It means there is only 5% risk that the groundwater will be depleted by the year 2020.

(iii) Gradual introduction of wastewater (shown in Figure 5.6), mainly for landscaping and agricultural purposes, reduces the burden on the groundwater supplies.

5. With 95% confidence we conclude that the budget for the water for both cases lies around 50,000 million SR, with a slightly higher cost for case 1.

6. Although there is more cost associated with case 1, it is recommended over case 2, for obvious reasons of satisfactory water quality and lower burden on the groundwater reserves.

7. The significance of uncertainty analysis lies in the fact that we can incorporate the notions of risk and reliability as rendered in the previous chapter. To each result the reliability concept was applied and analyzed.

8. Comparison of this study with similar studies found the results in good comparison with the other studies, but this study adds the extra research of incorporating the uncertainty analysis.

6.2.1 Model limitations

The developed model in this research has the following limitations:

1. The multi-objective model formulated is suitable for single aquifer planning rather than local level planning compared to water budget problem (combining all the aquifers together).

2. The quality of the groundwater is assumed to remain constant with time, but it may vary with respect to time as the water is pumped out from the aquifer.

3. For the groundwater withdrawals, there is a limit after which the pumping becomes infeasible. This can be incorporated in the model by allotting the amount of groundwater which can be economically pumped.

6.3 Recommendations

1. This model was developed and applied on a large scale to the Kingdom (on a national level). It is recommended that this model be modified and applied on a small scale, preferably to a single aquifer.

2. Suitable groundwater models can be incorporated into this multi-objective model.

3. Due to non-availability of data on groundwater, reserves were assumed to follow a triangular distribution with the parameters being proven, probable, and possible reserves. It is recommended that a thorough study be made on these three reserve categories.

4. Moreover, the quality of groundwater was also assumed to follow a triangular distribution due to insufficient data. Study in this direction is also recommended with special attention to changes in water quality with respect to the time, as well as with respect to the withdrawal rates, and depletion.

5. Preliminary treatment of groundwater is recommended before supplying to the various purposes in order to combat the deteriorating quality.

6. Agricultural water consumption must remain constant if not reduced.

7. Since the model predicts larger quantity of renewable groundwater, the increase in its use should be encouraged.

8. Groundwater recharge using secondary effluent is advised in order to replenish the depleted groundwater reserves.

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Appendix I: Sample MATLAB program for generation of random numbers following triangular distribution

```
// Program for generation of random numbers following triangular distribution
clear all;
for i=1:40
if rand<=2/3
a=275011;
b=1113714;
c=704111;
x(i,1)=sqrt((b-a)*(c-a)*rand)+a;
else
x(i,1)=-sqrt((b-a)*(b-c)*(1-rand))+b;
end
end
```

Appendix II Multiobjective water resources model

Objective function

The overall objective function is given as follows:

MINIMIZE

$$Z = P_1(d^-_5 + d^+_5) + P_2(d^-_9 + d^+_9) + P_3(d^-_8 + d^+_8) + P_4(d^-_{12} + d^+_{12}) + P_5(d^-_7 + d^+_7) + P_6(d^-_6 + d^+_6)$$

the constraints of the above objective function are as given below:

CONSTRAINTS:

A. Quantity Constraints:

I. Availability Constraints

1. Non Renewable Groundwater $q_{11} + q_{13} + q_{14} + d^-_1 - d^+_1 = Q_{NG}$
2. Renewable Groundwater $q_{21} + q_{22} + q_{23} + q_{24} + d^-_2 - d^+_2 = Q_{RG}$
3. Surface Water $q_{32} + q_{34} \leq Q_S$
4. Desalinated Water $q_{41} + d^-_3 - d^+_3 = Q_D$
5. Treated Wastewater $q_{52} + q_{53} + q_{54} + d^-_4 - d^+_4 = Q_W$

II .Demand Constraints

6. Domestic Consumption $q_{11} + q_{21} + q_{41} + d^-_5 - d^+_5 = D_D$
7. Landscaping and Gardening $q_{22} + q_{32} + q_{52} + d^-_6 - d^+_6 = D_L$
8. Industrial Usage $q_{13} + q_{23} + q_{53} + d^-_7 - d^+_7 = D_I$
9. Agricultural Usage $q_{14} + q_{24} + q_{34} + q_{54} + d^-_8 - d^+_8 = D_A$

B. Quality Constraint:

Total Dissolved Solids (TDS)

10. $q_{11}(T_{ng}-T_x) + q_{21}(T_{rg}-T_x) + q_{41}(T_d-T_x) + d^-_9 - d^+_9 = 0$

11. $q_{22}(T_{rg}-T_l) + q_{32}(T_s-T_l) + q_{52}(T_w-T_l) + d^-_{10} - d^+_{10} = 0$

12. $q_{13}(T_{ng}-T_i) + q_{23}(T_{rg}-T_i) + q_{53}(T_w-T_i) + d^-_{11} - d^+_{11} = 0$

13. $q_{14}(T_{ng}-T_a) + q_{24}(T_{rg}-T_a) + q_{34}(T_s-T_a) + q_{54}(T_w-T_a) + d^-_{12} - d^+_{12} = D_A$

C. Cost Constraint:

14. $C_{NR}(q_{11} + q_{13} + q_{14}) + C_{RG}(q_{21} + q_{22} + q_{23} + q_{24}) + C_{SW}(q_{32} + q_{34}) + C_{DW}(q_{41}) +$

$C_{WW}(q_{52} + q_{53} + q_{54}) + d^-_{13} - d^+_{13} = C$

$d^-_i, d^+_i \geq 0$ for i = 1, 2, ... 13

$q_{ij} \geq 0$ for i,j = 1,2, 3 13

Q_{NG} = Quantity of non-renewable groundwater

Q_{RG} = Quantity of renewable groundwater

Q_S = Quantity of surface water

Q_D = Quantity of desalinated water

Q_{WW} = Quantity of wastewater

D_D = Quantity of domestic demand

D_L = Quantity of landscaping and gardening demand

D_I = Quantity of industrial demand

D_I = Quantity of agricultural demand

D_D = Quantity of domestic demand

T_{ng} = TDS of non-renewable groundwater

T_{rg} = TDS of renewable groundwater

T_s = TDS of surface water

T_d = TDS of desalinated water

T_w = TDS of wastewater

T_x = Required domestic water quality

T_l = Required landscaping water quality

T_i = Required industrial water quality

T_a = Required agricultural water quality

C_{NR} = Unit cost of non-renewable groundwater in SR

C_{RG} = Unit cost of renewable groundwater in SR

C_{SW} = Unit cost of surface water in SR

C_{DW} = Unit cost of desalinated water in SR

C_{WW} = Unit cost of wastewater in SR

Appendix III SAS Program.

```
options nocenter ls=80;title ;
data trial1;
input _row_$ q1 q2 q3 q4 q5 q6 q7 q8 q9 q10 q11 q12 q13 #2
            n1 n2 n3 n4 n5 n6 n7 n8 n9 n10 n11 n12 n13 #3
            p1 p2 p3 p4 p5 p6 p7 p8 p9 p10 p11 p12 p13 _type_$ _rhs_;
cards;
obj1 . . . . . . . . . . . . .
   . . . . 1 . . . . . . . .
   . . . . 1 . . . . . . . . min 1
obj2 . . . . . . . . . . . . .
   . . . . . . . . . . . . .
   . . . . . . . . 1 . . . . min 2
obj3 . . . . . . . . . . . . .
   . . . . . . . 1 . . . . .
   . . . . . . . 1 . . . . . min 3
obj4 . . . . . . . . . . . . .
   . . . . . . . . . . . 1 .
   . . . . . . . . . . . . . min 4
obj5 . . . . . . . . . . . . .
   . . . . . . 1 . . . . . .
   . . . . . . 1 . . . . . . min 5
obj6 . . . . . . . . . . . . .
   . . . . . 1 . . . . . . .
   . . . . . 1 . . . . . . . min 6
con1  1 1 1 . . . . . . . . . .
   1 . . . . . . . . . . . .
   -1 . . . . . . . . . . . . eq Qng
con2 . . . 1 1 1 1 . . . . . .
   . 1 . . . . . . . . . . .
   . -1 . . . . . . . . . . . eq Qrg
con3 . . . . . . . 1 1 . . . .
   . . . . . . . . . . . . .
   . . . . . . . . . . . . . eq Qs
con4 . . . . . . . . . 1 . . .
   . . 1 . . . . . . . . . .
   . . . . . . . . . . . . . eq Qd
con5 . . . . . . . . . . 1 1 1
   . . . 1 . . . . . . . . .
   . . . . . . . . . . . . . eq Qw
con6  1 . . 1 . . . . . 1 . . .
```

```
     . . . . 1 . . . . . . . .
     . . . . -1 . . . . . . . . eq Dd
con7 . . . . 1 . . 1 . . 1 . .
     . . . . . 1 . . . . . . .
     . . . . . -1 . . . . . . . eq Dl
con8 . 1 . . . 1 . . . . . 1 .
     . . . . . . 1 . . . . . .
     . . . . . . -1 . . . . . . eq Di
con9 . . 1 . . . 1 . 1 . . . 1
     . . . . . . . 1 . . . . .
     . . . . . . . -1 . . . . . eq Da
con10 Tng-Tx . Trg-Tx . . . Td--Tx . .
     . . . . . . . . 1 . . . .
     . . . . . . . . -1 . . . . eq 0
con11 . . . . Trg-Tl . Ts-Tl . Tw-Tl .
     . . . . . . . . . 1 . . .
     . . . . . . . . . -1 . . . eq 0
con12 . Tng-Ti . . . Trg-Ti . . . . . Tw-Ti .
     . . . . . . . . . . 1 . .
     . . . . . . . . . . -1 . . eq 0
con13 . . Tng-Ta . .Trg-Ta .Ts-Ta  Tw-Ta
     . . . . . . . . . . . 1 .
     . . . . . . . . . . . -1 . eq 0
con14 Cnr Cnr Cnr Crg Crg Crg Csw Csw Cdw Cww Cww Cww
     . . . . . . . . . . . . 1
     . . . . . . . . . . . . -1 eq 0
proc lp GOALPROGRAM;
```

Appendix IV Table T1 Sample input data sheet for the year 2005 for case 1

	DD	LD	ID	Tng	Trg
Mean	1536.63	230.48	1273.33	a=2018	a=2768
SD	625.48	93.82	500.38	b=5612	b=5190
Ran #				c=3815	c=3979
1	1142.50	328.07	745.78	2569	4238
2	2757.53	274.64	1739.78	4173	5150
3	514.13	109.45	1235.07	3617	3690
4	1670.50	316.82	1139.11	4335	3783
5	2365.00	146.37	842.11	2606	4085
6	2367.71	338.78	1188.87	4100	3877
7	2572.70	272.74	1265.00	3592	3726
8	2029.74	215.77	1294.89	3660	4023
9	1284.84	309.32	1238.55	3983	3686
10	740.85	207.39	1383.04	4615	3440
11	1370.10	497.96	1936.63	2789	4302
12	1925.21	313.65	1943.98	3657	4020
13	2319.25	118.28	1374.91	4851	4442
14	2144.69	91.85	1527.68	3430	4047
15	2534.64	193.17	1634.22	4198	4141
16	1013.52	259.39	1317.07	4039	3620
17	3196.69	99.52	1647.92	5371	4216
18	909.65	205.38	1177.21	3281	3285
19	1794.74	360.77	1471.60	4274	2862
20	2049.36	188.18	1225.56	4112	3049
21	1160.51	184.44	872.66	4038	4763
22	1244.50	253.05	1611.96	3445	3496
23	1026.20	185.40	289.34	4243	4381
24	1437.39	165.75	115.14	3257	3432
25	1767.03	201.97	1311.66	3541	3848
26	2486.06	160.62	1307.54	3791	3979
27	1680.15	296.70	1085.23	4846	4080
28	2366.98	323.98	1722.80	4435	4094
29	600.20	396.42	2524.22	3844	4049
30	2756.68	203.14	859.57	4542	4466
31	1111.71	326.08	764.72	3329	3413
32	1270.09	261.02	1428.58	4492	3628
33	1135.50	76.99	586.88	3816	3935
34	919.04	184.77	1319.49	3356	3589
35	1603.92	259.97	1409.96	3869	3736
36	1350.08	179.28	1153.29	4483	3378
37	1141.83	172.47	1533.82	4236	4118
38	1600.37	67.95	1773.06	4558	3705
39	1179.15	312.99	2266.76	2338	3837
40	1751.27	190.85	1908.41	4689	3057

Appendix V Sample output of the year 2005 for case 1

Decision variables

Run #	q1	q2	q3	q4	q5	q6	q7	q8	q9	q10	q11	q12	q13
1	322.24	209.29	14217.77	0	0	0	1777.22	642.62	0	820.25	75	536.87	0
2	777.76	1336.79	13646.56	0	37.62	0	1705.82	0	642.62	1979.76	237.01	402.98	0
3	145.01	679.53	13646.56	0	24.98	0	1705.82	0	642.62	369.11	84.46	555.53	0
4	471.16	746.53	13646.56	0	69.38	0	1705.82	0	642.62	1199.33	247.43	392.56	0
5	667.05	277.11	14217.77	0	0	0	1777.22	642.62	0	1697.94	75	565	0
6	667.81	816.388	13646.56	0	71.26	0	1705.82	0	642.6	1699.89	267.51	372.48	0
7	725.63	836.47	13646	0	61.26	0	1705	0	642.62	1847.06	211.47	428.52	0
8	572.49	827.89	13646.56	0	42.76	0	1705.82	0	642.62	1457.24	173	466.99	0
9	362.39	837.12	13646.56	0	70.75	0	1705.82	0	642.62	922.44	238.57	401.43	0
10	208.95	896.97	13646.56	0	53.45	0	1705.82	0	642.62	531.89	153.93	486.06	0
11	386.43	1371.63	14217.77	0	0	0	1777.22	642.62	0	983.66	75	565	0
12	386.43	1371.63	14217.77	0	0	0	1777.22	642.62	0	983.66	75	565	0
13	654.14	833.08	13646.56	0	20.1	0	1705.82	0	642.62	1665.1	98.17	541.822	0
14	604.91	962.68	13646.56	0	16.85	0	1705.82	0	642.62	1539.77	75	565	0
15	714.89	1150.81	13646.56	0	36.57	0	1705.82	0	642.62	1819.74	156.59	483.4	0
16	285.86	875.28	13646.56	0	61.17	0	1705.82	0	642.62	729.65	198.21	441.78	0
17	901.63	1089.11	13646.56	0	18.32	0	1705.82	0	642.62	2295.05	81.19	558.8	0
18	256.56	685.06	13646.56	0	57.52	0	1705.82	0	642.62	653.08	147.85	492.14	0
19	506.2	0	13646.56	0	132.44	1059.92	1705.82	0	642.62	1288.53	228.32	411.67	0
20	578.02	712.99	13646.56	0	60.74	0	1705.82	0	642.62	1471.33	127.43	512.56	0
21	327.31	388.83	13646.56	0	28.26	0	1705.82		642.62	833.17	156.17	483.82	0
22	351.01	1161.62	13646.56	0	63.38	0	1705.82	0	642.62	893.48	189.66	450.33	0
23	289.52	31.64	13442.93	0	32.17	0	1680.36	0	642.62	736.97	153.22	257.69	229.08
24	405.41	19.65	13271.74	0	42.89	0	1658.96	0	642.62	1031.97	122.85	95.48	421.66
25	498.39	837.7	13646.56	0	44.9	0	1705.82	0	642.62	1268.63	166.04	473.95	0

26	701.19	795.76	13646.56	0	32.39	0	1705.82	0	642.62	1784.86	128.22	511.77	0
27	473.88	684.43	13646.56	0	57.5	0	1705.82	0	642.62	1206.26	239.2	400.8	0
28	667.61	1344.33	13646.56	0	62.44	0	1705.82	0	642.62	1699.37	261.53	378.46	0
29	169.28	2202.88	13646.56	0	77.7	0	1705.82	0	642.62	430.91	318.66	321.34	0
30	777.52	388.46	13646.56	0	34.24	0	1705.82	0	642.62	1979.15	168.89	471.1	0
31	313.55	365.57	13646.56	0	85.22	0	1705.82	0	642.62	798.15	240.85	399.14	0
32	358.23	988.27	13646.56	0	61.32	0	1705.82	0	642.62	911.85	199.69	440.31	0
33	320.26	76.02	13598.43	0	1.77	0	1699.8	0	642.62	815.23	75	510.85	54.14
34	259.21	820.03	13646.56	0	44.22	0	1705.82	0	642.62	659.82	140.54	499.45	0
35	452.38	971.79	13646.56	0	58.13	0	1705.82	0	642.62	1151.53	201.83	438.16	0
36	380.79	644.83	13646.56	0	47.73	0	1705.82	0	642.62	969.28	131.54	508.45	0
37	322.05	1033.35	13646.56	0	32.93	0	1705.82	0	642.62	819.77	139.53	500.46	0
38	451.38	1208.06	13646.56	0	0	0	1705.82	0	642.62	1148.98	75	565	0
39	332.58	1701.76	14217.77	0	0	0	1777.22	642.62	0	846.56	75	565	0
40	496.17	0	13646.56	0	61.28	1397.97	1705.82	0	642.62	1262.97	129.56	510.43	0

Appendix VI Sample output of the year 2005 for case 1

Negative deviational variables

Run #	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	n11	n12	n13
1	1023851	428522.8	0	28.51	0	0	0	0	0	680120	0	3927661	0
2	1578939	805156.6	0	0	0	0	0	0	0	0	0	0	0
3	769928.9	676869.2	337.77	0	0	0	0	0	0	0	0	0	0
4	836135.7	845224.7	0	0	0	0	0	0	0	0	0	0	0
5	960438.1	437022.8	0	0	0	0	0	0	0	680120	0	3673518	0
6	872869.2	789822.9	0	0	0	0	0	0	0	0	0	0	0
7	789091.3	669832.9	0	0	0	0	0	0	0	0	0	0	0
8	935253.1	686051.4	0	0	0	0	0	0	0	0	0	0	0
9	796253.9	761323.4	0	0	0	0	0	0	0	0	0	0	0
10	694747.5	907240.7	174.99	0	0	0	0	0	0	0	0	0	0
11	1049225	480322.8	0	0	0	0	0	0	0	680120	0	686007	0
12	932924.3	685322.8	0	0	0	0	0	0	0	680120	0	686007	0
13	1107766	961574.8	0	0	0	0	0	0	0	0	0	0	0
14	967185.9	633777.3	0	0	0	0	0	0	0	3008.05	0	0	0
15	1019088	813057.6	0	0	0	0	0	0	0	0	0	0	0
16	730692.3	775533	0	0	0	0	0	0	0	0	0	0	0
17	1013963	1081576	0	0	0	0	0	0	0	0	0	0	0
18	631111.8	596536.7	53.8	0	0	0	0	0	0	0	0	0	0
19	457247.2	827301.8	0	0	0	0	0	0	0	0	0	0	0
20	533562.4	791033.4	0	0	0	0	0	0	0	0	0	0	0
21	1365537	775165.9	0	0	0	0	0	0	0	0	0	0	0
22	717840.8	637230.8	0	0	0	0	0	0	0	0	0	0	0
23	1083936	823587.5	0	0	0	0	0	0	0	0	0	0	0
24	692803.2	590998.1	0	0	0	0	0	0	0	0	0	0	0
25	856917.4	657949.3	0	0	0	0	0	0	0	0	0	0	0

26	916756.5	716861.8	0	0	0	0	0	0	0	0	0	0	0
27	958995.1	960436.7	0	0	0	0	0	0	0	0	0	0	0
28	992541.5	868931.7	0	0	0	0	0	0	0	0	0	0	0
29	967481.3	729416.4	275.97	0	0	0	0	0	0	0	0	0	0
30	1118087	894259.9	0	0	0	0	0	0	0	0	0	0	0
31	684274.3	607809	0	0	0	0	0	0	0	0	0	0	0
32	772206.9	882432.9	0	0	0	0	0	0	0	0	0	0	0
33	899705.3	722898.2	0	0	0	0	0	0	0	33649.35	0	0	0
34	713474.2	614150	0	47.06	0	0	0	0	0	0	0	0	0
35	816629.3	735136.1	0	0	0	0	0	0	0	0	0	0	0
36	669327.8	880346.5	0	0	0	0	0	0	0	0	0	0	0
37	974398	821861.3	0	0	0	0	0	0	0	0	0	0	0
38	777094	893894.2	0	0	0	0	0	0	0	37500	0	0	0
39	857047.9	373922.8	0	0	0	0	0	0	0	680120	0	7924633	0
40	537457.3	922934.9	0	0	0	0	0	0	0	0	0	0	0

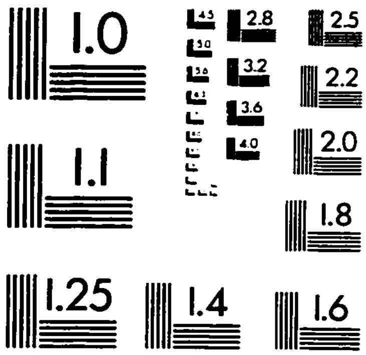
Appendix VII Sample output of the year 2005 for case 1

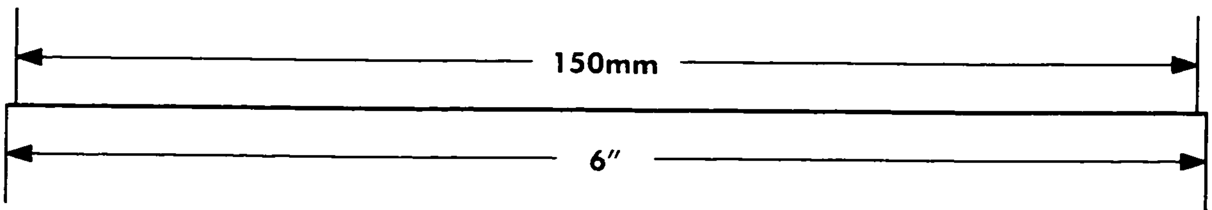
Positive deviational variables

Run #	p1	p2	p3	p4	p5	p6	p7	p8	p9	p10	p11	p12	p13
1	14749.31	1777.22	113.36	0	0	389.6	0	0	0	0	0	0	43860
2	15761.12	1743.44	1272.87	0	0	0	0	0	0	0	3051327	18389687	51331.7
3	14471.1	1730.8	0	0	0	0	0	0	0	0	1068047	8311703	45651.4
4	14864.27	1775.27	492.44	0	0	0	0	0	0	0	1774717	18268574	47968.4
5	15161.93	1777.22	991.05	0	0	571.3	0	0	0	0	53850	0	46251
6	15130.76	1777.08	993	0	0	0	0	0	0	0	1765947	15221980	49389
7	15208.67	1767.08	1140.17	0	0	0	0	0	0	0	1370411	8031948	49784
8	15046.9	1748.58	750.35	0	0	0	0	0	0	0	1399795	9466543	48758
9	14846.07	1776.57	215.55	0	0	0	0	0	0	0	1707003	13299521	47510
10	14752.49	1759.27	0	0	0	0	0	0	0	0	2379177	21504515	46655
11	15975	1777.22	276.77	0	0	219.7	0	0	0	0	3691638	0	47214
12	15975.74	1777.22	276.77	0	0	219.7	0	0	0	0	3691638	0	47214
13	15133.79	1725.22	958.21	0	0	0	0	0	0	0	2379204	26434335	49242
14	15214.15	1722.67	832.88	0	0	0	0	0	0	0	1399668	6368774	49248
15	15512.27	1742.39	1112.85	0	0	0	0	0	0	0	2614642	17009679	50453.4
16	14807.7	1766.99	20.76	0	0	0	0	0	0	0	1827222	13951144	47103
17	15637.3	1724.14	1588.16	0	0	0	0	0	0	0	3721603	33145030	51442
18	14588.18	1763.34	0	0	0	0	0	0	0	0	866929	3035602	46435
19	14152.76	2898.19	581.64	0	0	0	0	0	0	0	1002142	15865074	48569
20	14937.58	1766.56	764.44	0	0	0	0	0	0	0	1494681	13973319	48542
21	14362.71	1734.08	126.28	0	0	0	0	0	0	0	725071	15887249	46083
22	15159.19	1769.2	186.59	0	0	0	0	0	0	0	1775764	5633565	48234
23	13764.1	1712.54	30.08	0	0	0	0	0	0	0	0	17401289	44513
24	13696.82	1701.86	325.08	0	0	0	0	0	0	0	0	2209775	44862
25	14982.65	1750.74	561.74	0	0	0	0	0	0	0	1316256	7544084	48319
26	15143.52	1738.21	1077.97	0	0	0	0	0	0	0	1430833	11179186	49470

27	14804.87	1763.32	499.37	0	0	0	0	0	0	0	1964533	25748595	47806
28	15658.5	1768.26	992.48	0	0	0	0	0	0	0	3428774	20163740	50690
29	16018.72	1783.58	0	0	0	0	0	0	0	0	4406284	12021861	49718
30	14812.55	1740.06	1272.26	0	0	0	0	0	0	0	923840	22258487	48938
31	14325.69	1791.04	91.26	0	0	0	0	0	0	0	439216	3908981	46051
32	14993.06	1767.15	204.96	0	0	0	0	0	0	0	2528330	20146682	47843
33	13994.72	1701.79	108.34	0	0	0	0	0	0	0	0	11319188	45098
34	14725.81	1750.04	0	0	0	0	0	0	0	0	1126138	4577663	46762
35	15070.74	1763.95	444.64	0	0	0	0	0	0	0	1879199	11829104	48390
36	14672.19	1753.55	262.39	0	0	0	0	0	0	0	1577565	19597408	47099
37	15001.96	1738.75	112.88	0	0	0	0	0	0	0	2367101	17489014	47670
38	15306	1705.82	442.09	0	0	0	0	0	0	0	3162329	21178703	48858
39	16252.11	1777.22	139.67	0	0	404.6	0	0	0	0	746046	0	47699
40	14142.73	3165.08	556.08	0	0	0	0	0	0	0	1604119	21861031	49039

IMAGE EVALUATION TEST TARGET (QA-3)





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