Analysis of Sustainable Water Supply Options for Kuwait

by

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ABSTRACT

This thesis considers several options for improving the sustainability of Kuwait's water supply system. The country currently relies heavily on desalination and brackish groundwater extraction. The options considered for increasing the flux of potable water into Kuwait include expanding the desalination capacity, importing water from other countries, expanding the uses of reclaimed wastewater, and rainfall harvesting. Options for water storage are also considered, including both aquifer and surface systems. Case studies are presented which demonstrate the potential for indirect potable use of Kuwait's highly purified wastewater, and the importance of a storage reservoir as part of such a system. In order to assess the feasibility of rainfall harvesting, a model was constructed to simulate the runoff processes in the Rawdhatain drainage basin in northern Kuwait. Due to the coarse resolution of the input data, reasonable results could not be obtained using the input parameters gathered from available data. However, through sensitivity analysis, it was discovered that relatively minor variations in soil properties throughout the watershed could produce significant volumes of runoff during extreme rain events. Storage was considered for the small lens of fresh groundwater beneath the Rawdhatain basin or in a surface reservoir constructed in the drainage depression there. All of these options should continue to be considered as Kuwait attempts to expand its water supply in a sustainable manner, though further study will be needed especially in order to understand the hydrologic system at Rawdhatain more thoroughly.

Thesis Supervisor: Elfatih Eltahir
Title: Professor of Civil and Environmental Engineering

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Water in Kuwait: An Introduction to the Problem and Overview of Possible Solutions

1.1 Introduction to the Problem

Kuwait is a small country that is very rich in oil resources but extremely poor in water resources. Due to the arid climate, there is no permanent surface water in the country, and almost all of the groundwater is brackish or saline. As a result, nearly all of the potable water supplied to the country's 2.3 million residents is produced by desalination of seawater. This lack of readily available fresh water is an increasing problem throughout the world as arid regions become more and more densely populated. Thus, lessons learned in investigating options to improve Kuwait's water supply could be applied not only to other countries in the gulf region, but also to other dry climates such as southern Australia and the south-western United States.

Kuwait's water infrastructure consists of a network of desalination plants, aquifers, and a wastewater purification facility. A schematic of the system is shown in Figure 1-1. For the municipal freshwater supply, water from the Persian Gulf is desalinated and mixed with 10% brackish groundwater before it is distributed to homes and businesses. A separate supply line also delivers brackish water to homes for use in landscaping and other non-potable uses. The used municipal water is collected at wastewater treatment facilities and treated to varying standards up to the tertiary level (physical, biological, and chemical treatment). Some of this treated water goes to a new plant in Sulaibiya, where it undergoes further treatment with micro-filtration (MF) and reverse osmosis (RO). At the moment, some of this highly treated recycled water is distributed to farming areas, and the rest is discharged into the Gulf. The plan for the future is to expand the distribution to farms and there are proposals to construct an artificial lake for recreational use. The rest of the water used for agricultural irrigation is brackish groundwater. This supply system is not the most efficient use of the available resources, and with future population growth and increase in per capita demand, further supply options must be considered in addition to ensuring that the currently available resources are managed optimally.

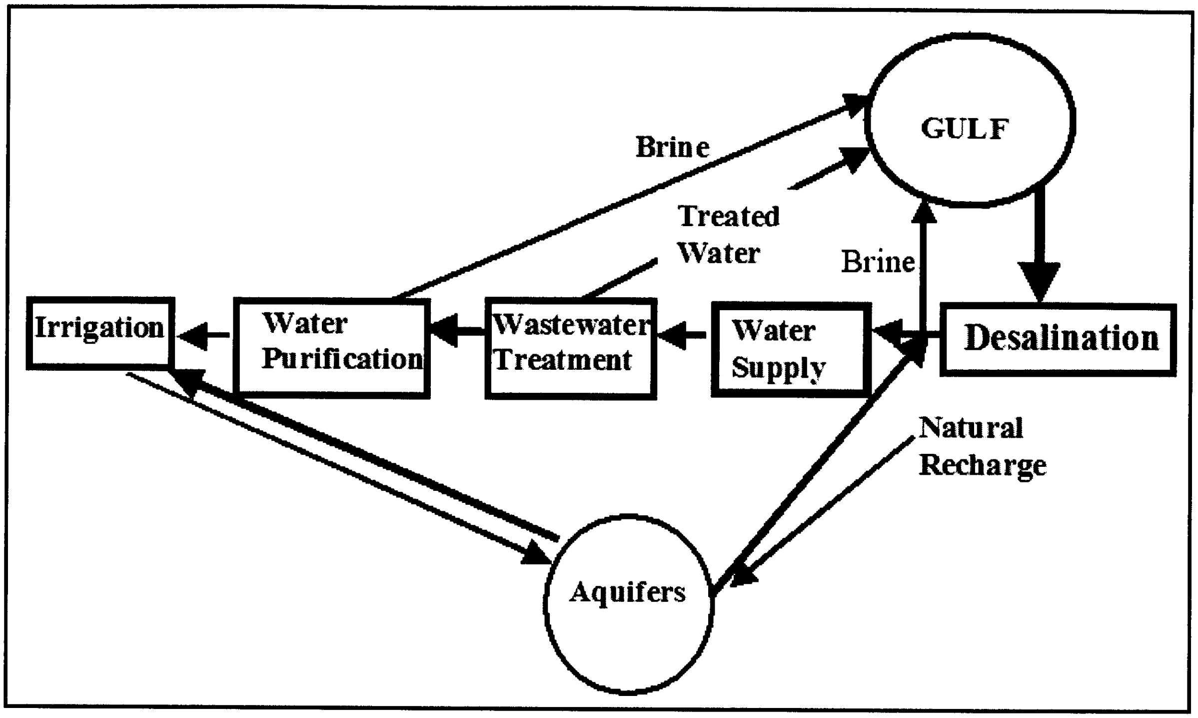

Figure 1-1 Water infrastructure schematic

There are basically four tiers of water resources available in Kuwait: desalinated seawater, brackish groundwater, tertiary treated wastewater and RO treated wastewater. These and any added sources must be allocated for maximum effectiveness. Desalinated water is the highest quality, the most expensive to produce, and the most used. This water should be used only where potable water is required, as in drinking, showering and cooking. Blending brackish groundwater with the desalinated water to improve the taste is a good use of the groundwater resource. However, using large quantities of brackish water for irrigation causes deterioration of the soil and is not an ideal plan for sustainable agriculture.

Tertiary treated wastewater is currently being dumped into the Gulf, where it may cause stress on the environment in Kuwait Bay or the Gulf as a whole. This water has relatively high nutrient concentrations, which may cause harm to the aquatic environment, but would be beneficial if the water were used for agricultural irrigation. There are health concerns associated with using this water, but it could be used safely for many valuable applications, depending on its quality. According to guidelines written by a variety of local and national governments, this water could probably be used safely for many crops, including orchards, animal feed, and possibly food crops (State of Arizona, EPA Victoria, US EPA). The RO treatment produces very high quality water (Table 1.1) and is also quite expensive. Several places use similarly treated water for indirect potable use by introducing it to drinking water aquifers though artificial recharge. These include Orange County California's Water Factory 21 and Groundwater Replenishment System, and programs in Belgium. In addition to supplying water to industrial clients, Singapore adds RO treated wastewater directly to its drinking water reservoirs. The RO water may be a good product for irrigating vegetables or other crops where the edible portion comes in contact with the irrigation water. However, for most agricultural uses, the additional expense of RO treatment is wasted since the nutrient rich tertiary treated water would be a more desirable product.

Table 1.1 Recycled water quality expected from the Sulaibiya wastewater reclamation facility (Adapted from Gagne, 2004)

	Tertiary effluent entering RO facility (monthly average)	Water reclamation plant product (monthly average)	WHO potable water guidelines
PH	7	6-9	6.5-8.5
TSS (mg/L)	12	<1	
BOD (mg/L)	5	<1	
Ammonia Nitrogen as N (mg/L)	<2	<1	1.5
Nitrate (mg/L as N)	<9	<1	10
Phosphate (mg/L as PO_4)	<15	2	
Fat, Oil and Grease (mg/L)	<0.5	<0.5	
Conductivity (mS/cm)	2000		
TDS (mg/L)	<1280	100	1000

Kuwait has several options for increasing its supply of potable water. The main options that have been considered in the past include importing water from neighboring countries, such as Iran or Iraq, that have available surface water, expanding the use of treated wastewater and increasing the storage of water in aquifers through artificial recharge or enhanced natural recharge. There are also several options for increasing the effective supply in times of increased demand (summer), or during maintenance of desalination plants. These involve collecting imported or RO treated water or excess desalinated water in times of lower demand to build a store of excess water. For this purpose, natural aquifers can be used for storage. This also helps to reverse the decline in groundwater quality caused by the over pumping over time. Alternatively, concrete storage tanks or similar above ground storage systems could be used to store water. One major concern that affects the relative attractiveness of each of these options is security. It is not politically feasible, or perhaps wise, to depend on imported water in an unstable region. However, water could be imported and stored for emergency use without creating a dependence on the imported water. Similarly, the performance of surface reservoirs is more predictable than that of aquifer storage, but exposed storage is also more susceptible to sabotage. The security factor must be considered for each option along with the usual engineering concerns of cost and technical feasibility.

Kuwait's current water system is not necessarily sustainable, and options should be analyzed for bringing operations in line with a plan that will provide a secure source of water for the future. For the purposes of this project, a sustainable water resource is defined as "a flux of water that is managed with the objective of maintaining the availability and quality of water as long as the current climate prevails." The use of groundwater at the current rates is not sustainable because the head levels have declined dramatically since pumping began, which is a sign that withdrawal rates far exceed the natural recharge to the system (Al-Ruwaih et al. 2000). Over time this causes increasing salinity and decrease in the quantity of water that can be produced. In addition, a government subsidy of around $715 million (2003) supports the current consumption of desalinated water, and the consumers generally do not pay for this very valuable resource (Darwish and Al-Najem 2005). If the government's oil revenues decrease, it will not be able to support this level of consumption. Figure 1-2 shows the water consumption in Kuwait and other water-stressed countries compared to the available water resources.

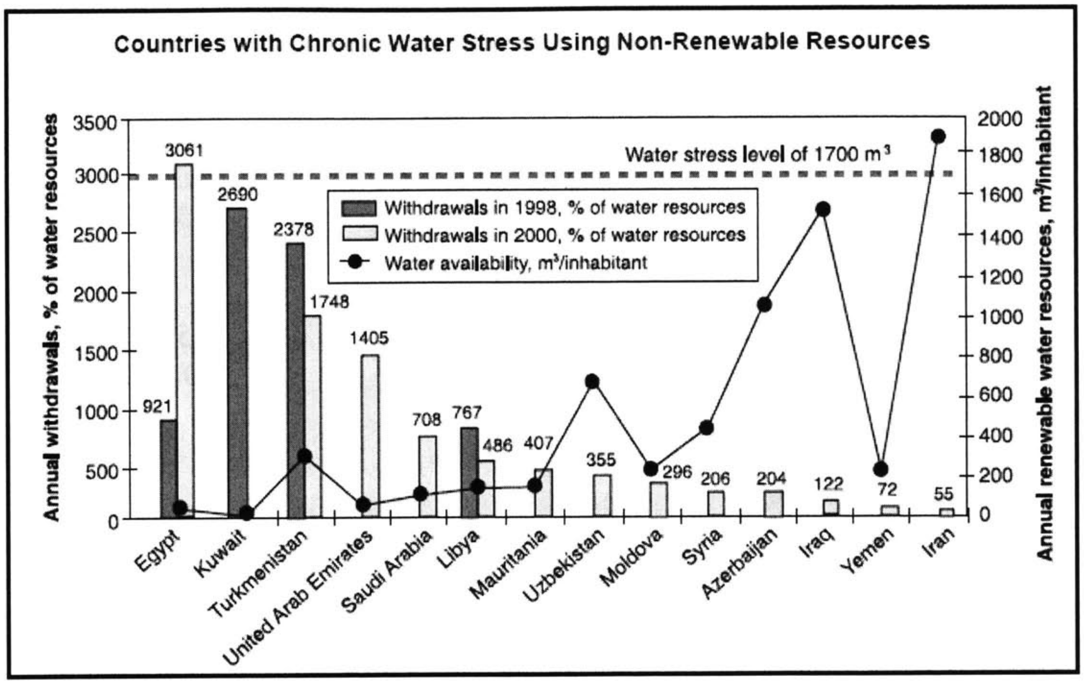

Figure 1-2 Comparison of water usage and available resources (Adapted from US EPA 2004)

With an average annual rainfall of only about 110mm (Al-Ruwaih et al. 2000), Kuwait uses about 0.43 cubic meters per person per day of desalinated water (Al-Qunaibet and Johnston 1985). This is significantly more than the average fresh water consumption in the United States of 0.33m^3 per capita per day (OECD1999) where most areas have adequate natural fresh water sources. Many European nations have consumption patterns that are even lower, in the range of 0.15m^3 per day per person (OECD 1999). This demonstrates that a high standard of living is possible using much less fresh water than the Kuwait average, though the estimates of Kuwaiti consumption may include leaks and other losses in the distribution system in addition to household usage. This consumption rate and the population of 2.3 million are both increasing, and without some control on water consumption or additional sources, the country will eventually face a drastic water shortage.

1.2 Options Overview

There are two main categories of options available for enhancing Kuwait's water supply. The first category to be considered is sources of additional water flux into the supply system. The second is storage options, which can be used to smooth peaks in demand and allow for smaller capacity supply systems. Potential water supply sources include expanding desalination capacity, importing water from Iran or other countries in the region, expanding the production and use of recycled wastewater, and capturing runoff. The two primary options to be considered for storage systems are storage in natural aquifers, and construction of surface reservoirs.

1.2.1 Flux Increase

As previously mentioned, the main options to increase the water supply in Kuwait include desalination, importation, wastewater recycling and rainfall harvesting. Each of these is discussed below, with emphasis in this thesis being on wastewater reuse and rainfall harvesting.

1.2.1.1 Desalination

Desalination currently supplies 90% of Kuwait's domestic water consumption. The remainder is brackish groundwater that is blended with distilled water to increase total dissolved solids (TDS) concentrations to potable levels. Expanding the desalination capacity should be considered as the status-quo option for increasing water supply in Kuwait. As such, it should be the basis of comparison in determining the feasibility of other options.

In 2001, Kuwait's desalination facilities produced about 386Mm^3 of potable water. Kuwait's Ministry of Electricity and Water operates five desalination plants with a total capacity of 1.17Mm^3/d (Fadlelmawla and Al-Otaibi 2005). Each of these facilities is a series of distillation units that use the multistage flash evaporation method of desalination. This method is energy intensive, so the cost of production is closely related to the cost of energy. This system produces water at a cost around $3 per cubic meter, assuming an energy cost of $0.06/kWh (Darwish and Al-Najem 2005). The cost is likely to increase dramatically with rising energy prices. The plants also co-generate electricity during the desalination process, which makes the overall process somewhat more efficient.

However, new facilities are able to desalinate water much more cheaply due to technological improvements that have been made over the past few years. These include reductions in the price of equipment, reduced energy requirements and advances in system design (Zhou and Tol 2005). As a result, newly built or expanded facilities may be able to produce desalinated water at a significantly lower cost than the existing facilites.

1.2.1.2 Importation

A variety of water importation schemes have been considered in the past. These include the "Turkish Peace Pipeline" scheme to import water to Gulf states from rivers in Turkey, and pipelines were also considered for importing water from Iraq or Iran. In 2001, plans were unveiled to construct a 540km pipeline from the Karkheh dam in southwestern Iran to Kuwait. This was expected to cost $2 billion to construct and would supply around 200 million liters per day of drinking water to Kuwait (BBC 2001). Plans to import water from Iran made further progress in 2004 and 2005, but no final agreement was ever made between the two governments (Iranian Daily News 2004 and 2005). Unrest in the region and the political implications of being dependent on upstream states for water security as well as the vulnerability of pipelines to sabotage or attack have halted importation plans for the time being. Other past proposals for importing water to the region have included towing icebergs from the Arctic and importing water in the empty holds of incoming petroleum tankers (Al-Alawi and Abdulrazzak 1994).

Due to the high cost of producing potable water in Kuwait compared to other places, importation should continue to be considered. In order to alleviate the dependence on other nations and the risk associated with pipeline vulnerability, these schemes should be considered in conjunction with storage systems. Water storage systems could help smooth variations in importation rates and a large stored reserve would reduce dependence on other nations. Approximately one year is required for the construction of additional desalination plants (Viswanathan and Al-Senafy 1998), so storage of at least a year's supply of water would greatly reduce the political risk of importation.

1.2.1.3 Wastewater Reuse

Kuwait has recently expanded its wastewater recycling capacity dramatically by building the world's largest membrane-based water reuse facility at Sulaibiya. The largest obstacle currently facing the expansion of wastewater reuse is essentially an image problem. In the future this water may be blended with desalinated water for the potable water supply, or injected into aquifers in an aquifer storage and recovery (ASR) project. Kuwait's wastewater recycling infrastructure is described in more detail in Section 3.6, and Chapter 3 reviews several case studies of wastewater reuse systems around the world.

1.2.1.4 Rainfall Harvesting

The fourth way to increase supply would be through rainfall harvesting. While Kuwait does not receive very much rain, it is possible that a simple system could be constructed to collect water from temporary streams that form after large storms. This type of system is expected to be much less expensive per volume of water collected than desalination and membrane purification processes. As a result, even if the system produces a relatively small volume of water, it could still be a cost effective way to supplement the water supply. The feasibility of rainfall harvesting is discussed further in Chapter 4, which includes the details of a model constructed to simulate runoff processes in a natural drainage system in northern Kuwait.

1.2.2 Storage

Storage systems can serve two major purposes. The first is seasonal storage, which smoothes cycles of high and low demand throughout the year. For example, desalination plants could operate at a nearly constant rate throughout the year, with excess capacity stored in the winter for use during the summer when demand is higher. The second category of storage is long-term storage, which can be used as an emergency supply in times of crisis, such as an interruption in the usual supply system. This type of storage would also reduce the political risk associated with water importation.

1.2.2.1 Aquifer Storage

Aquifer storage has been considered within Kuwait for both seasonal and long-term storage, but it has not been implemented at this time. Aquifer storage would have an additional benefits of recharging aquifers that have been depleted by over pumping and improving the quality of groundwater. However, there would also be losses of high quality injected water due to groundwater flow and mixing with the native groundwater.

Figure 1-3 shows the existing groundwater production areas in Kuwait. Of these, all produce brackish water except for the two small fields at Rawdhatain and Umm Al-Aish where Kuwait's only natural freshwater is produced. The brackish water fields should be considered for seasonal and short-term storage, because they are conveniently located near the population center at Kuwait City and the desalination and wastewater recycling facilities that would likely supply water for seasonal storage. However, for long-term storage, these fields are likely to loose a considerable amount of the injected freshwater due to mixing with the natural water.

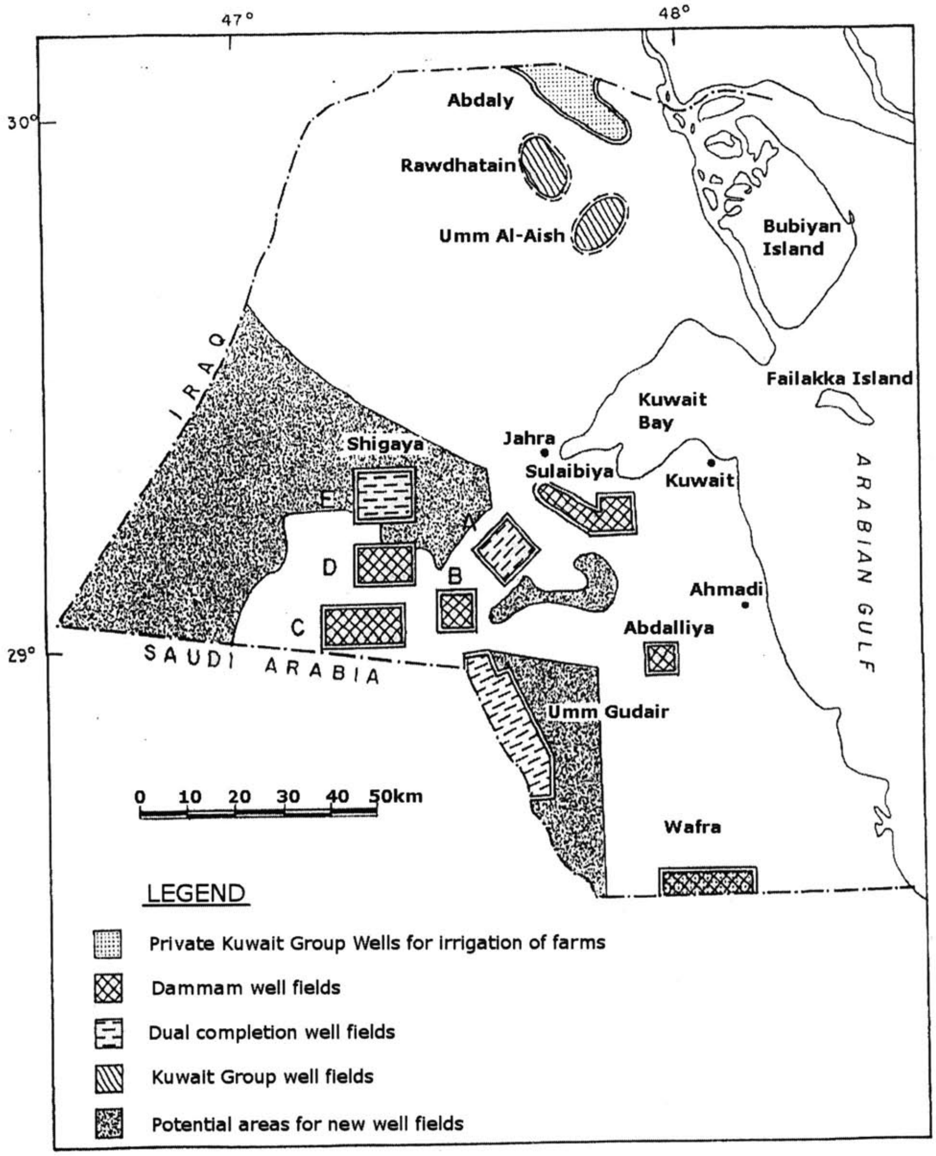

Figure 1-3 Map of Kuwait well fields (Adapted from Sayed and Al-Ruwaih 1995)

The freshwater lens at Rawdhatain is the best candidate for long-term storage, because there will be a higher recovery rate of fresh water. The groundwater at Umm Al-Aish is of poorer quality than that at Rawdhatain, so it is not as good of a candidate for aquifer storage (Beaumont 1977). The Rawdhatain aquifer may be too far from population centers and the major water production facilities to make it a practical site for seasonal storage. Aquifer storage is discussed in further detail in Chapter 5.

1.2.2.2 Surface Storage

Artificial storage in concrete tanks or similar systems avoids the issue of well clogging associated with aquifer storage and is expected to have a higher recovery efficiency. In order to provide a large water reserve, either one massive reservoir or a series of smaller reservoirs would be necessary. This would require a huge construction effort, and the cost may be prohibitive. Two basic methods of construction come to mind for constructing a large-scale reservoir. The first is to excavate the required volume for the reservoir, and construct a sealed box. The excavated soil could be placed back over the reservoir to protect it or moved to a different area. This would be extremely expensive, and for a large area, the construction of a roof able to hold the overlying soil could be a significant challenge. However, an underground reservoir would be somewhat more protected from sabotage than a surface reservoir. This is important if it is built as a strategic storage mechanism for emergency use. In order to store 1,000Mm^3 (1km^3) of water, a circular reservoir 5m deep would have to have a radius of nearly 8 kilometers.

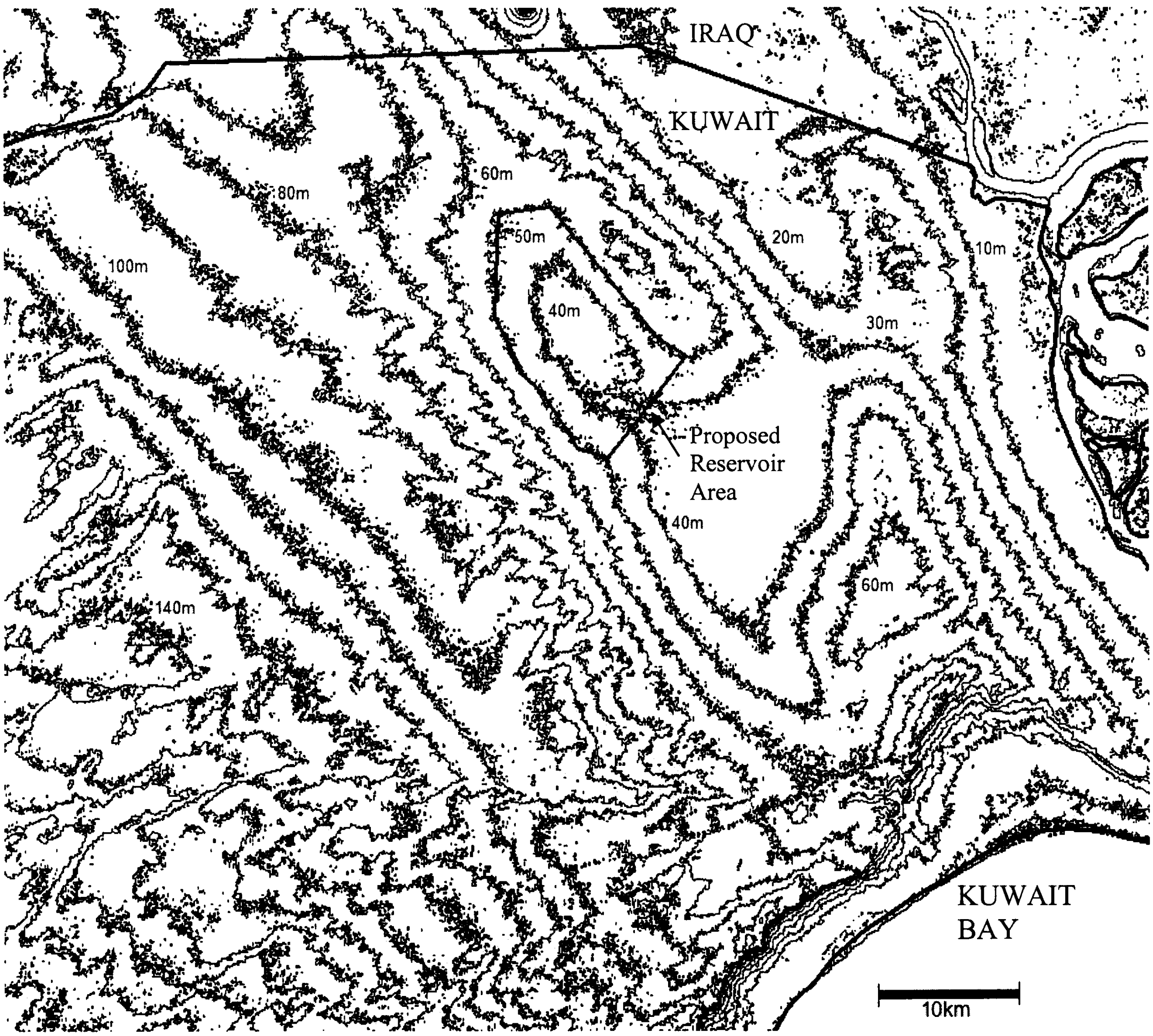

Figure 1-4 Elevation contour lines around the proposed reservoir area

For a surface reservoir, a large natural depression could be lined and then filled with water. This would significantly reduce the construction cost compared to an underground reservoir. However, due to the high potential evaporation rate in Kuwait, it would need to be covered. In addition, because of the large area, it might be desirable to construct a roof strong enough to allow traffic to pass over it. In designing this type of reservoir, one might also consider the nomadic population and create a top surface that could sustain foot and livestock traffic even if motorized traffic is prohibited. One potential site for this system is the Rawdhatain depression in northern Kuwait. As mentioned in the previous section, this location is far from population centers, but it is the largest natural depression in the country where this type of reservoir could be constructed without undertaking a huge earth-moving project. Elevation contour lines for this area are shown in Figure 1-4, and by lining the area bounded by the 50-meter contour line, a 1,000Mm^3 storage reservoir would be created with a surface area of 134km^2 and a maximum depth of 11m. Surface storage is discussed further in Section 5.3.

These options represent a wide range of possibilities that could improve the status of Kuwait's water resources. A combination of increased flux and implementing a storage system has the best chance for success, especially in terms of water security. This study focuses on better understanding the applicability of wastewater reuse, rainfall harvesting, and storage systems to Kuwait's environment.

Chapter 2
Background and Previous Studies

2.1 Introduction

Extensive studies have been performed on the groundwater in Kuwait to facilitate planning and use of this resource. This chapter outlines information that has been gathered about the overall groundwater system in terms of its physical properties and use and focuses specifically on the hydrogeology at Rawdhatain. Comparatively, very little research has been carried out on the surface hydrology in the drainage networks at Rawdhatain, but the available research in that field is reviewed here as well. Previous studies related to the feasibility of artificial recharge systems in Kuwait are also presented.

2.2 Groundwater in Kuwait

There are two regional aquifer systems in Kuwait: the Kuwait Group and the Dammam Formation. These regional systems begin as sandstones in the west and gradually shift to carbonate formations, which are dominant along the Gulf coast. Groundwater flow is predominantly west to east with some upward leakage occurring. The generalized stratigraphy of geologic formations in Kuwait is shown in Figure 2-1.

2.2.1 Kuwait Group Aquifer

The Kuwait Group aquifer represents the Neogene-Quaternary aquifer system in Kuwait. It is divided into three formations, with the Dibdibba nearest the surface and the Lower Fars then Ghar below. The Dibdibba formation is only present in the northern portion of Kuwait, and consists mainly of sand and gravel deposits. The freshwater lenses at Rawdhatain and Umm-Al Aish are located in the Dibdibba formation. The Kuwait Group aquifer ranges in thickness from 150m in the southwest to about 400m in the northeast. The piezometric head in this layer is about 100m above mean sea level (M.S.L.) at the southwestern edge of Kuwait and slopes downward toward Kuwait Bay (at the head of the Persian Gulf) where some groundwater is discharged through evapotranspiration at marshlands along the shoreline before reaching the bay (Al-Ruwaih et al. 2000). Recharge of the Kuwait Group consists mainly of upward leakage from the Dammam aquifer, though some recharge from rainfall infiltration occurs at least in the northern regions around Rawdhatain and Umm-Al Aish. Infiltration of irrigation water may also recharge the aquifer to some extent in the farming and urban areas. Flow into Kuwait across the Saudi Arabian border is estimated to be $2x10^4$ m^3/day (Senay 1981) to $1.4x10^5$ m^3/day (Al-Rashed 1993) in this layer.

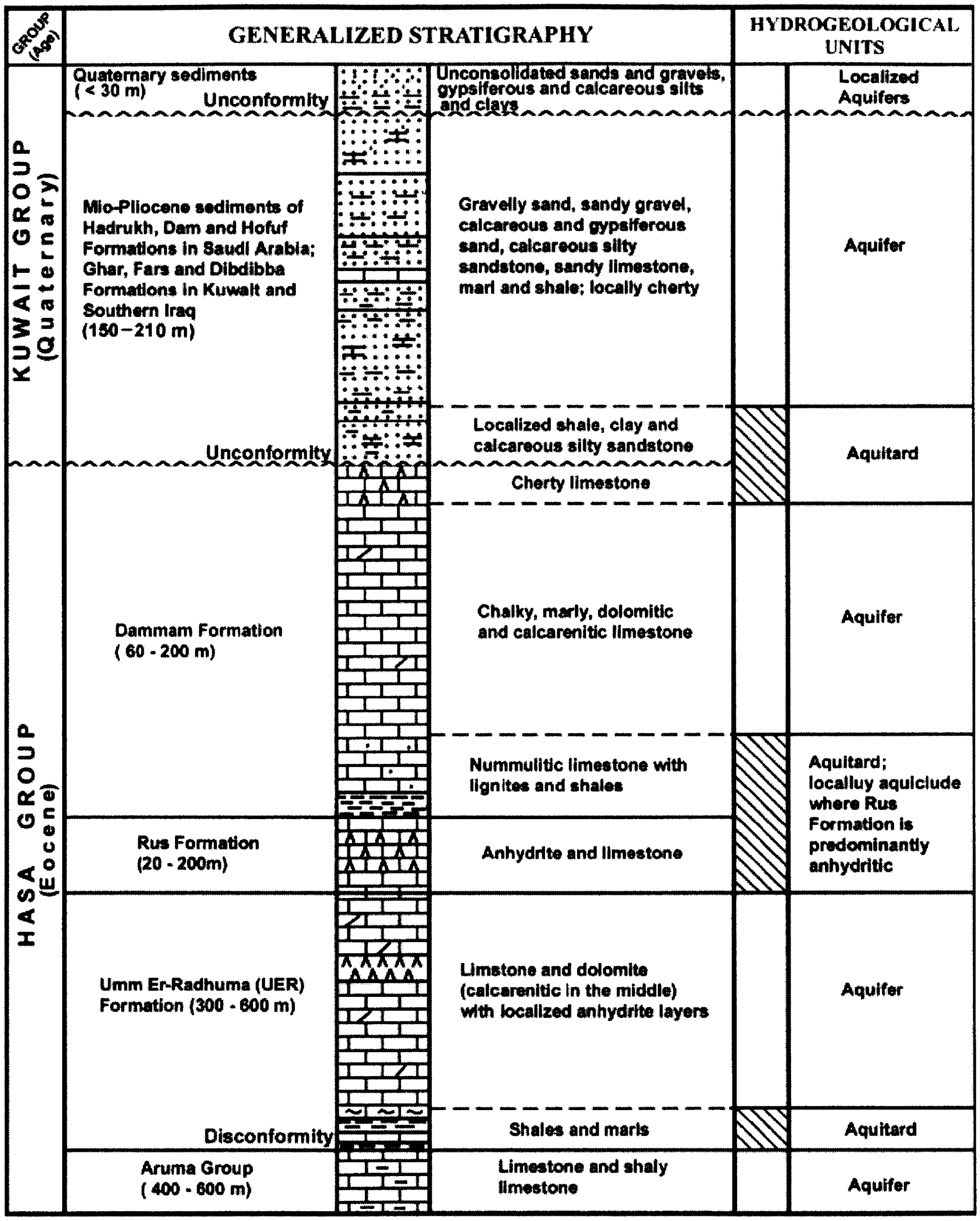

Figure 2-1 Stratigraphy of the aquifer system in Kuwait (Adapted from Al-Ruwaih and Hadi 2005)

2.2.2 Dammam Limestone Aquifer

The Dammam formation is the uppermost of three Eocene formations. The Dammam is underlain by the Rus anhydrite Formation that separates it from the Umm Al-Radhuma Formation. The Dammam and Umm Al-Radhuma aquifers can be considered as one system because there is good hydraulic continuity and balanced pressure between the two aquifer layers, especially where karst or faults are abundant. The Dammam limestone aquifer varies within Kuwait from 150m thick in the southwest to nearly 275m thick in the northeast. The piezometric head slopes from about 115m above M.S.L. in the southwest corner of Kuwait downward to the

Gulf. The head in the Dammam aquifer is 3 to 20 m higher than that in the Kuwait Group, which results in some upward leakage between the aquifers. The predominant source of recharge is precipitation on the Dammam Dome in Saudi Arabia, where the Dammam Formation is at the surface (Al-Ruwaih et al. 2000). The volume of flow into the recharge area is unknown, but it has been estimated that the flow across the boarder from Saudi Arabia is about $5x10^4$ to $7x10^4$ m^3/day (Senay 1981) or $1.8x10^5$ m^3/day (Al-Rashed 1993) through the Dammam limestone aquifer. According to Al-Rashed (1993), the groundwater flow entering Kuwait through the Kuwait Group and Dammam limestone aquifers decreased annually by $2.2x10^4$ m^3/day in the period between 1972 and 1988. These levels of recharge are significantly below the production rates of Kuwait's water fields, which indicates that the aquifers are being depleted or that there is leakage from adjacent formations. The water levels in production wells are also declining significantly (Al-Ruwaih 1981), which suggests that the aquifers are being depleted.

2.2.3 Water Production

Brackish water production began in Kuwait in 1953 on a small scale, and in 1960 large-scale production began providing domestic consumers with brackish water through a second supply pipe network. This is meant to be used for landscaping, toilet flushing and other household uses. However, anecdotal evidence suggests that desalinated water is often used for private landscaping instead of the brackish supply because desalinated water is better for plants and is not very expensive. In addition, about 10 percent of brackish groundwater production is used for blending with desalinated water to remineralize it and improve taste. In 2001, the total brackish water withdrawal was about $210Mm^3$, of which about 30% was for agricultural use (Fadlelmawla and Al-Otaibi 2005). The brackish water produced by the Ministry of Electricity and Water comes predominantly from three groups of water fields: Al-Shagaya fields A, B, C, D, and E, Al-Sulaibiya and Umm-Gudair. Most of these wells penetrate both the Dammam and Kuwait Group aquifers and are known as dual-completion wells. Private farms in the Wafra and Abdaly areas produce brackish water for irrigation, and the Kuwait Oil Company also produces some brackish groundwater. A map of Kuwait's water fields is shown in Figure 1-3.

The water level in the main brackish water production fields fluctuates noticeably in response to changes in pumping rates, and is declining on average. As reported by Al-Ruwaih (2000), the average water level in the Al-Sulaibiya field declined by an average of 1.5m per year between 1975 and 1990. The water level was expected to decline even more rapidly between 1990 and 2000 to cause a total head decrease of 91 to 116m in the eastern part of the field.. The head level in the Dammam aquifer at Al-Shagaya field D declined by over 30m between 1981 and 1989. However, the water level rose again in 1989 due to decreased pumping in this field corresponding to a shift in production among the Al-Shagaya fields (Al-Ruwaih et al. 2000). It is clear from Figure 2-2 that the fluctuations in water level are due to seasonal changes in pumping rates. The declines in head correspond to periods of high pumping rates and head levels recover when pumping is decreased. This effect is particularly clear in the Dammam limestone aquifer where the head levels fluctuate more widely. Most of the fields show a strong connection between the head fluctuations in the lower Kuwait Group and Dammam Formation aquifers, which suggests that these aquifers have a strong hydraulic connection in many areas (Al-Ruwaih et al. 2000).

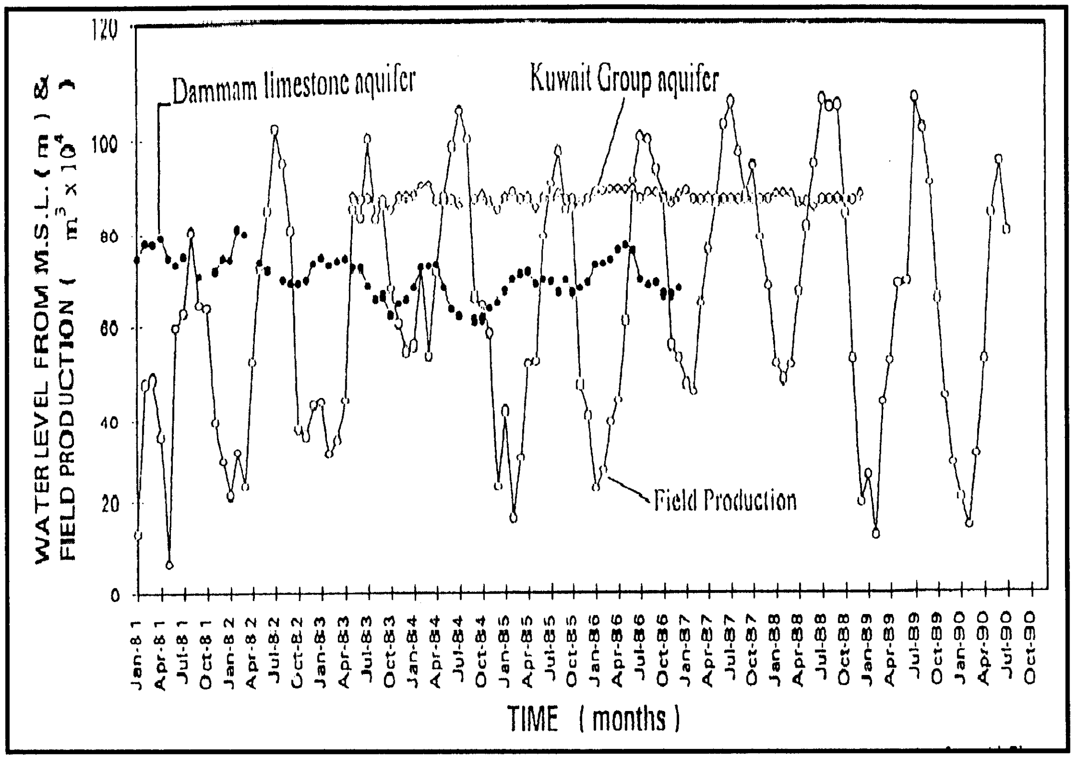

Figure 2-2 Fluctuation of water level and production in Shagaya Field D (Adapted from Al-Ruwaih et al. 2000)

Similar declines in head over time have been observed in the other major well fields in Kuwait, and some have also shown significant deterioration in groundwater quality due to over pumping. In 1994, Mukhopadhyay et al. concluded that Kuwait's groundwater resources were being mined because production rates are significantly greater than the underflow entering the country from Saudi Arabia. As a result, head levels have decreased and salinity concentration has increased near several of the major production fields (Mukhopadhyay et al. 1994). This study also concluded that the Kuwait Group and Dammam limestone aquifers could be dewatered in some locations due to current pumping practices. No major changes in groundwater extraction policy or management have been put in place since this study, so it can be assumed that these predictions apply under the current practices.

Table 2.1 Groundwater classification (Adapted from Freeze and Cherry 1979)

Category	Total Dissolved Solids (mg/L)
Fresh water	0-1,000
Brackish water	1,000-10,000
Saline water	10,000-100,000
Brine water	>100,000

Limited quantities of fresh water exist at the Al-Rawdhatain and Umm Al-Aish fields. Table 2.1 explains the classification of groundwater based on TDS content for reference. The current production in these fields is minimal in order to keep this natural fresh water as a strategic reserve. The reserve in the two fields is estimated to be around $1.8 \times 10^8 m^3$ (Al-Ruwaih et al. 2000). Production began in 1963 with an average rate of $9000 m^3/d$ from 26 wells. Extraction peaked in 1967 at $11000 m^3/d$. Due to deterioration of water quality, production was reduced to

$4500m^3/d$ in 1973, and by 1998, the field was only producing about $240m^3/d$. Currently only 14 of the original 26 production wells are still in use (Al-Ruwaih and Hadi 2005).

2.2.4 Groundwater at Rawdhatain

The freshwater supply at Rawdhatain consists of a lens about 4km by 7km in aerial extent and up to 30m deep, surrounded by the brackish water that forms the main Kuwait Group aquifer in this area. Figure 2-3 shows a basic schematic of the aquifer system. A map of the well field is shown in Figure 2-4, and Figure 2-5 shows groundwater quality with depth in two cross sections. The production and observation wells in the well field map were installed during the initial studies of the aquifer in the early 1960s by Parson's Corp.

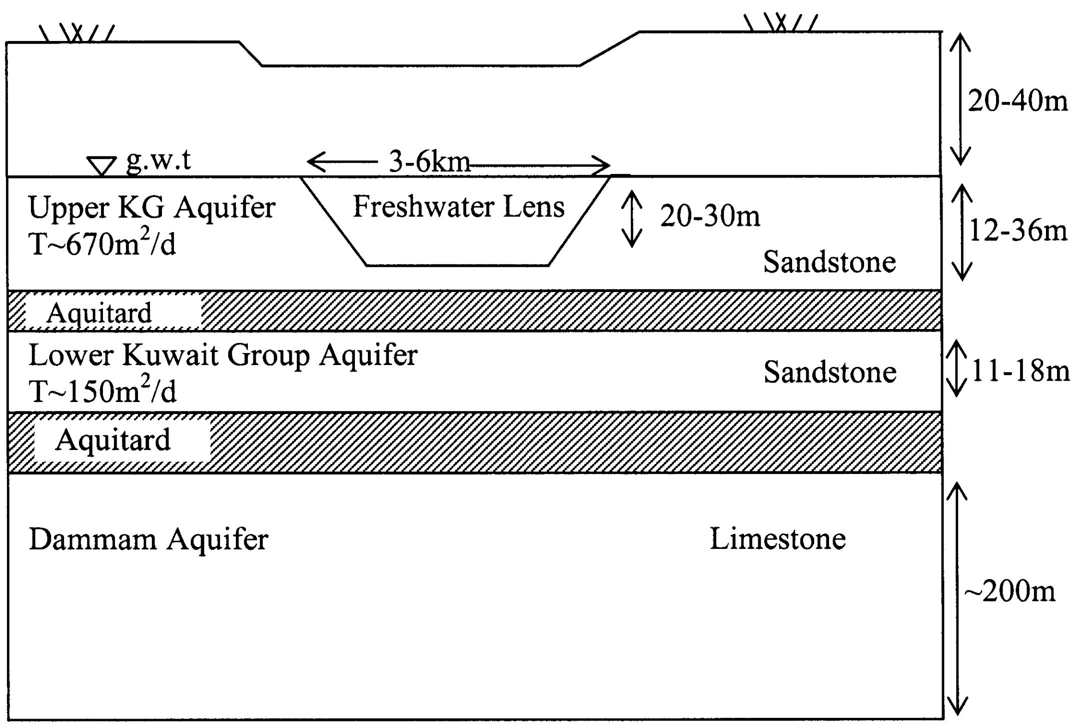

Figure 2-3 Schematic of the aquifer system at Rawdhatain

The zone of freshwater at Rawdhatain was created by infiltration of runoff that collects in wadis during severe storms. The lens is located near the center of the Rawdhatain drainage depression. The surface sediments are mainly sand and gravel of recent origin, but these merge with sands and gravels of the Dibdibba Formation (Pleistocene) below. The Dibdibba formation is about 107m thick at Rawdhatain and consists mainly of cemented sands, gravels and silts with a minor clay fraction.

The usable freshwater exists in the upper part of the saturated sandstone beds of the Dibdibba formation. The water bearing zones in the Dibdibba Formation here can be represented by two aquifers. The first has a saturated thickness ranging from 12 to 36 meters and contains fresh groundwater in the depression. The lower aquifer may vary in effective thickness between 11 and 18 meters or more and contains brackish water in the upper portion with increasing salinity deeper in the aquifer. Flow in the upper part of the first aquifer is under water table conditions, and in the second aquifer and the lower part of the first aquifer, flow is artesian (Senay 1977).

Depth to initial water level is 23m from the bottom of the depression and up to 46m from higher ground (Figure 2-5). Based on pumping tests carried out in 1973 as well as observations of water level and water quality since pumping began in 1962, this system can be considered as a coupled leaky aquifer. Senay (1977) estimates the transmissivities of the upper and lower aquifers as $670m^2/d$ and $150m^2/d$ respectively.

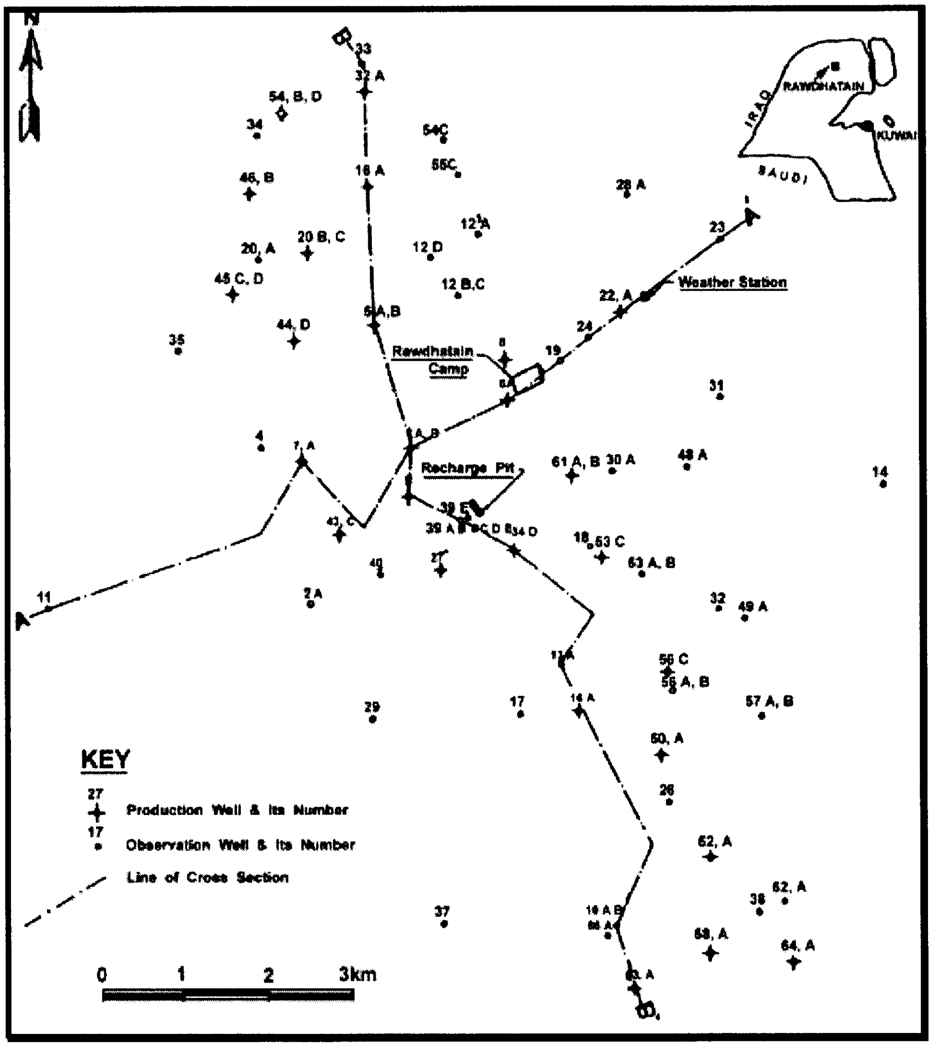

Figure 2-4 Map of Rawdhatain Water Field (Adapted from Al-Ruwaih and Hadi 2005)

The total dissolved solids (TDS) content in the upper most aquifer ranges from 200 to about 8,000ppm. As shown in Figure 2-5, salinity increases with depth throughout the area. Water quality deteriorated in response to pumping much faster than expected. The TDS values for produced water increased from 1,000ppm in 1967 to 1,400ppm in 1973 to about 3,200ppm in 1997 and 3,600ppm in 2004. Based on maps of water quality throughout the field, Al-Ruwaih and Hadi show that quality deterioration reached its peak between 1968 and 1973 and quality has been improving in response to the decreases in pumping rate (Al-Ruwaih and Hadi 2005).

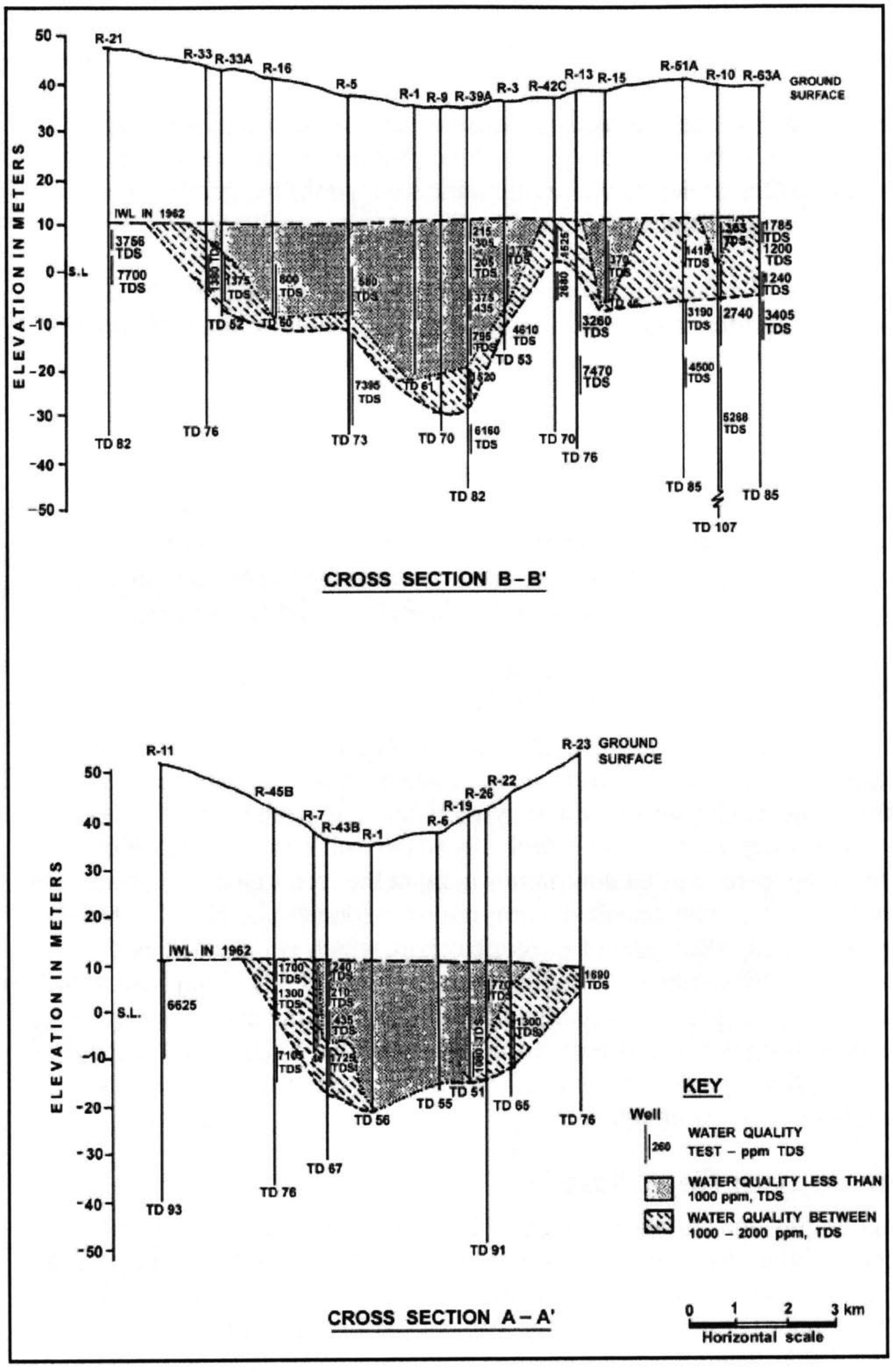

Figure 2-5 Cross-sections of Al-Rawdhatain Well Field showing water quality variation (Adapted from Al-Ruwaih and Hadi 2005)

Unfortunately, even after pumping at a low rate for almost 20 years, the chemical composition of the aquifer has not regained its original quality. Al-Ruwaih and Hadi (2005) suggest two reasons why the quality has not recovered. The first is that the transition zone between the fresh and brackish water has expanded due to continuous pumping that has caused deeper low-quality water to rise into the layer that is being pumped. The second problem is that production wells are often screened at several different depths within the same well, so the produced water is a combination of water from several different zones with different water qualities.

If water movement in the cone of depression is considered to be lateral in the lower (non-pumped) and upper (pumped) aquifers and vertical in the semi-permeable aquitard, Senay (1973) gives the following equation for the amount of brackish water gained by leakage:

$$Q_2 = \frac{Q_1}{1+\delta} \tag{2.1}$$

Where Q_2 is the rate of water gained by leakage from the second aquifer, Q_1 is the pumping rate from the first aquifer and δ is the ratio of the transmissivity of the second aquifer to the transmissivity of the first. While groundwater quality in the depression has not improved to its original levels, the TDS content in well R-1, located in the center of the freshwater lens, has recovered to near its 1962 concentration of 400ppm TDS (Al-Ruwaih and Hadi 2005).

Al-Ruwaih and Hadi (2005) have performed a comprehensive study of the groundwater quality at Rawdhatain, based on data since the original field investigations in 1962. Their analysis showed that the major groundwater chemical constituents are sodium bicarbonate, calcium bicarbonate, sodium chloride, sodium sulfate and calcium sulfate. It is undersaturated with respect to anhydrite, aragonite, calcite, dolomite and gypsum, and the mean value of P_{co2} is $2x10^{-3}$ atm. This P_{co2} value is representative of a deep closed environment system, which suggests that leakage from the lower aquifer contributes more to the recharge of the upper aquifer than infiltration does. The main genetic water types were found to be Na_2SO_4, $NaHCO_3$ and $MgCl_2$. This suggests mixing with water of meteoric origin, which is indicated by the dominance of sulfate, calcium and sodium ions (Al-Ruwaih and Hadi 2005). They also found the predominant geochemical processes to be simple dissolution or mixing and cation exchange. In general, this study seems to support the idea proposed by Senay that a significant amount of upward leakage is occurring from the deeper more saline aquifer into the upper freshwater aquifer as a result of continuous pumping operations.

2.3 Surface Hydrology at Rawdhatain

The combination of topography and surface sediment at Rawdhatain is somewhat unique in Kuwait and it is this combination that allows recharge to reach the Kuwait Group aquifer and form the freshwater zone. As previously mentioned, the surface sediment consists mainly of sand and gravel from the Upper Dibdibba formation. Parsons performed infiltration tests at Rawdhatain during 1962-1963. They found the average infiltration capacity to be about 9m/day (Parsons 1964). After a rainstorm in 1977, it was observed that recharge water reached the aquifer at well R-39A after 80-90 hours and caused the water level to rise about 1m (Al-Ruwaih and Hadi 2005). This illustrates that the vertical permeability is fairly high in this region, unlike in other parts of the Kuwait Group where the vertical transmissivity has been estimated as 100 times less than the horizontal transmissivity (Al-Ruwaih and Hadi 2005).

Al-Sulaimi et al. (1988) measured infiltration rates at 11 stations within the Rawdhatain drainage system. The results, given in Table 2.2, range from a low of 4cm/hr in the drainage depression to 67cm/hr in an upland area with shallow gravel deposits, with a great deal of variation in between. The infiltration rate depends largely on the depth of the gravel deposits of the upper Dibdibba Formation and the thickness of the overlying silty sand soil. It was found that infiltration rate could change drastically within a short distance depending on the surface sediment. Rates are lowest in the drainage depression, stream channels and lowlands where the silty sand is thicker (Al-Ruwaih and Hadi 2005). This is probably due to the deposition of silt and other sediment in these channels during runoff events.

Table 2.2 Infiltration rates of geologic formations within drainage area (Modified after Al-Sulaimi et al.1997)

Geologic Formation	Lithology	Station	Infiltration Rate (cm/hr)
Playa	Dense mud	4	4
Wadi fill	friable gravelly sand or aeolian sand	2.2	67
Desert floor deposits	compact gravelly muddy sand to sandy mud	1 5	35 48
Upper Dibdibba	Gyperetic/calcretic gravelly sand	2.1 6 7 8 11 12	15 22 21 24 10 21

Al-Sulami et al. (1997) performed a detailed geomorphological analysis of several "paleo drainage systems" throughout Kuwait. These drainage systems, including the one at Rawdhatain, were formed in a wetter climate, and have persisted in the current desert environment. They used detailed topographic maps and high-resolution aerial photographs to delineate watersheds and precisely identify and characterize individual channels. This study identified 12 sub-basins in the Rawdhatain watershed, and these stream networks are shown in Figure 2-6. The individual basins range from 3.2 to 309km^2, with a total area of about 670km^2. The basins have an average of 85 streams each and an average total stream length of 95km. This results in a total stream length for the entire drainage system of over 1100km.

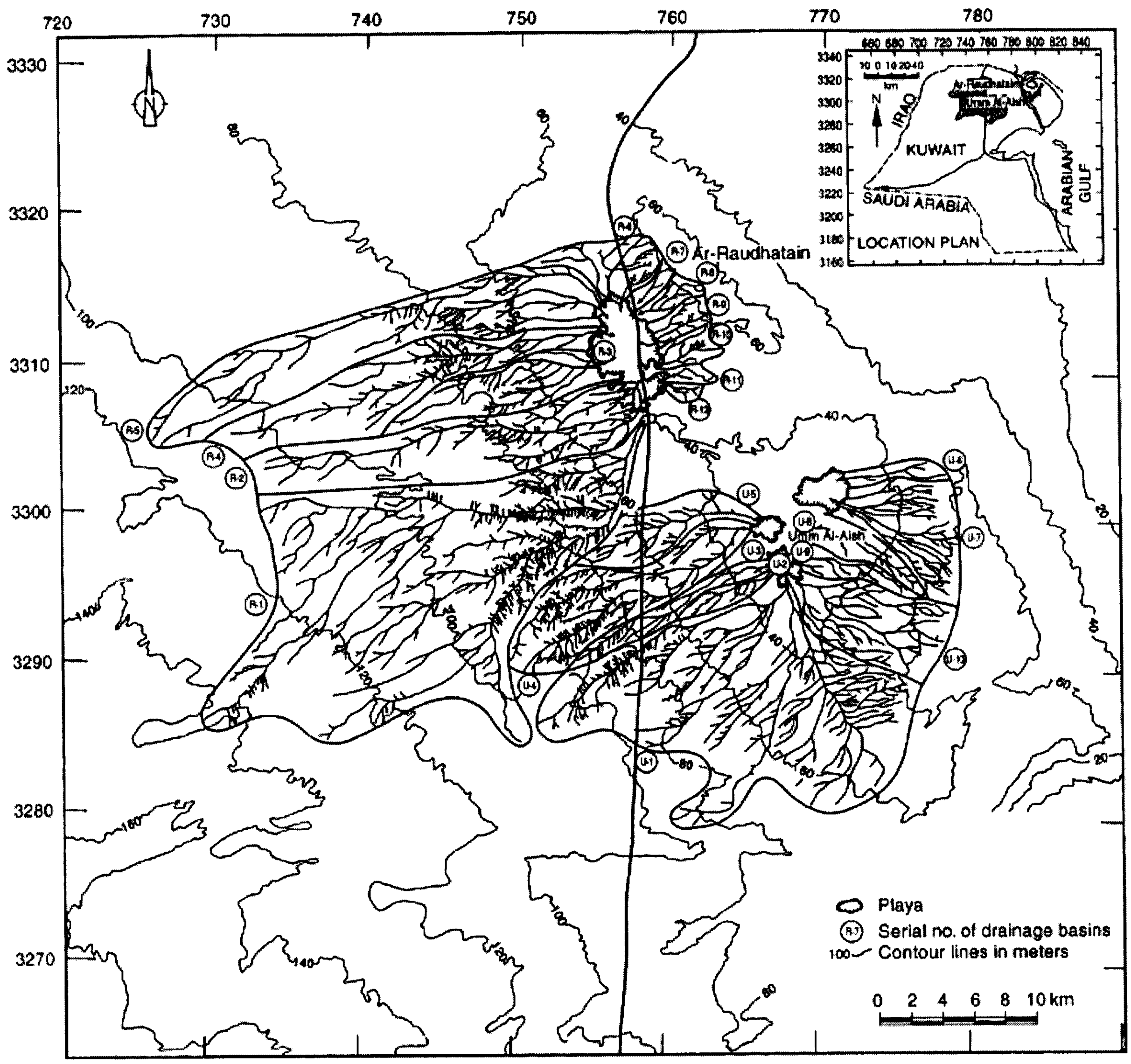

Figure 2-6 Drainage networks in Rawdhatain and Umm Al-Aish (Adapted from Al-Sulaimi et al.1997)

2.4 Artificial Recharge Studies

As early as 1964, Parsons built a recharge pit in the Rawdhatain depression for collecting surface runoff from occasional rainstorms. The average infiltration capacity of the pit was 9.1m/d. They determined that 4-8mg/L chlorine solution should be added to counteract bacterial and algal growth. No significant recharge was recorded through the recharge pit except on two occasions, once in 1970 and once in 1977 (Mukhopadhyay and Al-Sulaimi 1998).

During 1972-73 and 1977, the Ministry of Electricity and Water did recharge experiments using injection wells in the Rawdhatain water field. These tests were designed to study the clogging effects of injection and to determine the quality of recovered water compared to the injected water. In the first test, clogging was noticed within 100min of recharge, but was cleared within a few minutes of backpumping. In the second test, no clogging was noticed. In this second test, about 10% of the injected water was recovered with no quality change, and about 52% was recovered with less than 1000mg/L TDS (Senay 1977).

Kuwait Institute for Scientific Research (KISR) conducted similar well-recharge studies at three wells in the Sulaibiya and Shagaya field C water fields. They concluded that the Kuwait Group aquifer provides higher recovery efficiency than the Dammam Formation, but that it is also more susceptible to clogging effects. Based on several selection criteria combining both desirable aquifer characteristics and practical site considerations, a site near the Sulaibiya and Shagaya fields was proposed for artificial recharge with desalinated water to create an emergency reserve of potable water (Mukhopadhyay and Al-Sulaimi 1998). For this project, Mukhopadhyay and Al-Sulaimi assume a conservative recovery efficiency of 20% for water with a TDS content of 1500mg/L or less, and determine that a volume of 82,000ML should be injected in order to create an emergency supply of 45ML/d for one year. They estimate that it would take between 5 and 10 years to inject this supply through 35 injection-recovery wells. However, this would create a significant head buildup in the injection region, causing the piezometric head level to be 40-75m above ground surface by the end of the injection period. While this proposal seems to have been at a fairly advanced stage of planning in 1998, we do not know of any further progress toward the implementation of such a storage system. However other researchers are now considering this site for the proposed injection of RO treated wastewater from the Sulaibiya water reclamation plant (Kuwait-MIT Center Technical Meetings, March, 2006).

Chapter 3
Experiences in Wastewater Reuse and Water Storage with Comparison to Kuwait

3.1 Introduction

Many governments around the world have implemented wastewater reuse as a major part of their water resource planning. Wastewater is the only water resource that does not become scarcer with population growth and increases in per-capita consumption. Historically, partially treated wastewater has often been used for agricultural purposes, but advanced technology now allows highly treated wastewater to be used safely for industrial applications and indirect potable use. This section describes several communities that use membrane treatment to reclaim wastewater, as well as their use of aquifer and surface storage systems. These systems are compared to the wastewater recycling facility in Kuwait to understand the potential uses of this water.

3.2 Orange County, CA

Orange County, CA receives only 13 to 15 inches of annual rainfall, and sustains a population of approximately 2.5 million people, with a significant agricultural economy. The massive groundwater basin underlying half of the county supplies about 75 percent of the county's total water demand. By 1956, the water table had dropped below sea level and saltwater had encroached as much as 5 miles inland from the Pacific Ocean. In order to prevent degradation of the water supply, Orange County installed a seawater intrusion barrier in the 1970s (OCWD 2001). This system is supplied largely by reclaimed wastewater from Water Factory 21. Orange County is now planning to expand the barrier and increase the recharge to its drinking water aquifer through the Groundwater Replenishment System.

3.2.1 Water Factory 21

The Orange County Water District (OCWD) has been injecting reclaimed water from Water Factory 21 to prevent seawater intrusion into its drinking water aquifer since 1976. OCWD currently operates a series of 23 multi-point injection wells along the coast in order to provide a hydraulic barrier against further encroachment of seawater. Much of the water injected in these wells flows inland to recharge the aquifer that provides most of Orange County's drinking water. After considering deep well water, imported water, reclaimed wastewater, and desalted seawater, OCWD decided to use a blend of deep well water and recycled wastewater to create the barrier. A major consideration in this decision was the reliability of supply, since this type of use receives last priority when water supplies are diminished by drought or interruption of importation systems. This option also has the environmental advantages of reducing the amount of wastewater discharged into the ocean by 18.5 million cubic meters annually, and reducing dependency on the State Water Project and Colorado River imported supplies (OCWD 2001).

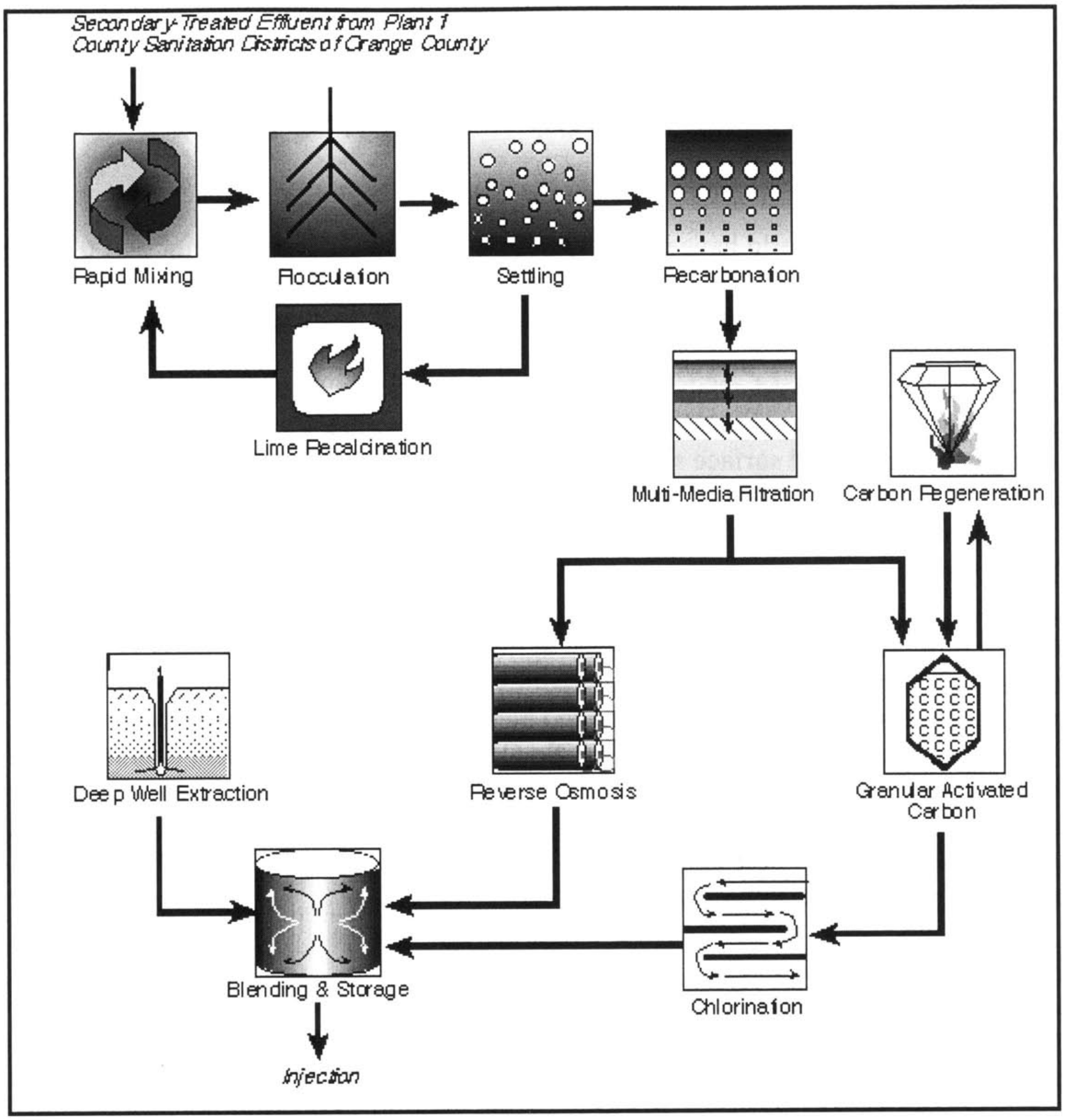

Figure 3-1 Water Factory 21 process schematic (Adapted from OCWD 2001)

Water Factory 21 effluent is a blend of 19,000m^3 per day reverse osmosis-treated water, 34,000m^3/d carbon adsorption-treated water, and 33,000m^3/d deep well water. This blend has a total dissolved solids (TDS) content of 500 mg/L or lower, and meets all California Department of Health Services primary and secondary drinking water standards. Figure 3-1 shows a schematic of the treatment train at Water Factory 21. To produce the reclaimed wastewater, secondary-treated effluent is subjected to a chemical clarification process, followed by recarbonation to lower the pH. The water is then passed through multi-media filtration beds consisting of anthracite coal, sand, and fine and coarse garnet to reduce turbidity. At this point the treatment flow splits. Two-thirds of the stream undergoes granular activated carbon treatment to remove organic compounds. The other portion undergoes reverse osmosis (RO). The RO system is used to ensure that the TDS concentration of the effluent is less than 500 mg/L. RO is very effective in removing TDS as well as other minerals, ammonia, and total organic carbon (TOC). Additional pretreatment used before the RO process consists of antiscalant addition, sulfuric acid addition (to obtain a pH of 5.5), and cartridge filtration. The

RO system operates at an 85% recovery rate and removes 90% of the TDS content of the inflow water. The concentrated brine is discharged through the County Sanitation District's ocean outfall. The activated-carbon stream is treated with chlorine, then blended with the RO and deep well water and injected. The OCWD is considering expanding the wastewater reclamation facility to allow for injection of 100% reclaimed water (OCWD 2001).

3.2.2 Orange County Groundwater Replenishment System

A new state-of-the-art wastewater purification system is planned to provide additional recharge to the municipal drinking water aquifer used by the OCWD. The Groundwater Replenishment (GWR) System treatment train will consist of microfiltration, reverse osmosis, ultraviolet light and hydrogen peroxide treatment. Microfiltration will remove small suspended particles, protozoa, bacteria and some viruses from the treated wastewater. RO membranes will then eliminate salts, viruses, pesticides and most organic compounds to create "near-distilled quality" water (Groundwater Replenishment System, 2004). The ultraviolet (UV) light and hydrogen peroxide treatment will provide a powerful oxidating environment to break down remaining compounds and thoroughly disinfect the product water prior to use. The purified water will then be percolated into the groundwater basin where it will remain for at least one year before it is pumped for use as a drinking water source. In the aquifer, the GWR System water will mix with water from other sources, and a portion of the product water will also be used to expand the seawater intrusion barrier (GWR System, 2004). Figure 3-2 shows a map of the proposed system.

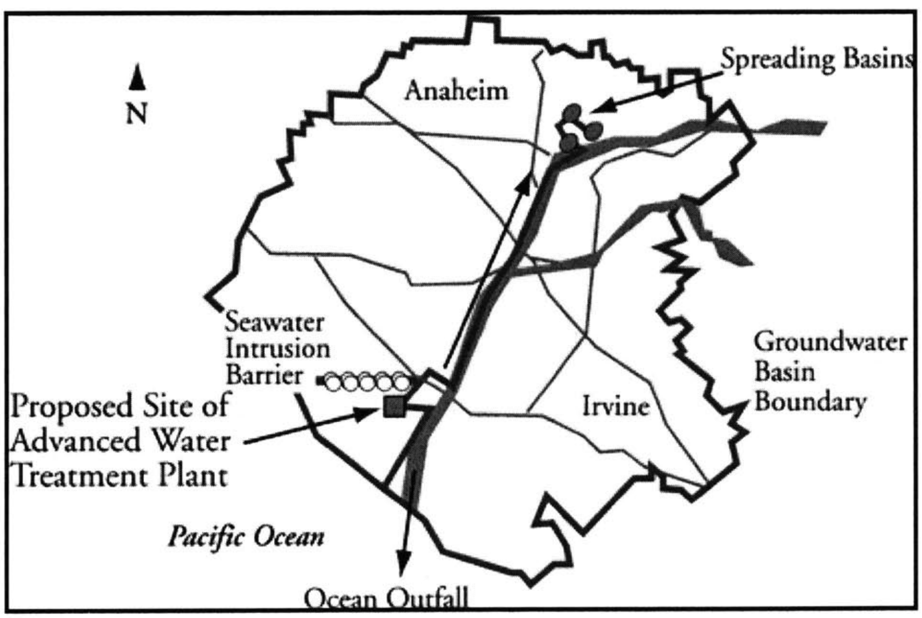

Figure 3-2 Map of the proposed GWR system for Orange County, CA (Adapted from Groundwater Replenishment System, 2004)

While the system will not be operating until 2007, pilot-scale tests have been done using the actual source water to be used for the full-scale operation. In 2001, findings were released concluding that the water produced by this system would not only be safe for consumers, but that it would improve the groundwater basin's overall quality. A risk-assesment type study was also conducted to compare the possible health risks associated with three possible sources: the Santa Ana River, imported water from northern California and the Colorado River, and GWR System water. In this study, it was assumed that water from each source was consumed directly, without considering percolation and storage in the aquifer.

In the category of non-carcinogenic health effects, it was found that none of the sources should pose a significant risk to public health, and that the potential risk associated with the GWR System water would be lower than that of the other two sources. Similarly, the carcinogenic risks associated with consumption of the GWR System water should be lower than the other two sources. In addition, the GWR System water is "projected to pose much less risk...from bacteria, parasites and viruses" than the two alternative supplies, assuming all processes in the treatment facility are operating fully and properly (GWR System 2004).

3.3 Flanders, Belgium

In July 2002, the Intermunicipal Water Company of the Veurne region (IWVA) began producing infiltration water from wastewater effluent to artificially recharge an unconfined aquifer in a dune water catchment in St. Andre, in the Flanders district (Figure 3-3). Like Orange County's GWR system, this is an example of "planned indirect potable use" because the water is pumped back out of the ground for drinking water use. Primary and secondary treatment are completed in a traditional wastewater treatment plant in Wulpen. Some of this water is then pumped to the Torreele treatment plant for advanced treatment. Torreele uses a combination of microfiltration (MF) with a maximum pore size of 0.1μm, RO, and UV irradiation for treatment of the wastewater treatment plant effluent. Anti-scalant and acid are added to the water prior to RO treatment, and the RO process has a recovery rate of 75%. Reverse osmosis was chosen for this application in order to provide low nutrient and salt contents. The infiltration water is a blend of RO product water and 10% MF filtrate. The MF filtrate is blended with RO product to re-mineralize the water in order to match the salt content of the natural dune water (IWVA 2005).

The purified water infiltrates into the ground through a pond, and is extracted from 112 extraction wells at least 40m from the edges of the pond. The minimum residence time of the recharged water in the aquifer is 40 days. The Torreele facility produces 2,500,000 m^3 per year, and recharges the dune area at a mean rate of 285 m^3/h. The extraction wells pump 400 m^3/h of groundwater that is subjected to aeration and rapid sand filtration to produce drinking water. The "re-use" project produces between 40 and 50% of the area's drinking water demand through advanced treatment of wastewater. The withdrawal from the dune water catchments has been reduced by 30%, and the groundwater levels are expected to rise as a result of this project (IWVA 2005).

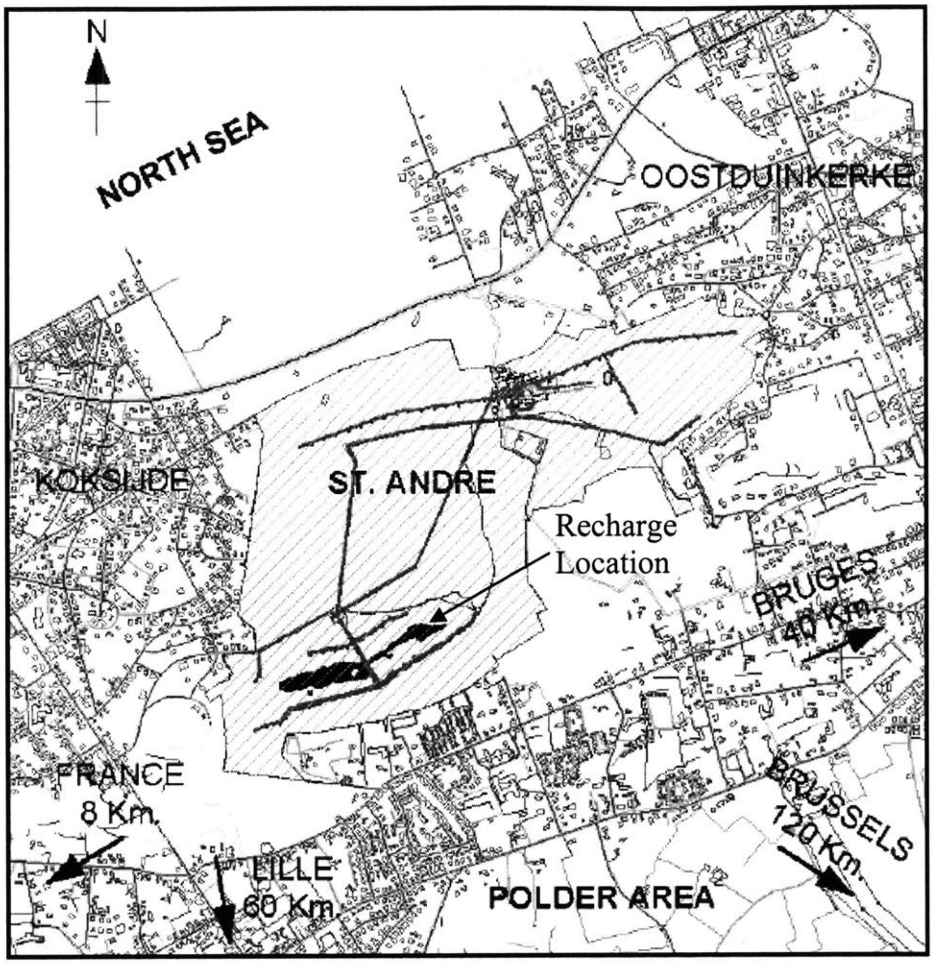

Figure 3-3 Map of St. Andre and the recharge location for the Torreele project (Modified after Van Houtte et al. 2005)

3.4 South Australia, Australia

The state of South Australia has been using Aquifer Storage and Recovery (ASR) systems since the early 1990s. Most of these projects are in and around the city of Adelaide (Figure 3-4), and have a combined purpose of managing excess surface water and enhancing the groundwater supply. As of June 2005, there were 22 ASR systems injecting 2 million cubic meters per year of rural and urban storm water runoff, and 5 more schemes were planned for imminent development. One additional ASR project is in the trial stages of using treated wastewater from the Bolivar wastewater treatment plant as the source water. A similar study of the potential for injecting water from the Christies Beach wastewater treatment plant into the nearby limestone aquifers has been completed with favorable results. The recovered water from these ASR systems is typically used for irrigation, industrial and recreational purposes, but studies are being done to investigate the potential for using ASR water for potable supply where the source water was pre-treated storm water (Government of South Australia 2006).

The artificial aquifer recharge in South Australia is mainly through recharge wells due to minimal available space, lack of suitable shallow unconfined aquifers, and the presence of suitable deep confined aquifers. Several of the ASR projects use wetlands as pretreatment systems, where collected runoff is filtered and some chemical constituents are removed as it passes through the wetland system. While this has been the historical approach, systems for mechanical filtration are also being considered. As the use of ASR expands, the size of individual projects is also being expanded from single-well systems to larger networks of injection and recovery wells. The government of South Australia projects that the use of ASR as an alternative water supply could increase by an order of magnitude in the future (Government of South Australia 2006). This would be the result of adopting ASR technology in more areas and expanding the source water supply types and end uses as described above. In order for the program to expand to this degree, studies must be done to investigate the storage capacity of the local aquifers and to further understand the impact of injecting storm water or treated effluent into the aquifers.

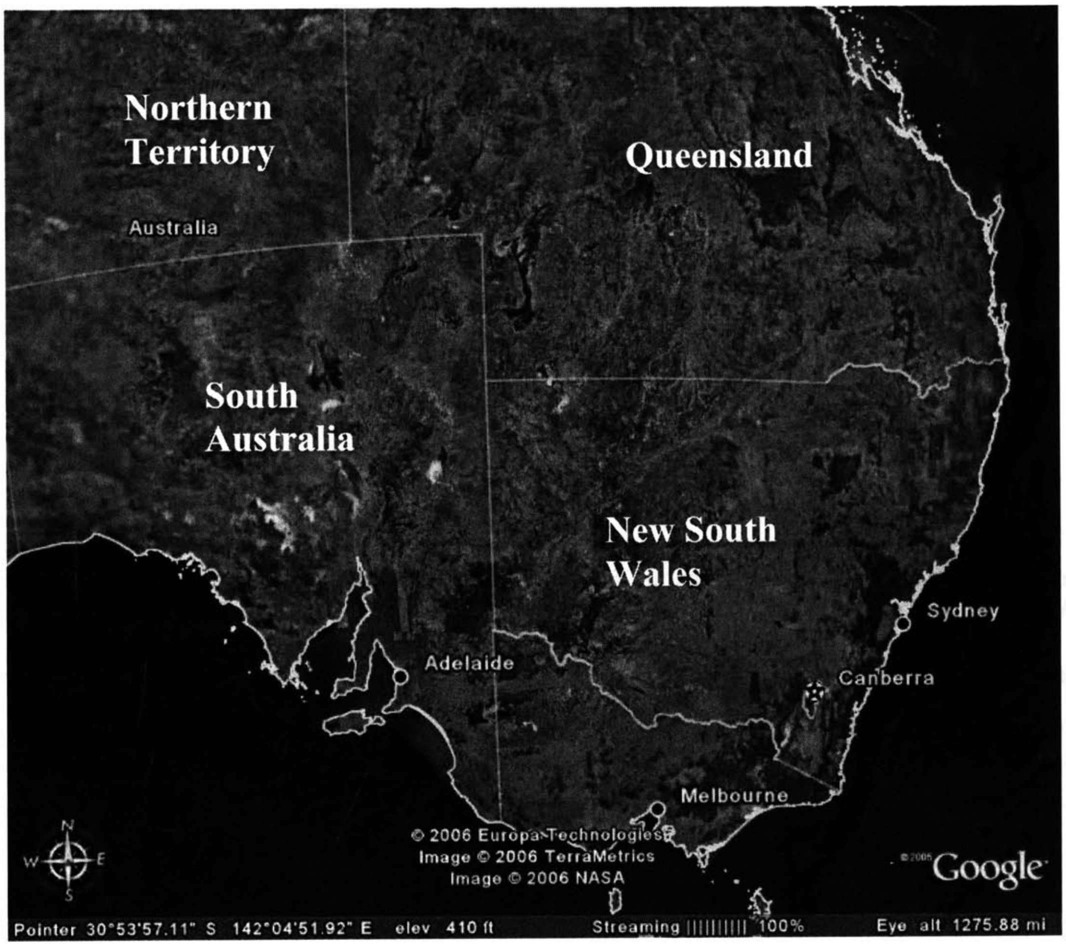

Figure 3-4 Map showing the location of Adelaide, South Australia (Image from Google Earth)

3.5 Singapore

Singapore is a small island state with no natural lakes. As of 2004, about half of Singapore's land was being used as catchment areas for collecting runoff in several reservoirs. The supply network includes 19 raw water reservoirs and 14 storage or service reservoirs. Approximately half of the water demand in Singapore is supplied by these reservoirs. In addition to collecting water from undeveloped catchments, the Public Utilities Board (PUB) plans to begin harvesting stormwater from residential developments and highly urbanized catchments (Public Utilities Board of Singapore 2004).

In 2001, the PUB began new initiatives to increase water supply from unconventional sources for non-potable use. This was the beginning of the NEWater wastewater reclamation program. Since then, three facilities have been built that use microfiltration, Reverse Osmosis and UV treatment to produce water for industrial processes, such as wafer fabrication and cooling towers (Figure 3-5). Many industrial facilities expressed their preference for NEWater because its organics content is one tenth that of the available tap water. The three existing NEWater "factories" have a total capacity of 76,000 m^3 per day, and more are planned for the near future (PUB 2006).

More recently, PUB accepted a proposal from a "Panel of Experts" to use NEWater for indirect potable use by mixing it with raw water in reservoirs. Conventional treatment is then used to produce the public drinking water supply from these reservoirs. Currently, PUB introduces 11,000m^3 per day (1% of total daily water consumption) into the raw water reservoirs. They plan to increase this amount gradually to about 2.5% of total daily water consumption by 2011. They also plan for 15% of the total water demand to be met by direct non-potable use of NEWater by 2010. The treated water is advertised as being cleaner than both the local reservoirs and tap water, in addition to meeting WHO and USEPA drinking water standards. Based on tests of the existing NEWater facilities, the product water is at least as good as the local tap water when measured for color, clarity, organics, and bacteria count (PUB 2006).

The remainder of Singapore's water needs are met by importing water from nearby Malaysia. However, due to disagreements about supply and pricing, Singapore is becoming more self-sufficient in the area of water resources. Besides the expansion of wastewater reuse, this strategy also includes the construction of a new desalination plant that was scheduled to be operating by 2005.

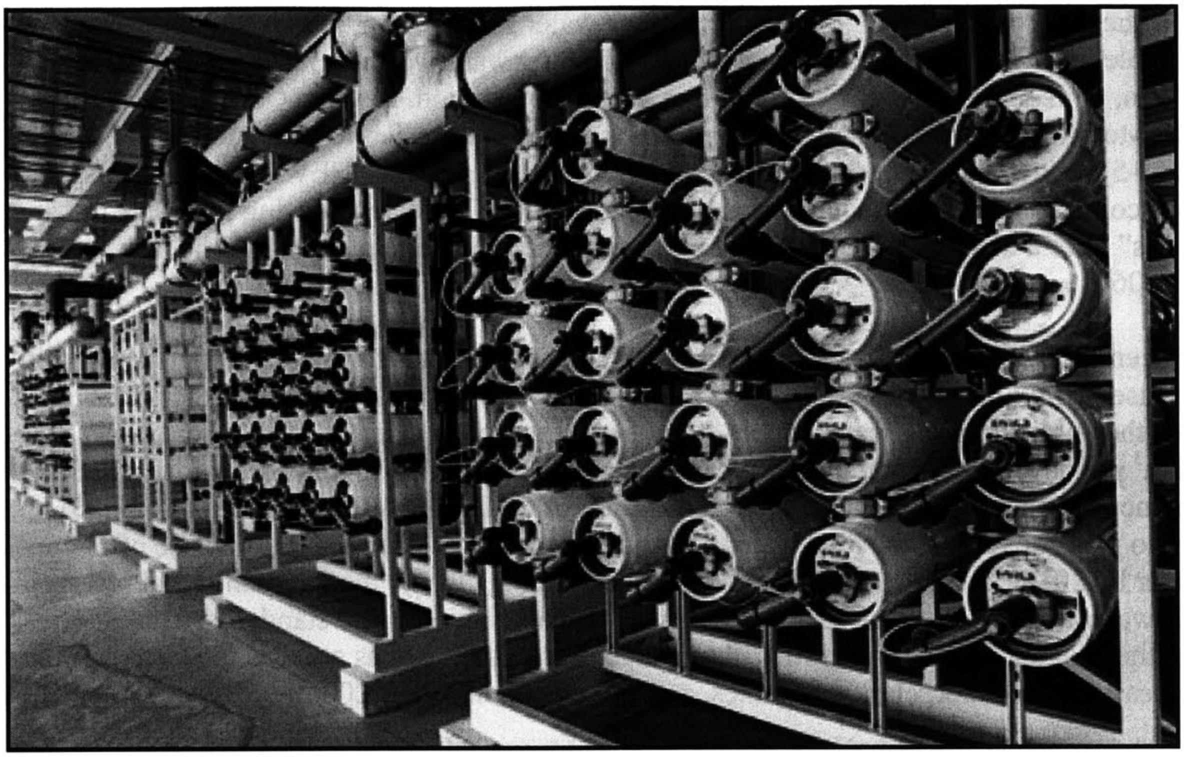

Figure 3-5 Reverse osmosis modules at Seletar NEWater Factory (Adapted from PUB 2005)

3.6 Wastewater Reclamation at Sulaibiya, Kuwait

A new membrane-based wastewater reclamation facility was recently constructed in Sulaibiya, Kuwait that is the largest facility of its type in the world since it fully came on line in December 2005. It was planned to convert 380,000m^3 per day of municipal effluent to 322,000m^3 per day of highly reclaimed water (Gagne 2004). Because of its extremely arid climate and increases in population and per-capita water demand, Kuwait is interested in using reclaimed water for non-potable uses in order to reduce the demand for potable water. The current plan for the new facility is to combine the product water with brackish groundwater and use existing brackish water infrastructure to distribute the blend. The primary expected use is agricultural irrigation, along with other non-potable uses. It is hoped that this will reduce the demand for drinking water from non-potable uses (Gagne 2004 and discussions at Kuwait-MIT Center For Natural Resources and the Environment meetings, March 2006).

The municipal wastewater feeding the Sulaibiya facility will undergo preliminary treatment at a facility in Ardiya before being pumped to Sulaibiya (Figure 3-6). It will then enter a wastewater treatment plant that will provide secondary treatment through anaerobic and aerobic biological stages, and clarification. The effluent from the wastewater treatment plant will then travel to the purification system where it is treated with ultrafiltration (UF) and reverse osmosis. UF was chosen as the preferred pre-treatment method over conventional tertiary clarification and filtration because it reduces the plant's chemical consumption and provides more reliable quality of water feeding the RO units. This is important to prevent premature clogging or fouling of the RO membranes. The UF membranes will remove all suspended solids, protozoa and most bacteria. The RO membranes will provide further removal of bacteria and viruses, and will reduce the total dissolved solids (TDS) content from an average of 1280mg/L in the wastewater

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to 100mg/L. Finally, a stripper is used for CO_2 removal to adjust pH, and the water is chlorinated before blending and distribution (Gagne 2004).

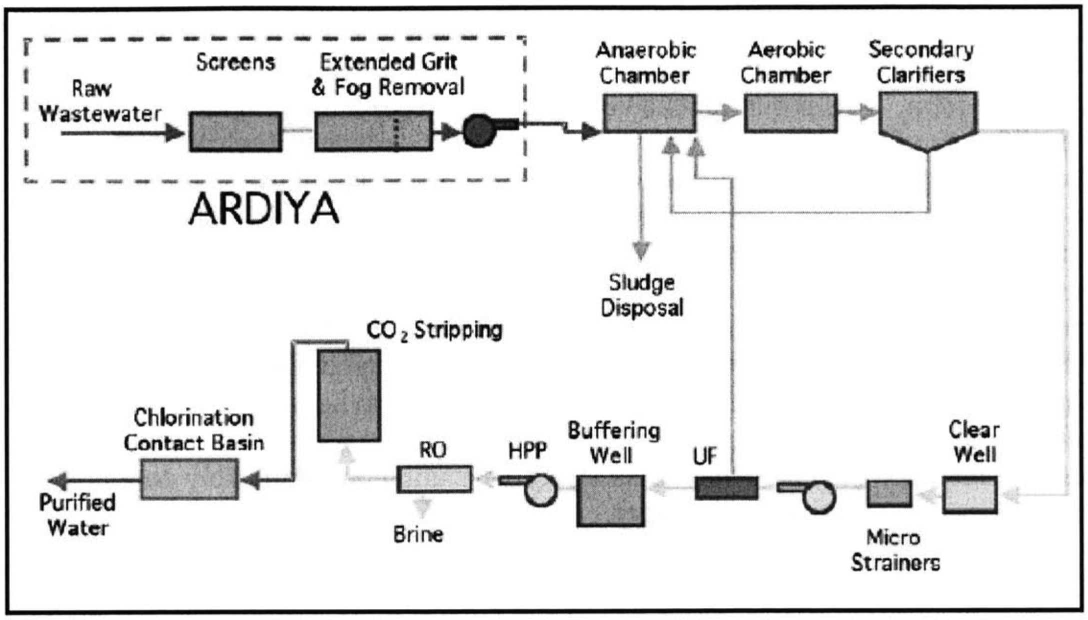

Figure 3-6 Schematic of the treatment system at Sulaibiya, Kuwait (Adapted from Gagne 2004)

The UF process is made 100% efficient by recycling the UF waste back to the biological treatment stage. The RO process is limited to 85% efficiency by the precipitation of calcium phosphate that would occur at higher concentrations in the brine. The brine from the RO process is discharged into the Gulf. The expected water quality for the system is given in Table 1.1. The TDS content of the product water is significantly below the WHO guideline for potable water, but there is no published data comparing the expected water quality to Kuwaiti drinking water standards. The published specifications for the treatment plant indicate monthly average values for total coliforms as less than 2.2 colonies/100mL and 5 MPNIU/10L for enteric viruses (Gagne 2004).

3.7 Comparison and Conclusions

The prevalence of storm water injection systems in South Australia illustrates runoff collection as a viable option to increase aquifer storage and improve groundwater quality. Runoff pretreatment in wetlands will probably not be feasible in Kuwait due to climate considerations, but mechanical filtration can be accomplished, and runoff from the barren desert in north Kuwait should not contain pollutants of concern other than silt and suspended solids that may clog the injection system. Mild chlorination should be sufficient to limit biological growth due to any nutrients in the collected water.

Singapore has a hot climate like Kuwait, but unlike Kuwait it is normally humid and rainy. Surface storage in Kuwait would not be able to be filled by capturing large volumes rainfall, but this example does show that construction of large surface reservoir networks can be practical in nations with very limited natural water resources.

Chapter 4
Rainfall Harvesting

4.1 Introduction

It is possible that rainfall harvesting could be used to increase the water supply flux in Kuwait. Rainfall harvesting involves efficiently capturing runoff and storing it for use at a later time. It is most often used to collect water in rainy seasons in order to store excess supply that can be used in dryer months. The collected runoff may be stored either in surface reservoirs or injected into aquifers. Some examples of rainfall harvesting systems are discussed below.

In order to assess the feasibility of this type of system for Kuwait, a runoff model was constructed for the Rawdhatain drainage area. This location was chosen because it is the most prominent drainage system in Kuwait, and the most likely to produce significant amounts of runoff (Al-Sulaimi et al.1997). In addition, it supplies recharge to the fresh groundwater lens in this area. This chapter discusses the tools and data used to construct this model as well as the results obtained.

4.2 Experiences with Rainfall Harvesting

No literature is available discussing rainfall harvesting over large arid watersheds like the one considered in Kuwait. However, small-scale systems have been used historically for rainwater collection and storage, especially in rural areas. The traditional use of dams to form water reservoirs can also be considered a form of rainfall harvesting. Various organizations are now beginning to promote the use of small-scale rainfall harvesting systems at the household level to reduce the demand on municipal water systems for landscaping.

The municipal water supply systems in Singapore and South Australia described in Chapter 3 include significant use of rainfall harvesting systems. About half of the surface area of Singapore is utilized as catchments that drain into water supply reservoirs (PUB 2004). Similarly, South Australia has many systems in place that collect storm runoff and store the water in aquifers for later use (Government of South Australia, 2006).

The International Rainwater Catchment Systems Association (IRCSA) has promoted the use of rainfall harvesting systems in several regions of China. They were involved in building about 5 million rainwater harvesting systems with a total storage capacity of 2.8 billion cubic meters in 1999. These projects have created a decentralized system for domestic water supply for around 21 million people, and supplied water for more sustainable irrigation of one million hectares of land (Zhu, 1999). The use of storage systems has increased the agricultural productivity of many farming areas, allowing for self-sufficiency of farming communities, even in dry years. In the drier areas where collection efficiency is a concern, the collection area was sometimes lined with plastic sheeting or concrete. Many of the storage containers are underground cellars or masonry tanks, which were covered to reduce evaporation loss and maintain good water quality. The IRCSA has determined that the annual precipitation should be at least 300mm for irrigation purposes and 200mm for domestic use in order for these types of systems to be economically feasible. However the rural areas of China where these systems were installed are quite poor, so the determination of economic feasibility is probably very different than it would be in Kuwait. Similar systems are being promoted in rural areas of India, Brazil, and Kenya.

Urban rainfall harvesting systems have also become popular in dry areas like cities in Texas and southern Australia. These programs promote the collection of runoff from roofs and paved surfaces for storage in cisterns like the system shown in Figure 4-1. The Texas legislature passed a bill in June of 2005 requiring the formation of a Rainfall Harvesting Evaluation Committee to study the feasibility of using rainwater as a source of water supply in the state. The state has also published a manual on Rainfall Harvesting. Due in part to the high cost of water from the municipal supply, several corporations in Texas have installed rainfall harvesting systems for irrigation and process water. These include the Advanced Micro Devices semiconductor fabrication plant in Austin, and Reynolds Metals in Ingleside. A total of 400 full-scale rainwater harvesting systems have been installed in Central Texas by professional contractors, along with countless "do it yourself" installations. In addition, more than 6,000 rain barrels have been installed through an incentive program initiated by the City of Austin (Krishna, 2005). Rainfall harvesting seems to be gaining momentum in areas like Texas that have a fair amount of rainfall during parts of the year, but are otherwise quite dry. The shortage of surface water and good quality groundwater has made small-scale rainfall harvesting systems attractive, and large-scale systems are being considered for expansion of the public water supply.

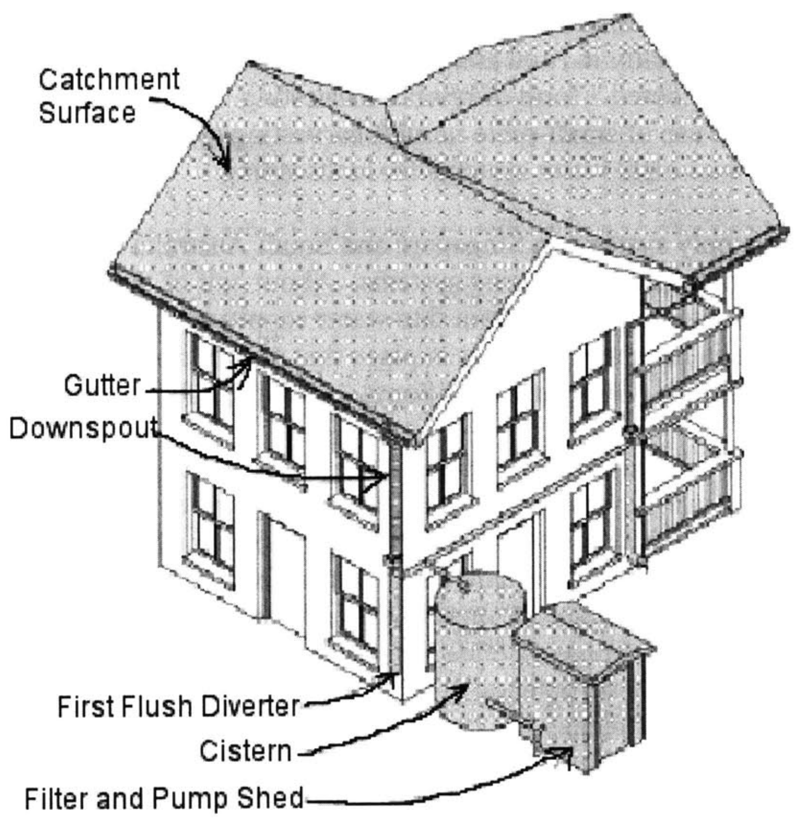

Figure 4-1 Rooftop catchment for rainfall harvesting (Modified after Krishna, 2005)

4.3 Modeling Tools

In order to model the system at Rawdhatain, several elements were required. First, runoff and infiltration were modeled for design storms using KINEROS2, a model that uses kinematic flow equations to route flows through a network of watershed elements. Then a simple program was developed to determine the behavior in a reservoir as water is removed for storage while simultaneously evaporating and infiltrating.

4.3.1 KINEROS2

KINEROS2 was developed by the Southwest Watershed Research Center in Tucson, AZ, a branch of the United States Department of Agriculture's Agricultural Research Service (ARS). The model was designed to simulate single storm events in small semi-arid watersheds. It describes the processes of interception, infiltration, surface runoff and erosion. KINEROS2 requires the watershed to be subdivided into a network of overland flow planes and open channel elements. It then routes the flow through this network using finite difference techniques to solve the partial differential equations describing overland flow, channel flow, erosion and sediment transport. Spatial variation in rainfall, land cover and soil properties are accommodated since these parameters can be defined separately for each element.

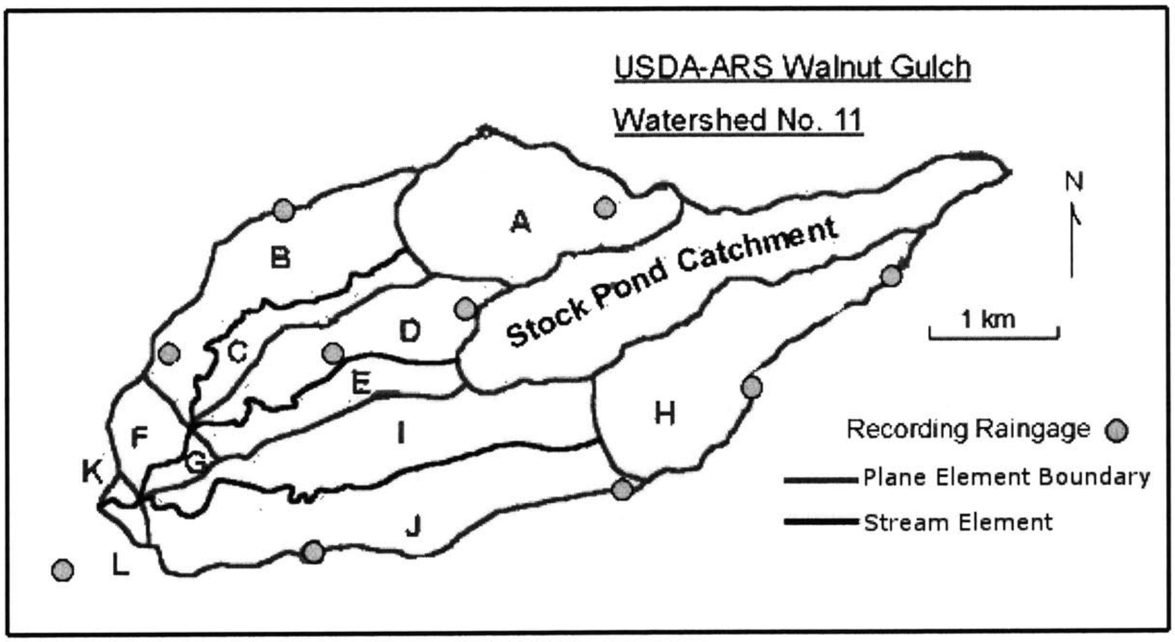

Figure 4-2 Sample watershed discretization (Modified after USDA 2006)

As shown in Figures 4-2 and 4-3, each stream element in the watershed has up to four contributing elements. In this example the area labeled "Stock Pond Catchment" does not contribute to runoff because of detention ponds located within the element. The upstream contribution can be from one or two stream elements, or from one overland flow plane element. There is also lateral flow into each stream from two plane flow elements. Figure 4-3 shows a schematic of how the elements of the watershed in Figure 4-2 would be related in the model.

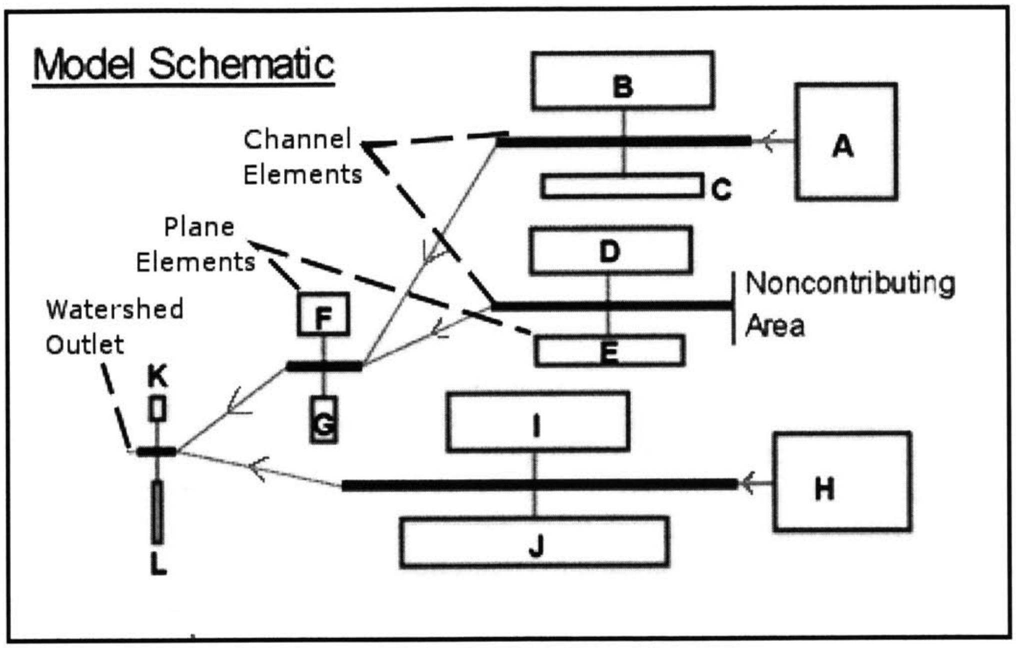

Figure 4-3 Sample watershed schematic (Modified after USDA 2006)

In order to simplify the process of discretizing the watershed and assigning soil properties and other parameters to each element, ARS has developed a Geographic Information Systems (GIS) tool called AGWA (Automated Geospatial Watershed Assessment) that acts as a user-friendly interface for writing KINEROS2 input files, running simulations and visualizing the results. AGWA is an extension for the ESRI Software ArcView3.x. AGWA uses layers of GIS data representing the elevation, soil type and landcover characteristics of the watershed combined with user inputs to write the KINEROS2 input files. AGWA breaks the watershed into plane and channel elements based on the elevation data provided and input from the user to determine how much land area must contribute flow before a stream is designated. It then processes the landcover and soil maps to assign properties to each watershed element that correspond to the input variables required by KINEROS2. After a simulation is run, AGWA can also be used to visualize the results in a GIS map. This makes it easy to compare results among watershed elements or between two simulations of the same watershed.

4.3.1.1 Rainfall

KINEROS2 will distribute rainfall at different rain gages throughout the watershed, but each watershed element will have a uniform rainfall distribution. The rainfall for the element is determined by interpolating the values at the three gages closest to the centroid of the element. Due to the lack of rainfall data, this feature of KINEROS2 was not used. Instead, a uniform distribution of rainfall over the entire watershed was used for each design storm.

4.3.1.2 Infiltration

Rather than subtracting a constant rate of infiltration from the rainfall rate in order to determine runoff, KINEROS2 uses a more realistic method to calculate the infiltration rate based on equations from soil physics. For given soil properties, KINEROS2 tracks the soil infiltration capacity (or infiltrability) f_c as a function if infiltrated depth I.

The basic parameters are needed to describe the soil's infiltration properties are the field effective saturated hydraulic conductivity, K_s, the integral capillary drive, G, and the porosity, ϕ. KINEROS2 also uses an algorithm to redistribute soil moisture during breaks in the rainfall, and for this it requires a parameter referred to as the pore size distribution index, λ, which describes the soil hydraulic characteristics. There is also an optional coefficient of variation of the soil's hydraulic properties. Another optional parameter designates a fraction of soil volume made up of large rocks. These represent solid volumes of larger than capillary size that restrict storage. In addition, KINEROS2 can take inputs of each of these parameters for two soil layers. However, this layering capability is not utilized if the soil parameterization is performed using AGWA. The initial relative saturation, S, is the one event-dependent variable used. Water content by volume, θ, is given by $\theta = \phi S$. The upper limit of S is 1, which corresponds to water content equal to the porosity, and is represented by S_{max} or θ_s.

The general equation for infiltrability, a dynamic term for the property sometimes called infiltration capacity, is given below in Equation (4.1) (Parlange et al., 1978).

$$f_c = K_s\left[1 + \frac{\alpha}{\exp(\alpha I / B) - 1}\right] \tag{4.1}$$

where B is $(G+h_w)(\theta_s-\theta_i)$, combining net capillary drive, G, surface water depth, h_w, and unit storage capacity, $\Delta\theta = (\theta_s-\theta_i)$. The parameter α represents soil type, with a value near 0 for sand, in which case Eq. (4.1) approaches the Green-Ampt relation, and α is near 1 for well-mixed loam, in which case Eq. (4.1) approaches the Smith-Parlange infiltration equation (Parlange et al, 1978). KINEROS2 assumes a value for α of 0.85, which best represents most soils (USDA 2006).

Runoff is determined by the excess of the rainfall rate over f_c. Initially, some portion of rainfall, $r(t)$, increases the infiltrated depth, I, without causing runoff, because at small I, f_c is very large. As I increases, $r(t)$ will exceed $f_c(t)$ at some point and ponding will occur. The value of I corresponds to a rainfall depth that has infiltrated, but also can be used to calculate the wetted soil depth, given by $z=I/\Delta\theta_I$ (USDA 2006).

To account for the increase of infiltrability when rainfall stops briefly, KINEROS2 uses a redistribution method developed by Smith et al. (1993) and Corradini et al. (1994). Because the design storm used in this case did not include intermittent periods of rainfall, these equations are not presented, but they are available in the KINEROS2 documentation.

4.3.1.3 Overland Flow

KINEROS2 uses kinematic flow equations describing Hortonian overland flow. As described above, ponding occurs when the rainfall rate exceeds the infiltrability of the soil at the surface. This also occurs when a lower restricting layer of soil prevents soil water from moving downward in the soil column, causing the porosity in the upper layer to become fully saturated. Ponding results in runoff in the direction of the local surface slope.

Runoff can be viewed at a large scale as a one-dimensional flow process that relates the flux to the unit area storage by the power relation:

$$Q = \alpha h^m \tag{4.2}$$

where Q is discharge per unit width, h is the storage per unit area, and α and m are related to the slope, surface roughness and flow regime, as described below. This flux equation is used in conjunction with the continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = q(x,t) \tag{4.3}$$

where t is time, x is distance measured in the slope direction, and q is the lateral inflow rate. For overland flow, Eq. (4.2) is substituted into Eq. (4.3) to obtain the kinematic flow equation:

$$\frac{\partial h}{\partial t} + \alpha m h^{m-1} \frac{\partial h}{\partial x} = q(x,t) \tag{4.4}$$

The upstream boundary must be specified to solve Eq. (4.4). If no flow enters from upstream, i.e. the upstream boundary is a flow divide, the boundary condition is $h(0,t)=0$. Otherwise, the upstream boundary condition is given by:

$$h(0,t) = \left[\frac{\alpha_u h_u (L,t)^m W_u}{\alpha W} \right]^{\frac{1}{m}} \tag{4.5}$$

where the subscript u refers to the upstream element, W is the width and L is the length of the upstream element. This condition is necessary to satisfy continuity of discharge between the upstream and downstream elements at the boundary (USDA 2006).

KINEROS2 solves the kinematic wave equations using a four-point implicit finite difference method. The numerical solution for Eq. (4.4) using this method is:

$$h_{j+1}^{i+1} - h_{j+1}^{i} + h_j^{i+1} - h_j^i +$$
$$\frac{2\Delta t}{\Delta x}\left\{\theta_w\left[\alpha_{j+1}^{i+1}\left(h_{j+1}^{i+1}\right)^m - \alpha_j^{i+1}\left(h_j^{i+1}\right)^m\right] + (1-\theta_w)\left[\alpha_{j+1}^{i}\left(h_{j+1}^{i}\right)^m - \alpha_j^{i}\left(h_j^{i}\right)^m\right]\right\} - \Delta t\left(\bar{q}_{j+1} + \bar{q}_j\right) = 0 \tag{4.6}$$

where θ_w is a weighting parameter (usually between 0.6 and 0.8) for the x derivatives at the advanced time step (USDA 2006). The subscripts j refer to time steps, where $t(j+1) = t(j) + \Delta t$. Similarly, the superscripts i refer to the points in the finite difference grid along the x axis, so that $x(i+1) = x(i) + \Delta x$.

KINEROS2 provides two options for defining α and m in Eq. (4.4), either the Manning hydraulic resistance law or the Chezy law may be used. When running KINEROS with AGWA, the Manning resistance law is used as the default. This defines α and m as:

$$\alpha = 1.49\frac{S^{1/2}}{n} \qquad \textit{and} \qquad m = \frac{5}{3} \tag{4.7}$$

where S is the slope, n is the Manning's roughness coefficient for overland flow, determined by characteristics of the surface, and English units are used.

When using AGWA, the average length, width and slope of an element can be determined from a Digital Elevation Model (DEM) dataset and the designated land cover type determines the Manning's roughness coefficient.

4.3.1.4 Channel Routing

KINEROS2 uses the kinematic approximation to the equations of unsteady, gradually varied flow to represent free surface flow in channel elements. Channel segments can receive uniformly distributed time-varying lateral inflow from overland flow elements on one or both sides, and from one or two upstream channels or an upstream overland flow element. The total area of the overland flow elements covers the entire extent of the watershed, so rain falling on the channel is not considered.

The equations used for channel routing are similar in form to those for overland flow, where the continuity equation for a channel with lateral inflow is:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_c(x,t) \tag{4.8}$$

where A is the cross-sectional area, Q is the channel discharge, and $q_c(x,t)$ is the net lateral inflow per unit length of the channel. This can be rewritten using the kinematic assumption, since Q can be expressed as a unique function of A. This gives:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial A}\frac{\partial A}{\partial x} = q_c(x,t) \tag{4.9}$$

Using the kinematic assumption, channel discharge is related to cross-sectional area by:

$$Q = \alpha R^{m-1} A \tag{4.10}$$

where R is the hydraulic radius. The values for α and m are determined by Manning's equations as they were for overland flow (USDA 2006).

The numerical solution that KINEROS2 uses for these equations is the same four point implicit technique used for overland flow surfaces, but A is used instead of h, and the geometric changes with depth must be considered based on channel geometry. This is discussed further in the KINEROS documentation (USDA 2006).

In arid and semiarid watersheds, infiltration within the channel elements may have a significant effect on runoff volumes and discharge rates. Because the trapezoidal channel approximation normally used to determine the area-volume relationship for channel elements introduces significant error in determining the area of channel covered by water at low flow rates, KINEROS2 uses an empirical expression to estimate an "effective wetted perimeter" (USDA 2006). This equation is:

$$p_e = \min\left[\frac{h}{0.15\sqrt{BW}}, 1\right] p \tag{4.11}$$

where p_e is the effected wetted perimeter for infiltration, h is the water depth, BW is the bottom width of the trapezoidal channel, and p is the channel wetted perimeter at depth h. Based on this equation, p_e is less than p until a threshold depth is reached, at which point p_e and p are identical. The product of the effective wetted perimeter and the infiltration rate gives the channel loss rate. KINEROS2 can also accommodate detention structures and circular conduits, but these features were not utilized in this modeling exercise.

Overall, KINEROS2 is an appropriate model for routing flow in semi-arid watersheds, particularly because of the way it deals with infiltration. Most models developed for wetter climates assume interaction between streams and groundwater. In this case, infiltration through the channel bed during a storm event is not a significant loss mechanism. This type of model will not perform accurately for areas with deep water tables and ephemeral stream flow.

4.3.2 Reservoir Model

A simple program was written in Visual Basic to simulate a reservoir upstream of a dam that is being used as part of a rainfall harvesting system. This requires the user to input an area-volume relationship for the desired dam location as well as constant infiltration, evaporation and pumping rates. Infiltration and evaporation are designated per unit area, so as the program steps through the simulation in time, these losses depend on the reservoir area at each time step. Figure 4-4 shows the input form. The "cell area" input option is used if the area-volume relationship is given in terms of the cell size of a DEM grid. For example, area may be given in cells, and volume in cells*meters. If the area-volume relationship is given in units of m^2 and m^3, then the cell area should be designated as one.

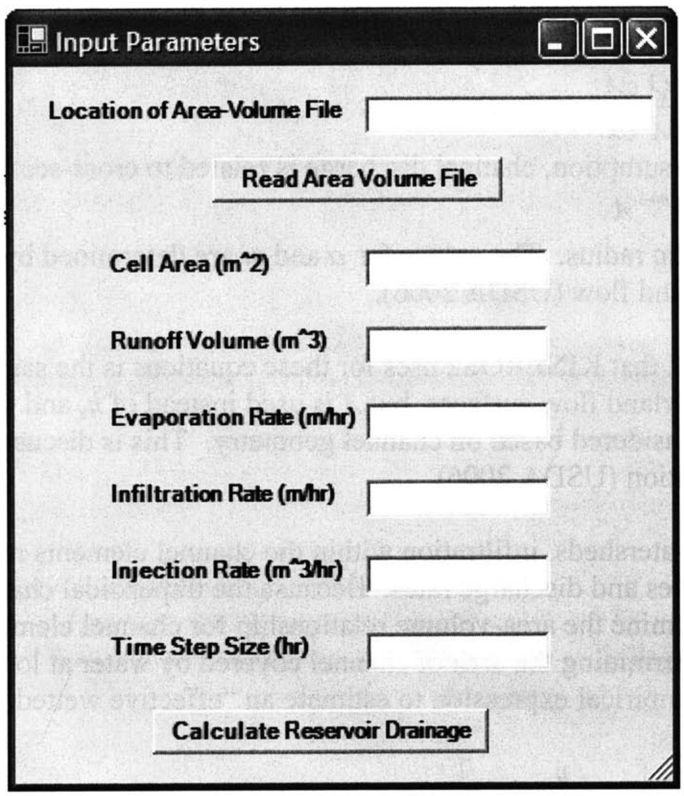

Figure 4-4 Input form for reservoir calculations

The output from this program is a text file that gives the total volume that contributed to each evaporation, infiltration and injection. A flow-chart for the program is shown in Figure 4-5 below.

The use of a constant infiltration rate in this case assumes that there is no restricting lower soil layer, and the soil below the reservoir reaches an equilibrium rate of infiltration. This is a rough approximation since the head level in the reservoir will be decreasing, but it is appropriate for a first order approximation.

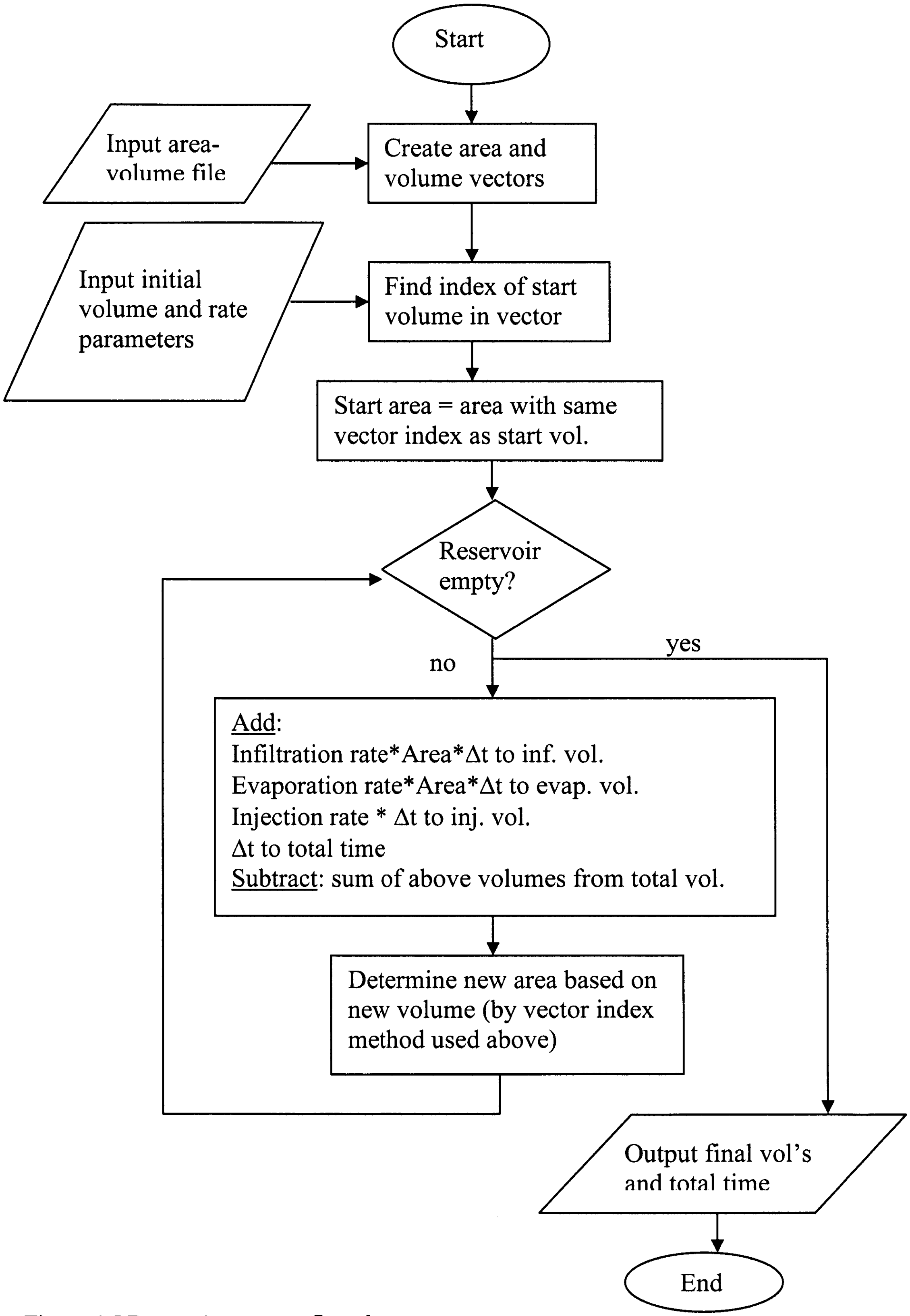

Figure 4-5 Reservoir program flow chart

Table 4.1 Model Overview

Model	Primary Inputs	Outputs
KINEROS2	Watershed topography Soil properties Land cover Storm event	Runoff hydrograph Infiltration volume Sediment transport
Reservoir	Area-Volume relationship Infiltration and Evaporation rate Injection rate Initial storage volume	Infiltration volume Evaporation loss Injected volume Time required

4.3.3 Model Interaction

These models were chosen and designed so that the output from one stage could be easily used to determine the input for the next stage of the model. Table 4.1 summarizes the primary inputs and outputs from each of the models. The runoff results from KINEROS2 are the initial condition for the reservoir model. In addition, the infiltration calculated by both KINEROS and the reservoir program could be fed into a groundwater model to determine the aquifer response. If aquifer storage is used, the injection calculations from the reservoir program would also be included in the groundwater model. This could be used to predict both the improvement in groundwater quality due to the injection of freshwater and the expected losses of freshwater during the storage period.

4.4 Model Setup and Input Parameters

Much of the data needed to setup the hydrologic model of the Rawdhatain system was not available at a high resolution. Instead, most of the input parameters were based on low-resolution data from worldwide databases. As a result, all results and calculations are quite approximate, and the models could not be calibrated to observations. The specifics of the data used as inputs for these models are described in this section.

4.4.1 Runoff Model

No previous studies have been done to determine the hydrologic parameters relevant to the formation of surface runoff at Rawdhatain, and the hourly rainfall data collected in Kuwait is not available to MIT researchers at this time. As a result, aggregate soil data was used along with 90m resolution elevation data and approximated design storms.

4.4.1.1 Elevation

The Digital Elevation Model (DEM) used to delineate and subdivide the watershed is from the NASA Shuttle Radar Topography Mission (SRTM) dataset, available through the United States Geological Survey (USGS) Seamless data distribution system. This data exists for most places between the latitudes of 60°N and 56°S at 30m (1 arc-second) resolution, but this high-resolution data is only released for the United States. Special permission is required to gain access to the 30m data for other countries.

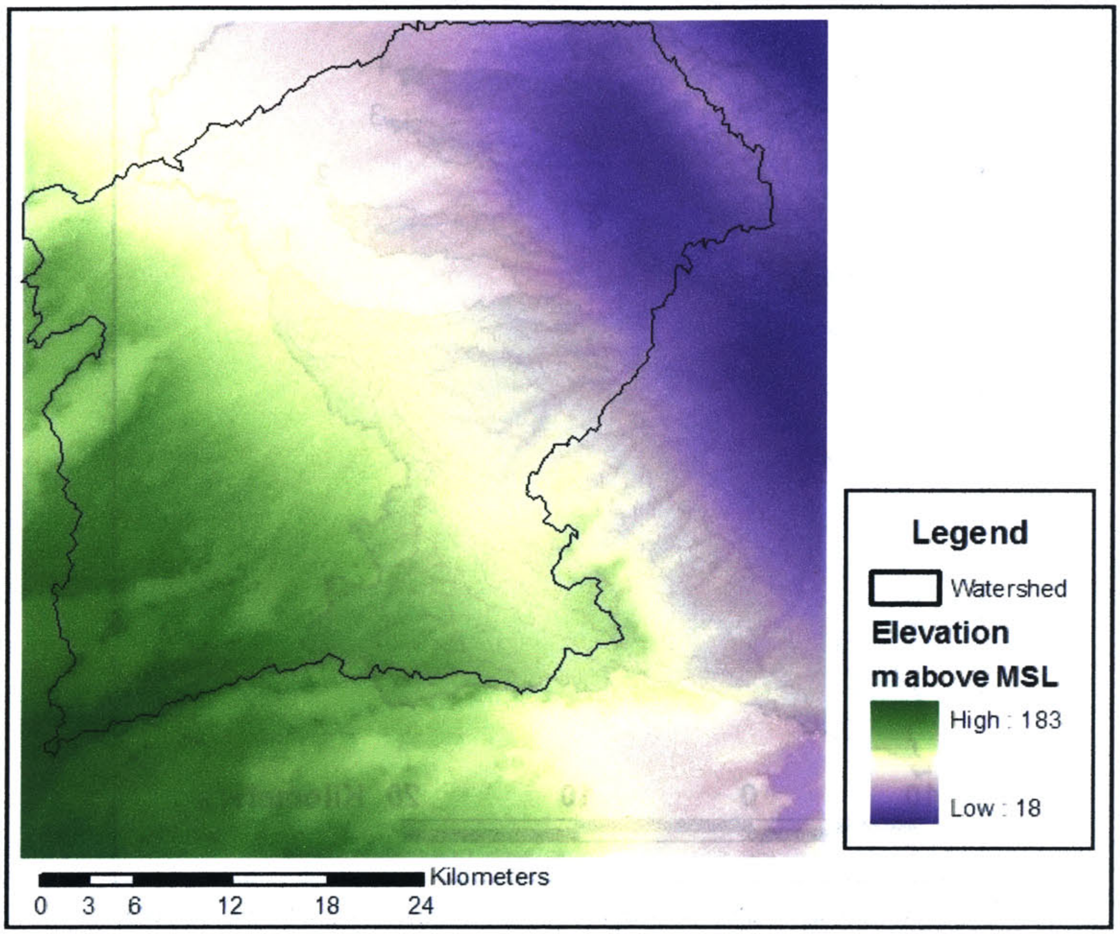

Figure 4-6 DEM of Rawdhatain watershed

However, 90m (3 arc-second) data is available for international applications. This 90m resolution data was used for this project. The elevation of each grid cell is given at 1m resolution. The data has been "finished" compared to the original shuttle data, meaning that researchers have filled in anomalies called "spikes" or "pits," but some voids still exist in the data. The finishing process also smoothed the elevation variation at coastlines and in water bodies. The DEM used for the Rawdhatain area is shown in Figure 4-6. The wadis or "paleo drainage networks" around the drainage depression are visible in the figure.

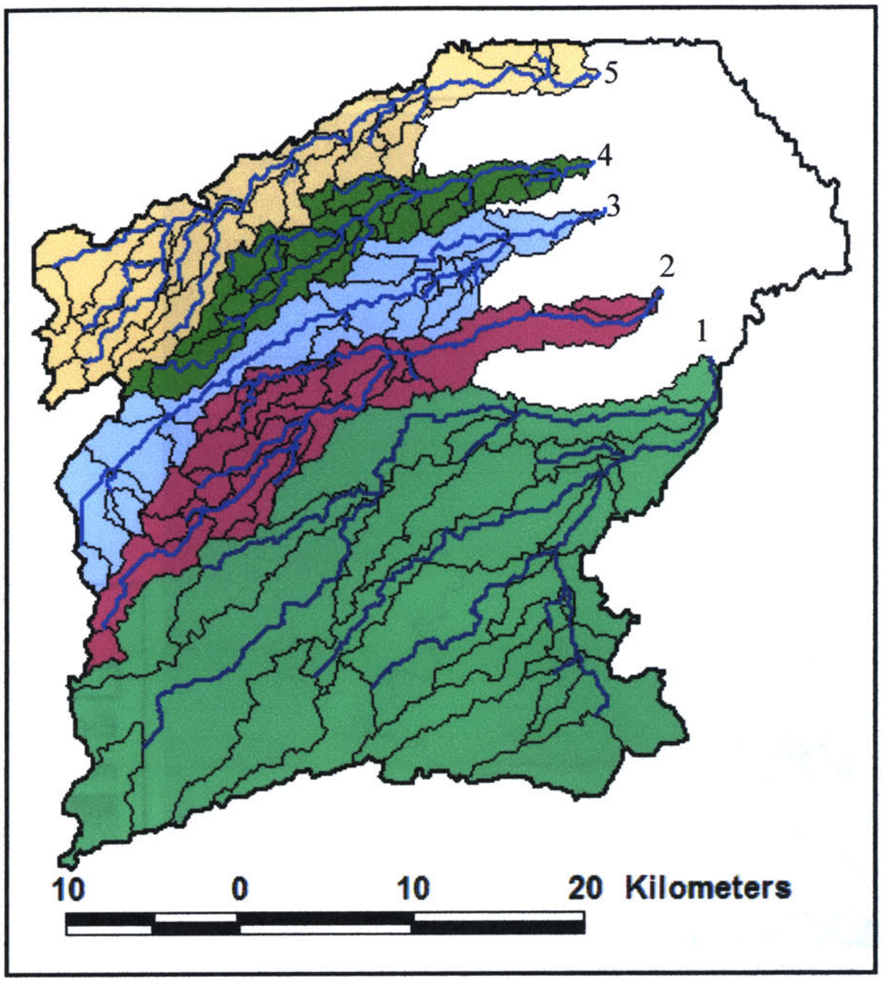

Figure 4-7 Major sub-basins and watershed elements delineated by AGWA

The stream network and watershed elements were determined by AGWA for specified outlet positions corresponding to the full watershed and several sub-watersheds (Figure 4-7). AGWA first calculates the flow direction for each cell of the DEM based on the steepest local slope. Based on this calculation, a flow accumulation grid is calculated. The flow accumulation value for each cell represents how many other cells eventually drain into it. This determines a basic stream network by defining any cell with 2500 or more contributing cells as a "stream" cell. The watershed is then delineated by determining all of the cells that drain to the designated outlet point. Sub-basins were created by placing additional outlet points on major streams in the watershed. These were placed approximately at the 50m contour line to avoid the extremely flat portion of the watershed in and around the depression.

Each sub-basin is further divided into plane and channel elements based on a specified contributing source area (CSA) required to form a channel. The CSA was set at 2.5% of the sub-basin area based on recommendations in the KINEROS2 documentation.

4.4.1.2 Soil Properties

Since no detailed soil survey is available for this area, the soil type was determined from the Food and Agriculture Organization of the United Nations (FAO) soil map of the world. The predominant soil type in the Rawdhatain area is designated as a Yy12-a soil (soil unit number 3616). This is described as a Yermosol (Y), which is defined as having a weak ochric A horizon, an aridic moisture regime, and lacking permafrost within 200cm of the surface. The subclass Yy denotes Gypsic Yermosols, which are defined as Yermosols not showing takyric features and having a gypsic horizon within 125cm of the surface (FAO 1974).

AGWA includes a database file that lists the components that make up each soil unit and the fraction for each. A separate table lists the properties for each of the possible components. The properties for a given soil unit are determined by averaging the properties of the components. While soil units may have different components for two layers ("top" and "sub"), AGWA only considers soil properties in the first layer ("top"). This table includes fractions of sand, silt and clay as well as other relevant properties. AGWA then uses this information to calculate the soil parameters that are required for KINEROS2 input and creates a table listing properties for each soil type within the watershed. Table 4.2 below shows the values calculated for the Rawdhatain watershed. For further explanation of these variables, refer to Section 4.3.1.2.

Table 4.2 Soil properties calculated by AGWA

Rock	Splash	Ks (mm/hr)	G (mm)	Por	Smax	Cv	Fract_sand	Fract_silt	Fract_clay	Dist	Cohesion
0.225	128.288	11.113	115.6	0.459	0.928	1	0.463	0.311	0.227	0.302	0.008

The hydraulic conductivity was adjusted during simulations to better reflect the available data on infiltration rates. Analysis was done using the *Ks* values calculated by AGWA from the FAO soil data, and adjusted based on the infiltration measurements by Al-Sulaimi et al.(1988). Based on the measured values, *Ks* was set to 20cm/s for the plane elements and 8cm/s for the channels. Simulations were run at these values as well as a range of smaller conductivities that were required to generate significant runoff in the model.

4.4.1.3 Land Cover

Based on the Landsat image in Figure 4-8, the area of interest appears to be essentially barren sand. A small area on the eastern end of the watershed has some vegetative cover, but most of this area is in the portion of the watershed not included in the sub-basins that were modeled (Figure 4-7). The required input parameters for running KINEROS from AGWA are percent cover, interception, Manning's N, and percent impervious. Based on the assumption of barren sand, the percent cover, interception and percent impervious were all set to zero. KINEROS2 recommends a value for Manning's N of 0.01 for barren sand (USDA 2006), so this value was used.

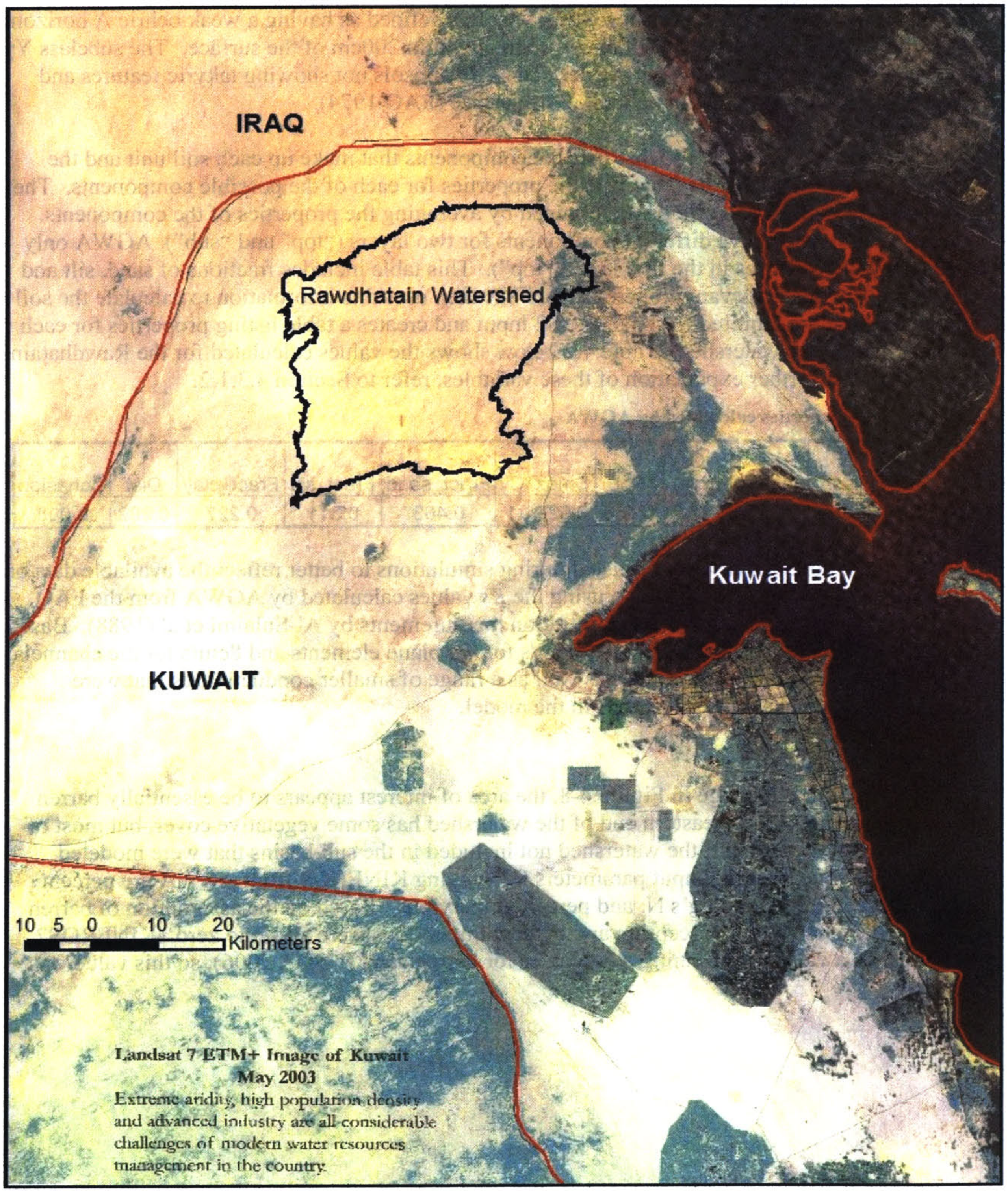

Figure 4-8 Landsat image of Kuwai

4.4.1.4 Storm Event

Rainfall data is collected in Kuwait at multiple weather stations, including one shown in the map of the Rawdhatain well field (Figure 2-4). According to contacts there, research agencies have one-hour time resolution records for at least one station, but this data has not been made available to MIT researchers at this time. As a result, an accurate design storm could not be formulated. However, we do have estimates of average yearly rainfall between 105.6mm and 110mm (Al-Sulaimi et al. 1997, Al- Ruwaih 2000), and Al-Sulaimi et al.'s calculation of 28.1 rainy days per year between 1955 and 1986 (1977). Al-Sulaimi et al. (1997) also gives rainy days per month, with an average of 6 in January and 4.5 in December, the two rainiest months. The monthly average precipitation in December and January is 18.2mm and 24.1mm respectively. Based on these numbers, an "average" rain event produces around 4mm of precipitation.

KINEROS2 simulations were run with a variety of storm events. Based on the above data, a reasonable storm was first estimated to be about 10mm over 10hours. This is a first guess for an event that would be heavier than average but not extremely rare. This design storm was simulated with different initial soil moisture conditions ranging from 15% saturation to 90% saturation. This represents how the initial saturation varies throughout the rainy season, with the first storms occurring on extremely dry soil and wetter conditions prevailing later in the season. Other storms were also simulated, with increasing volume and intensity in order to produce runoff events. The intensity of each storm was distributed according to the SCS type II storm distribution. This is the assumed distribution that AGWA uses for writing design storms based on a single depth and duration relationship.

4.4.2 Reservoir Model

The environmental input parameters for the reservoir model are infiltration rate and evaporation rate. The infiltration rate was designated as 4cm/hr as measured by Al-Sulaimi et al. (1988) in the area of the drainage depression. The model was also run with no infiltration, which would be the limiting case if the soil is saturated down to the depth of a confining layer and no further infiltration takes place. The evaporation rate was set at 2.2mm/d, based on estimates by Al-Sulaimi et al. (1997) for monthly potential evaporation in January. Water will not be limiting above the reservoir, and it is assumed that transport mechanisms will be able to support this level of evaporation. Based on these assumptions, the actual evaporation rate can be set equal to the potential evapotranspiration rate.

4.5 Results

Using the available data, the model did not simulate runoff for reasonable design storms, and even very intense events produced insignificant flows at the sub-basin outlets. However, a significant volume of runoff was generated when the soil properties were altered from what has been measured in the past. The area-volume relationship was calculated for each sub-basin assuming a dam was placed at the outlet. This revealed that for 1mm of runoff over a given sub-basin, the maximum depth at the outlet would be 0.5-2m. The wide shallow reservoirs that would be created are not practical for runoff collection. However a simulation was run for extraction of water from a reservoir formed at sub-basin 2.

4.5.1 Runoff Results

A range of design storms was used to simulate runoff processes in the Rawdhatain watershed. Based on rainfall data, it was assumed that a typical storm event would result in 10mm of rainfall over about 10 hours. To obtain a range of possible results, we estimated that this same volume of precipitation could occur over durations of 5 to 20hours. Initial saturation was varied between 15% and 90%. Hydraulic conductivity (Ks) values were also varied between 22.22mm/hr and 222.2mm/hr for plane elements and 8mm/hr to 80mm/hr for channel elements. Since no runoff was generated for any sub-basin or any storm with the high Ks values, those results are not tabulated here. The lower bound Ks values (8 and 22mm/hr) are "minimum Ks values" in Tables 4.3 and 4.4. In addition, no runoff was generated by 10mm of precipitation in 10hrs, so the 20hr storm was not simulated. No runoff reached any basin outlet for the 10mm, 5hr storm either, so a 5hr, 20mm storm was simulated. The results for this storm at 90% initial saturation and minimum Ks values are presented in Table 4.3. Sub-basin four had the highest runoff rate in terms of percentage of rainfall, so a summary of its results is presented in Table 4.4 for the range of storms.

Table 4.3 KINEROS2 results for 20mm, 5hr, 90% saturation design storm with "minimum" Ks

Sub-basin	1	2	3	4	5	Total
Area (km^2)	611.65	144.12	131.40	91.29	166.46	1144.92
Plane Inf (mm)	19.683	19.606	19.629	19.579	19.606	19.648
Channel Inf (mm)	0.065	0.095	0.08	0.107	0.094	0.078
Storage (mm)	0.115	0.153	0.132	0.186	0.155	0.133
Runoff (mm)	0.00012	0.0037	0.0022	0.0047	0.001	0.0013
Runoff (m^3)	71	531	290	428	167	1487

Simulations were also run using the hydraulic conductivities calculated by AGWA from the FAO soil database. These were 11.11mm/hr for plane elements and 210mm/hr for channels (default Ks in Table 4.4). These values produced much higher runoff rates for sub-basin four as shown in Table 4.4, but they do not relate to measured infiltration values in the literature.

Table 4.4 KINEROS2 results for sub-basin 4

	Minimum Ks Values, 90% saturation			Default Ks Values, 90% saturation		
Storm depth, duration	10mm, 10hr	10mm, 5hr	20mm, 5hr	10mm, 10hr	10mm, 5hr	20mm, 5hr
Plane Inf (mm)	10	9.888	19.579	9.798	9.834	18.108
Channel Inf (mm)	0	0.0048	0.107	0.02	0.051	1.783
Storage (mm)	0	0.0004	0.186	0.0003	0.0003	0.0004
Runoff (mm)	0	0	0.0047	0	0.00001	0.0172
Runoff (m^3)	0	0	428	0	0.5	1572

The model was also tested to determine what type of storm would be necessary to produce a significant amount of runoff under the "minimum Ks" conditions specified. The longest storm event allowed by KINEROS is about 16 hours, because no more than 1000 data points can be included in one event, and the time step is always one minute. A long event was used because, based on anecdotal evidence, extreme storm events in Kuwait may last several days but are not necessarily severely intense. For sub-basin four, a depth of 60mm is required in 16hrs to produce runoff at 9% of rainfall volume with 90% initial saturation. This is still a small percentage of runoff, considering the storm is more than half of the average yearly rainfall. In addition, in order to have a 90% initial saturation condition, another storm must have occurred recently.

Table 4.5 Results for 10hr, 10mm, 90%sat. storm, with Ks reduced to produce runoff

Kchannel = 0.17mm/hr, Kplane = 0.44mm/hr						
Basin#	1	2	3	4	5	Total
Area (km^2)	611.65	144.12	131.40	91.29	166.46	1144.92
Runoff (mm)	1.22	1.26	1.67	1.85	0.93	1.29
Runoff (m^3)	7.48E+05	1.81E+05	2.20E+05	1.69E+05	1.55E+05	1.47E+06
Kchannel = 0.084mm/hr, Kplane = 0.22mm/hr						
Basin#	1	2	3	4	5	Total
Runoff (mm)	1.94	2.14	2.60	2.78	1.47	2.04
Runoff (m^3)	1.18E+06	3.08E+05	3.42E+05	2.54E+05	2.45E+05	2.33E+06

Finally, the model was tested to determine what hydraulic conductivity is required to produce a significant amount of runoff with the 10mm, 10hr storm under 90% saturation conditions. In order to produce 1-2mm of runoff from this storm, the "minimum" reasonable Ks values given above were divided by 50-100. This gives saturated hydraulic conductivity between 0.08-0.17mm/hr for channels and 0.22 to 0.44mm/hr for plane elements. Table 4.5 shows results for each sub-basin under these conditions. Figure 4-9 shows the runoff produced in sub-basin 4 for a 10mm storm at 90% saturation with different storm durations and hydraulic conductivity values.

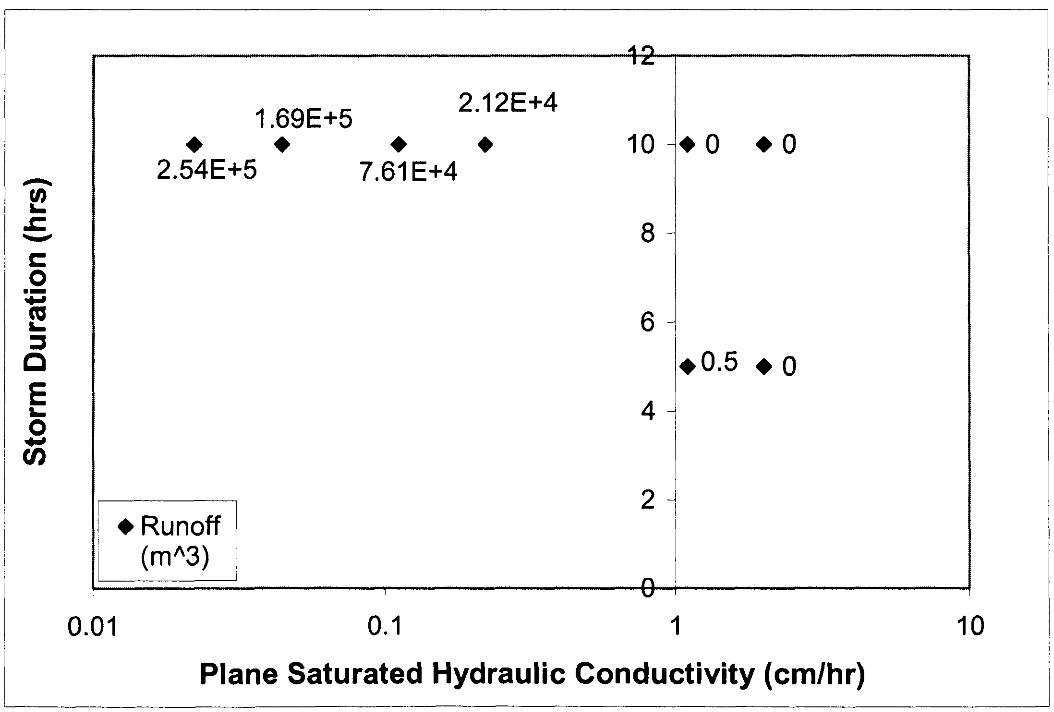

Figure 4-9 Runoff generated in sub-basin 4 during at 10mm storm

Figure 4-10 shows the typical hydraulic conductivities of a range of unconsolidated sediments. The values required to obtain 10-20% runoff from the 10mm storm are within the typical range for silt or silty sand. It seems quite reasonable that with the spatial variability of soil properties, a significant portion of the watershed could fall in this range. This is certainly more likely to account for the observed runoff than one half of the yearly average precipitation falling in a single storm.

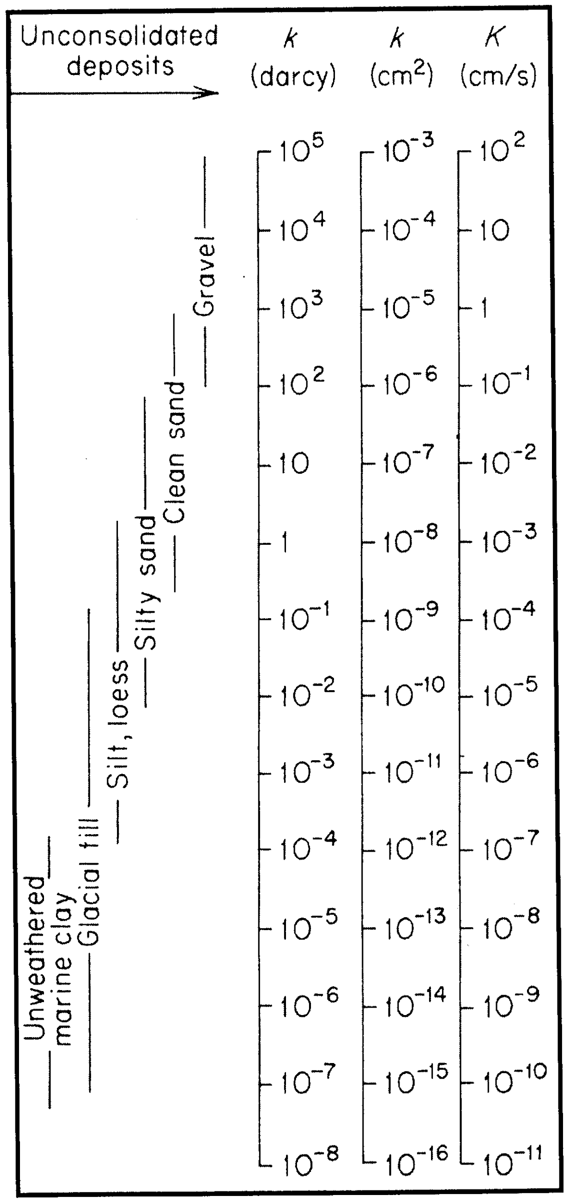

Figure 4-10 Typical hydraulic conductivities of soils (Adapted from Freeze and Cherry 1979)

4.5.2 Reservoir Results

Based on the area-volume calculations, 1mm of runoff over the watershed will produce very shallow reservoirs at some locations. For sub-basin 1, 1m of water at the outlet corresponds to a volume of 1.17 million cubic meters, compared to 0.6 million cubic meters that would result from 1mm of runoff. Even two millimeters of runoff would produce a reservoir with its deepest point at 1m. The same is true for sub-basin 5. The other outlet locations would fill to a maximum depth between 1 and 2m with 1mm of runoff. Figure 4-11 shows the area and volume of a reservoir at the outlet of sub-basin 2 with varying maximum depths. The flat topography indicates that it may be necessary to construct a basin that will concentrate the water in a smaller area than would be achieved by simply building a dam.

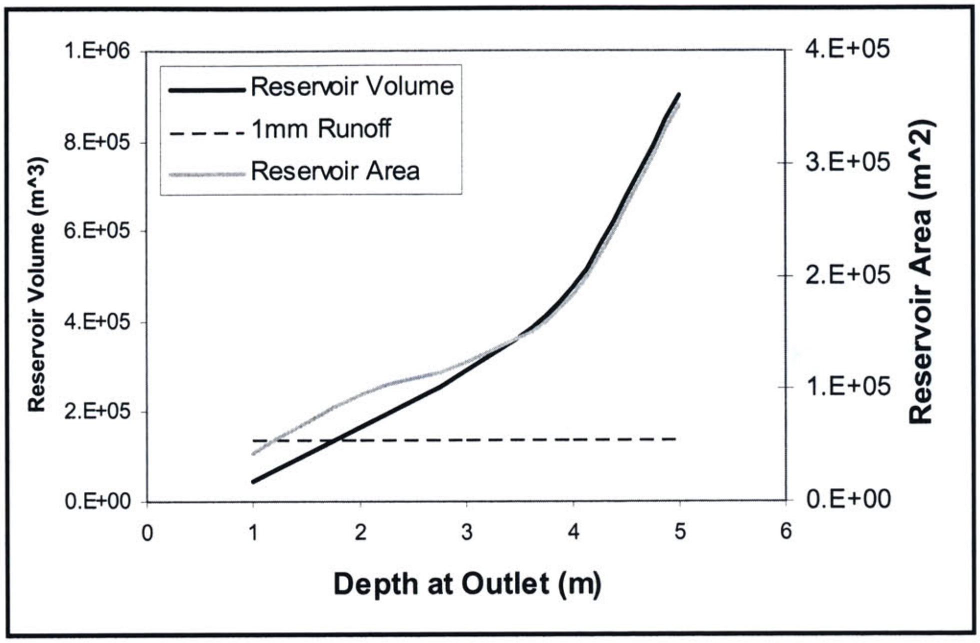

Figure 4-11 Area and volume of reservoir at sub-basin 2 outlet

The area and volume relationships were interpolated down to an outlet depth of 0.5m. Below this depth, it would be very difficult to extract water with pumps. The model was run for sub-basin 2 with a runoff volume of 280,000m^3, which corresponds to 2mm of runoff over the basin. The injection rate was set at 1000m^3/hr. Figure 4-12 shows the results of the calculations. The evaporation volume was 250m^3 with infiltration, and 1500m^3 with no infiltration the evaporation volume was 1500m3, neither of which is visible on the graph. Emptying the reservoir to approximately 0.5m deep at the outlet took 6 days with infiltration from the reservoir and 11days if there is no infiltration loss.

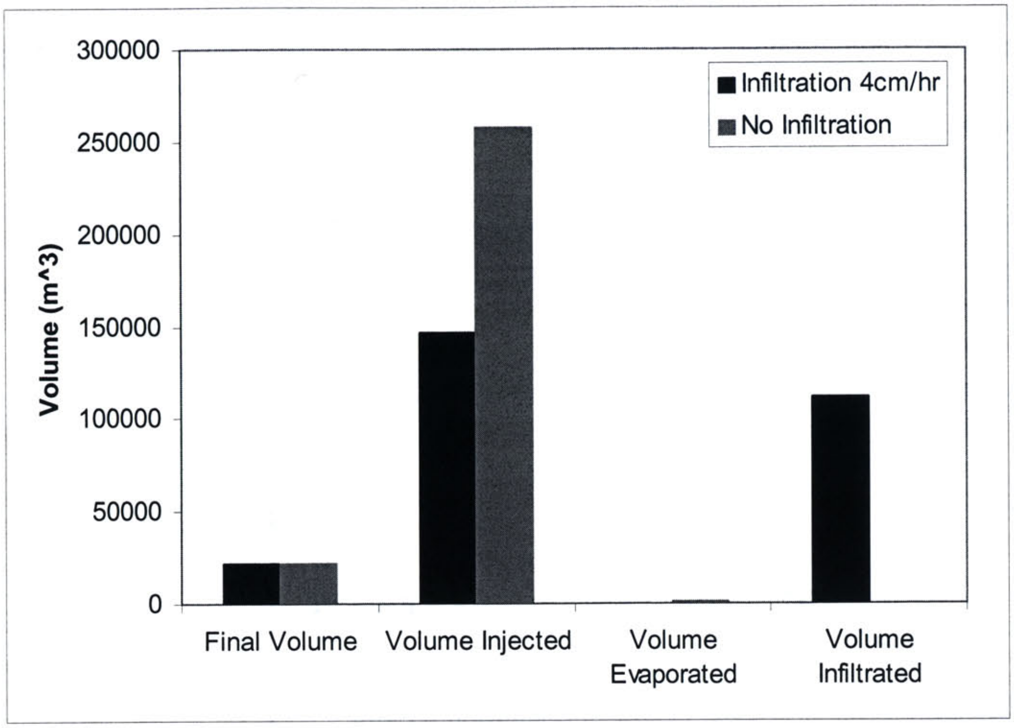

Figure 4-12 Water balance for a reservoir at the sub-basin 4 outlet

4.6 Conclusion

Simulating the Rawdhatain surface hydrology system using KINEROS2 and the data available does not generate any appreciable runoff for a reasonable storm event. However, Al-Sulaimi observes that "severe storms develop rather substantial short-duration flows in areas of integrated surface drainage and accumulate as playa lakes (Al-Sulaimi et al. 1997)" in reference to Rawdhatain and other similar drainage networks. The two factors that are most likely to contribute to this error are variations in the characteristics of typical storm events and soil properties. The storm required to produce runoff under assumed soil conditions is too intense to be realistic, so it is more likely that the soil characteristics are not represented accurately.

The soil properties are known to vary substantially within the watershed, and this is not accounted for by the aggregate data available. It is likely that the classical concept of "partial area" runoff creation applies to this watershed. This hypothesis states that only small areas of most watersheds contribute to runoff due to spatial variations in soil properties (Freeze 1974). Over most of the basin, the infiltration capacity is almost always higher than the rainfall rate, but some discrete areas have low enough infiltration rates that they become saturated at the surface and runoff is observed. For example, it is possible that a crust forms over the top of the soil or that there is a confining layer that effectively limits the depth available for infiltration in some areas. It is not unreasonable that variations in the conductivity of surface sediments or the presence of a shallow confining layer could have a net effect similar to the low hydraulic conductivities required to produce runoff over the whole watershed in the model. The disconnect between the model simulations and observations is probably due to the wide variability in soil properties and rainfall events that was not accurately simulated in the model. Overall, more study is needed to fully understand this important natural system.

The experiences with small-scale systems suggest that household level rainfall harvesting might be another feasible option for Kuwait. Runoff collection would be much more efficient in the urban areas than in the desert, but the water would need to be treated more thoroughly before it is used. Kuwait City has a storm sewer system that is separate from the sanitary sewer, but studies of the system suggest that the collected water is dumped into the Gulf (Shepherd 2003). This existing collection system could be used directly for rainfall harvesting. The water availability would be unpredictable, but it could be used to supplement the supply if a storage system were available. Alternately, educational initiatives could encourage individuals to collect storm water on their own properties for irrigation use. This is unlikely to be a popular program unless water use is charged to the consumer.

Chapter 5
Water Storage Options

5.1 Introduction

The two possibilities for water storage in Kuwait are aquifer storage and surface storage. These each have different advantages and disadvantages, so the costs and benefits must be weighed carefully, considering the policy, economic, and technological implications. Several technologies are available for introducing water to aquifers for storage, and these must be evaluated in light of the planned injection water and the local geology. Surface storage is somewhat more straightforward, but because of Kuwait's arid environment, strategies should be developed to minimize evaporation losses from such a system. Energy and water balances should be done to compare specific systems that are considered for implementation, and the differences in uncertainty in these parameters between the two types of storage are likely to be significant. In addition, there are trade-offs in terms of construction and operating costs as well as security concerns that should be considered.

5.2 Aquifer Storage

Aquifer storage has the advantage of a lower initial cost, and it is more protected than a surface reservoir. However, there is potential for significant water losses due to groundwater flow and blending with the native groundwater. The local hydrogeology must be considered to determine if this type of system is feasible.

5.2.1 Hydrogeology

The two formations that contain usable water throughout Kuwait are the clastic Kuwait Group and the limestone Dammam formation. Within these layers, three aquifers can be identified that are separated by aquitards. The aquiclude underlying this aquifer system is made up of the nummulitic limestone with lignites and shale intercalations that make up the lower Dammam Formation and the underlying anhydritic Rus Formation. The deepest usable aquifer (Dammam aquifer) is made up of chalky and dolomitic limestone in the middle part of the Dammam formation. The top of the Dammam Formation consists of hard chertified karstic limestone, and this along with the basal clay of the Kuwait group make up the first aquitard. The middle aquifer (Kuwait Group aquifer) is made up of the sandy deposits overlying this basal clay in the Kuwait group. Above this is a layer of silty sand that makes up the second aquitard. The uppermost aquifer is formed by the sand and gravel in the uppermost part of the Kuwait Group (Dibdibbah Formation). The Dibdibbah Formation only extends over the northern region of Kuwait, while the other two aquifers extend throughout the country.

Kuwait's groundwater is predominantly brackish to saline. Salinity in the main Kuwait Group and Dammam Formation aquifers ranges from around 3000mg/L in the southwest to more than 100,000mg/L in the northeast. This compares to an average seawater salinity of 35,000mg/L. A map of salinity in the Dammam Formation is shown in Figure 5-1, and salinity in the two aquifers is similar in most locations (Fadlemawla, 2005). Due to the high salt content of groundwater in the north, brackish water is produced from water fields in the south of Kuwait, as shown in Figure 1-3. The two Kuwait Group well fields in the north, Rawdhatain and Umm Al-

Aish, are freshwater lenses in the Dibdibbah Formation that are surrounded and underlain by high salinity water from the surrounding Kuwait Group Aquifer.

The freshwater lenses at Rawdhatain and Umm Al-Aish are located below large drainage basins where runoff from wadis collects after heavy rainstorms. The soil in this area is quite sandy, so some of the ponded water infiltrates into the ground and over time, this process has formed these freshwater lenses overlying the brackish water in the surrounding Kuwait Group (Al-Sulaimi et al.1997).

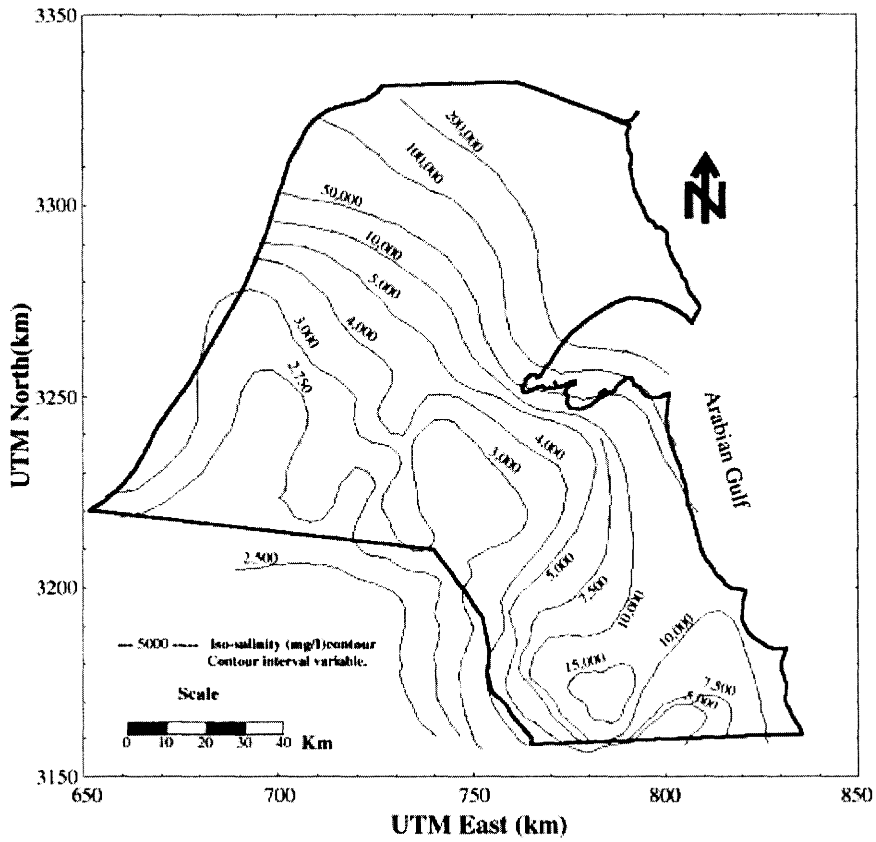

Figure 5-1 Iso-salinity map of the Dammam Aquifer (Adapted from Fadlelmawla and Al-Otaibi 2005)

These areas of natural fresh groundwater seem ideal for long-term storage of high quality water. Recovery efficiency should be higher in these areas because injected freshwater will have less opportunity to mix with brackish water. If freshwater is injected into the main aquifers that are currently exploited, it will become contaminated by the natural groundwater more quickly because of the high salinity of the surrounding water and mixing caused by the continuous pumping. However, Rawdhatain and Umm Al-Aish are in a more remote area of the country, so they are not as practical for short-term storage. Other researchers are currently investigating the possibility of injecting recycled wastewater into the Dammam formation in an area closer to Kuwait City, which is a more practical option for a storage-recovery system with a shorter residence time (Kuwait-MIT Center for Natural Resources and the Environment Technical Meetings, March 2006). The selected site is relatively close to both the source of injection water (RO treated wastewater or desalinated water) and the population centers where it will be used.

The focus of this study will be on use of the fresh water lens at Al-Rawdhatain for long-term storage. This is largely due to the lack of data available for the Umm Al-Aish aquifer, as well as the larger size of the Rawdhatain aquifer and its drainage basin. Chapter 2 discusses the specific properties of these aquifers as determined by previous studies.

5.2.2 Aquifer Storage Methods and Technology

A variety of systems are available for artificially recharging groundwater aquifers. These systems include surface basins, trenches, shafts, and wells, and differ in the depth at which the recharge water is introduced to the native sediment (Figure 5-2). Where surface sediments are relatively permeable and the aquifer is near the surface, infiltration basins are often employed. The recharge water is spread over a relatively wide basin area and allowed to infiltrate through to the underlying aquifer. Problems with this type of system occur when low permeability layers or regions of contamination separate the surface sediments from the aquifer. In addition the sediment can become clogged over time, reducing the infiltration capacity. Trenches or shafts can be excavated to reach sufficiently permeable sediment or to bypass regions of low permeability or contamination. Injection wells must be used to recharge deep or confined aquifers. Injection wells penetrate through to the depth of the aquifer, so the water does not infiltrate through the unsaturated region or vadose zone.

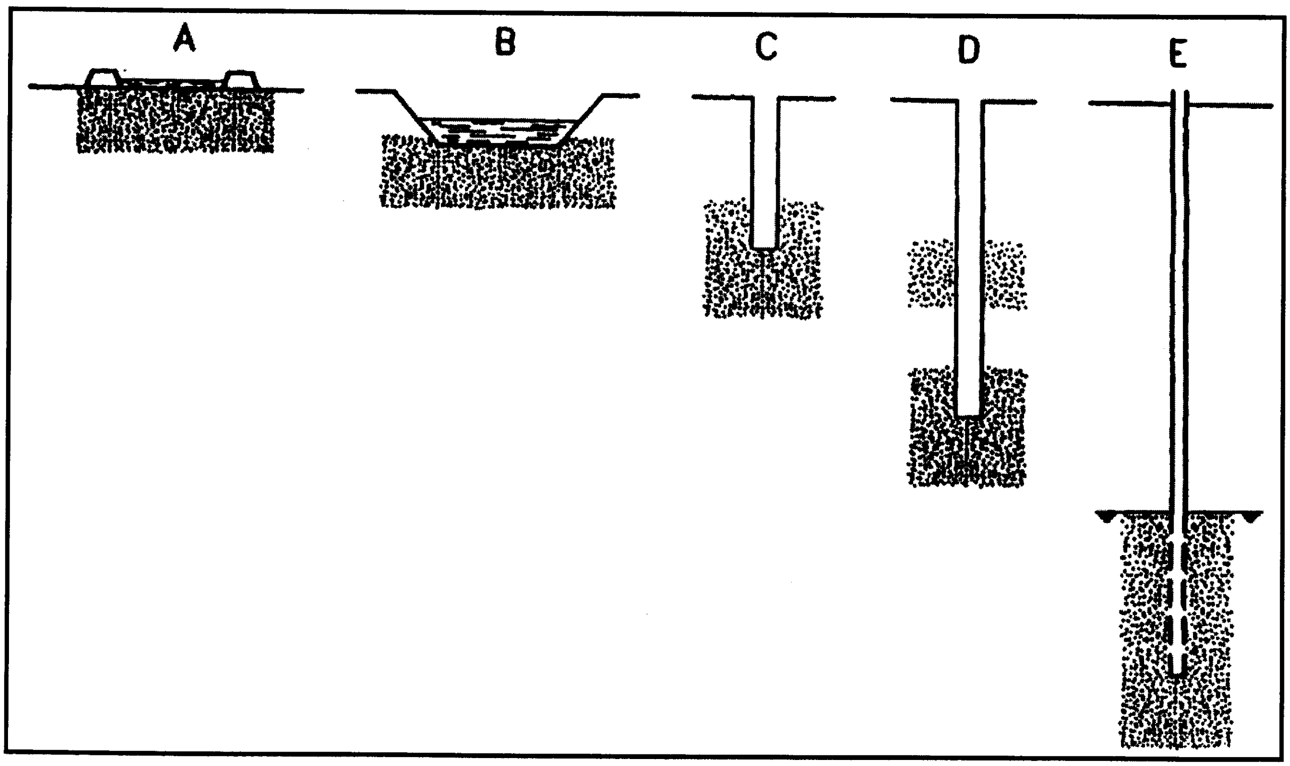

Figure 5-2 Traditional artificial recharge systems for increasing depths: surface basin (A), excavated basin (B), trench (C), vadose zone well or shaft (D), and aquifer injection well (E) (Adapted from Bouwer 1999)

In the Rawdhatain drainage depression, the infiltration rate of the surface sediment has been measured as 4cm/h, compared to much higher rates in the surrounding area, and the water table is located about 25m below ground surface (Al-Ruwaih and Hadi 2005). Because of these properties and the necessity of minimizing evaporation losses, surface infiltration systems are not an attractive option. If more permeable material lies near the surface, trenches could be dug up to 6 or 7 meters. Alternately, shafts can be drilled into the vadose zone to a depth up to 50m (Bouwer 1999). For direct injection, wells can be drilled that penetrate the aquifer.

Another important consideration is the possibility of physical, chemical, or biological clogging of the walls of the trench, shaft or well. Pretreatment such as coagulation or sand filtration may be required depending on the suspended solids content of the recharge water and the characteristics of the sediment. Trenches and shafts are less expensive than wells and can be replaced if they become clogged, but it is also more difficult to prevent clogging in these systems. Recharge wells can be back-pumped and periodically redeveloped to prevent and remediate clogging and extend the useful life of the well.

5.2.2.1 Seepage Trenches

Where surface infiltration basins are not desirable but permeable material occurs within about 2-5m of the surface, seepage trenches can be a cost effective option for enhancing aquifer recharge. The trenches are backfilled with coarse sand or fine gravel and water is applied to the surface of the backfill. The trench is covered to prevent exposure to the elements and disturbance by animals or people. Some variations on this system have been used to minimize clogging, including T-shaped trenches with somewhat finer material in the wider T-layer, or placing geotextiles on or in the backfill to filter the water. If clay zones are present in the trench area, they can be covered with plastic sheets to prevent sloughing and keep the clay and mud from entering the trench. Additional precautions should be made to ensure that the water entering the trench has a very low suspended solids content. The recharge rate for a trench can be estimated as 20 percent of the recharge rate calculated for a vadose zone well (Eq. 5.1), where the trench section has a width and length equal to the diameter of an equivalent well. For example, a 1m diameter well with 10m water depth recharges as much water as a 5m section of trench that is 1m wide, 10m deep and full of water (Bouwer 1999).

5.2.2.2 Vadose Zone Wells

Where permeable sediment is not within trenchable depth, vadose zone wells may be drilled up to about 50m below the surface. Vadose zone wells, also known as dry wells or recharge shafts, are usually 1-2m in diameter, terminating in permeable sediment above the level of the groundwater table. They are commonly used for infiltration of storm runoff in areas with relatively low rainfall and no storm sewer system. As with recharge trenches, contaminated sediment between the well site and the aquifer may eliminate this recharge option. However, where groundwater is deep, dry wells are much cheaper than recharge wells. As a result, they can be an attractive alternative to recharge wells that penetrate into the aquifer.

As with all recharge systems, the possibility of clogging must be considered. In vadose zone wells it is impossible to remediate clogging by pumping or redeveloping the well because it is in the unsaturated zone and water cannot flow into it. Several considerations can be made to minimize or prevent clogging. First, the water in the well should be protected from sloughing of clay layers in the wall of the well. This can make the water muddy and cause clay to accumulate, forming a clogging layer deeper in the well where more permeable layers normally allow the most infiltration to take place. To avoid this, the well can be filled with sand and a perforated pipe or screen can be placed in the center of the well to apply the water for recharge. Plastic sheets or geotextiles also may be placed on the sides of the well where clay layers occur.

In addition, the water may need to be treated to remove suspended solids, assimilable organic carbon, nutrients, microorganisms and other clogging agents. If these steps are taken, any clogging that occurs is likely to be due to microbial activity, with either bacterial cells or metabolic products causing the problem. Thus, it is possible that a long period of drying would allow enough biodegradation to permit additional use for recharge (Bouwer 1999).

Approximate recharge rates for vadose zone wells have been determined from Zangar's equation for reverse augerhole flow. For vadose zone wells in uniform soil materials with groundwater levels significantly below the bottom of the well, the recharge rate can be approximated as

$$Q = \frac{2\pi K L_w^2}{\ln(2L_w/r_w) - 1} \tag{5.1}$$

where Q is the recharge rate, K is the hydraulic conductivity of the soil material, L_w is the water depth in the well, and r_w is the radius of the well (Bouwer 1999).

5.2.2.3 Aquifer Wells

If the vadose zone has restricting layers or contaminated areas, well recharge is used. As with other recharge systems, clogging around the well is of primary concern and pretreatment may be necessary. It may also be desirable to maintain a chlorine residual in the water to prevent biofilm formation. In addition, periodic pumping can reduce the incidence of clogging. This can be accomplished using a range of pumping schedules, from a few minutes every day, to pumping once a month or once a year until clear water comes out. Well redevelopment or rehabilitation methods like surging or jetting may also be used periodically to maintain recharge rates, though regular pumping is the easier and often cheaper option. Increasing injection pressure in order to improve injection rates can actually increase clogging effects and is not recommended. Higher pressures may compact the clogging layer and decrease the injection rate. If higher injection pressure does initially produce faster injection rates, this implies higher loading rates of nutrients and organic carbon, which may speed the growth of biomass and increase clogging that way. Thus if clogging is observed in the form of decreased injection rates, it is best to remediate the clogging through pumping, injection of chlorinated water, or redevelopment, rather than attempting to overcome the clogging effects by increasing the injection pressure (Bouwer 1999). An injection well fitted with a permanent pump can also be used as an "aquifer storage and recovery" (ASR) well. ASR wells are used to inject surplus water into the aquifer when it is available, and pump water back out of the aquifer in times of increased demand. In addition to storing excess runoff, this type of system can be used to smooth the production rate of a water treatment plant over the course of the year. When demand is lower in winter excess water can be stored, and when demand increases in the summer the water is extracted and may only need to be disinfected before it is distributed.

5.2.2.4 Other possible configurations

In the Rawdhatain region, the major concern for the recharge project is evaporative losses. Based on previous studies, the surface infiltration rates vary widely, and the surface of the drainage basin has fairly low infiltration capacity. However, this is most likely due to build up of silt and clay deposited after runoff events. The area has a layer of silty sand underlain by more permeable gravel and sand deposits of the Upper Dibdibbah formation. The depth of the silty sand and thickness of gravel deposits below the surface varies with location (Al-Sulaimi et al.1977). This is the cause of the variability in surface infiltration rates. The aquifer containing the freshwater lens is in saturated sandstone beds in the Dibdibbah formation, between 23 to 46 meters below the surface, depending on surface elevation (Al-Ruwaih and Hadi 2005). As a result, it is reasonable to assume that trenches, dry wells, and recharge wells would all allow water to reach the aquifer easily. However, for maximum efficiency, water should be introduced deep enough to minimize evaporative losses. Further work will be required to determine the minimum depth required to achieve negligible losses to evaporation. Depending on the required depth, several alternate recharge configurations may be considered based on modifications of the trench and dry-well concepts.

If water can be introduced at trenchable depths, one may consider variations of the seepage trench to maximize infiltration capacity. For example, a trench network may be dug with the perforated supply pipes placed at the bottom of the trenches, allowing water to infiltrate through the natural soil matrix. This is likely to be effective because the soil is naturally quite permeable. A branching network, like the one shown in Figures 5-3 and 5-4 could be used to inject water over a large area using a single vertical injection point.

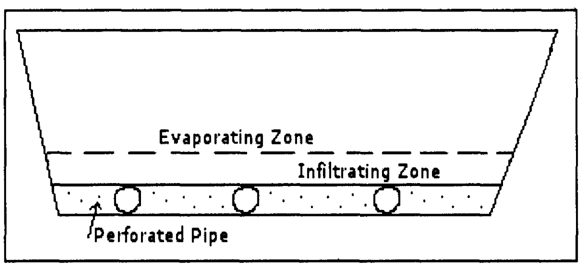

Figure 5-3 Cross-Section of branched trench

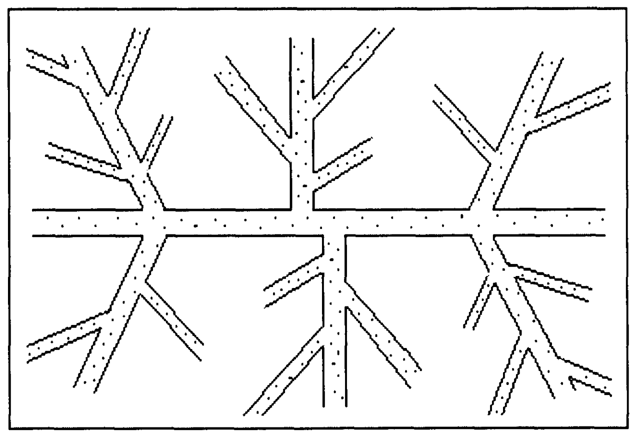

Figure 5-4 Aerial view of branched trench network

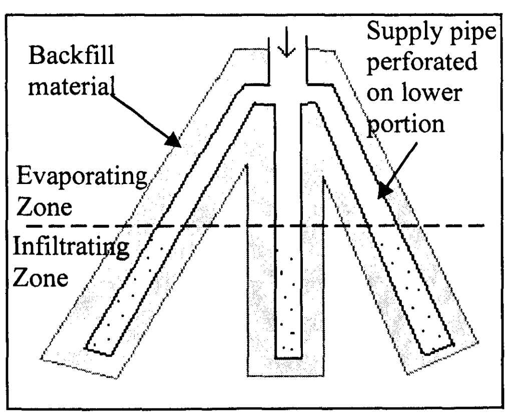

Figure 5-5 Cross-section of diagonally drilled dry well

If trench networks will allow an undesirable amount of evaporation, a series of dry wells may be required. In order to minimize evaporation, the supply pipes should have perforations only in the bottom section of the pipe, below the depth where evaporation prevails. Bore-holes may be drilled on a diagonal to allow injected water from one central location to reach a wider area and provide more rapid infiltration. A schematic of this type of shaft system is shown in Figure 5-5.

5.2.2.5 Construction

Trenches are dug with backhoes, and backfilled with fine gravel or coarse sand. A perforated pipe normally lies on top of the backfill and supplies the recharge water. This pipe can then be covered to prevent exposure to the elements or the public. Shafts are essentially a vertical configuration of the trench concept. A hole is drilled with a bucket auger and backfilled, then a vertical perforated pipe or well screen is placed in the center of the backfill. Construction of recharge wells is similar to the construction of pumping wells, using conventional well drilling techniques and sand or gravel envelopes around the well screen in unconsolidated materials. It is important to construct an injection well in a manner that ensures that air will not become entrained in the flow and cause blockages. To prevent this, the well should terminate well below the water level to avoid free falling water, and the pipes themselves should have full flow. In order to prevent partially full pipe flow, a variety of pipe sizes can be installed to accommodate different flow conditions. Alternately, an exit valve can be placed at the bottom of a single pipe to regulate flow and ensure full pipe flow in that way. In addition, the well should be equipped with a dedicated pump to allow periodic pumping of the well to control clogging (Bouwer 1999).

5.2.3 Potential Problems for Aquifer Storage

There are several problems that can be encountered with aquifer storage. Clogging of the well or infiltration area is the most common reason for premature failure of injection systems. It can occur as a result of silt or other suspended material in the injection water, or nutrients in the water can stimulate microbial growth around the injection site, and the resulting biofilms act in the same fashion as small particles to block flow. As a result, injection water is often pre-treated, and wells may be back-pumped regularly and redeveloped occasionally to overcome this problem.

Mukhopadhyay et al. performed a study in 2004 to determine the compatibility of RO treated wastewater and desalinated seawater for injection into the Kuwait Group aquifer. Cores could not be extracted from the unconsolidated portions of the aquifer, but when the consolidated and semi-consolidated samples were studied, it was determined that particles greater than 8μm in diameter should be removed to prevent clogging (Mukhopadhyay et al. 2004). If all sediment in the region of the injection site is unconsolidated a larger filter size could be used.

In addition to clogging, other issues that must be investigated with regards to the available aquifer and injection water include chemical compatibility and recovery efficiency. Recovery efficiency depends on the hydraulic gradient, dispersivity, aquifer transmissivity, porosity, and the time of storage in the aquifer (Merritt 1985). For long-term storage, the selected site should have a small hydraulic gradient in order to minimize loss of injected water. According to other researchers, the recovery efficiency for water stored in the freshwater lenses at Rawdhatain and

Umm Al-Aish would be very high because the transition zone between injected water and native groundwater is insignificant (Senay 1977).

Chemical compatibility is important because reactions between the injected water and the aquifer material or native water may cause precipitation of solids or dissolution of the aquifer material. Either of these processes can dramatically effect the injection and recovery efficiencies of the storage system. No problems of chemical compatibility were found during compatibility tests by Mukhopadhyay et al. (2004).

In addition to injection efficiency, recovery efficiency is an important concern. Depending on aquifer properties, the amount of injected water that can be withdrawn at a later time can vary significantly. This is obviously an important aspect to study in relation to the selected aquifer, because how much water can be recovered determines whether the project is practical from an engineering standpoint. Thus, the aquifer must be sufficiently conductive to allow introduction of water at a reasonable rate, but it cannot be so conductive that injected water immediately blends with natural water and flows away from the well.

Field studies should be done to investigate the soil properties more carefully at the proposed site in order to verify that favorable conditions exist for the planned type of recharge project. In addition a pilot-scale system should be built to simulate the operational performance before a large-scale recharge system is built. This pilot study will help determine if clogging is likely to occur and what pretreatment should be used. For example, if a biofilm forms, it might be necessary to remove nutrients from the injection water or chlorinate the water. On the other hand if siltation is observed, settling or pre-filtration of the water may be necessary, and incompatibility of injection water with natural water or aquifer material may require chemical pre-treatment. Pilot studies are also important to determine the expected injection and recovery efficiencies for a project. These parameters are difficult to estimate from lab tests due to aquifer heterogeneity, but are extremely important for determining the project performance.

5.3 Surface Storage

In order to reduce the inherent uncertainty in recovery efficiency associated with aquifer storage, a large reservoir could be constructed to store water above ground. This would allow storage of water with minimal operating expenses, but the initial construction cost would be very high. Surface storage systems are common throughout the world for capturing rainwater and stream flow, but adapting this technology to Kuwait's climate may present a significant challenge. Because potential evaporation rates are much higher than the precipitation in Kuwait throughout the year and runoff is quite low, Kuwait does not have the type of site that would normally be utilized for a water reservoir. However, it is possible that a fully enclosed reservoir could be used for storing runoff, imported water, and water from other sources to create a valuable reserve.

5.3.1 Storage Potential at Rawdhatain

One possible location for such a reservoir is the natural depression at Rawdhatain. This basin could be lined on the bottom and covered, creating a large volume available for storage. This construction method limits the potential reservoir sites, but the construction would be easier and less expensive than if the reservoir were placed in a flat area where much more excavation would be required. As shown in Figure 5-7, the selected reservoir location is not particularly close to population centers, but it is convenient to possible sources of imported water, and a pipeline could be built from the supplying nation to the reservoir, with a second pipeline providing water to Kuwait City from the reservoir.

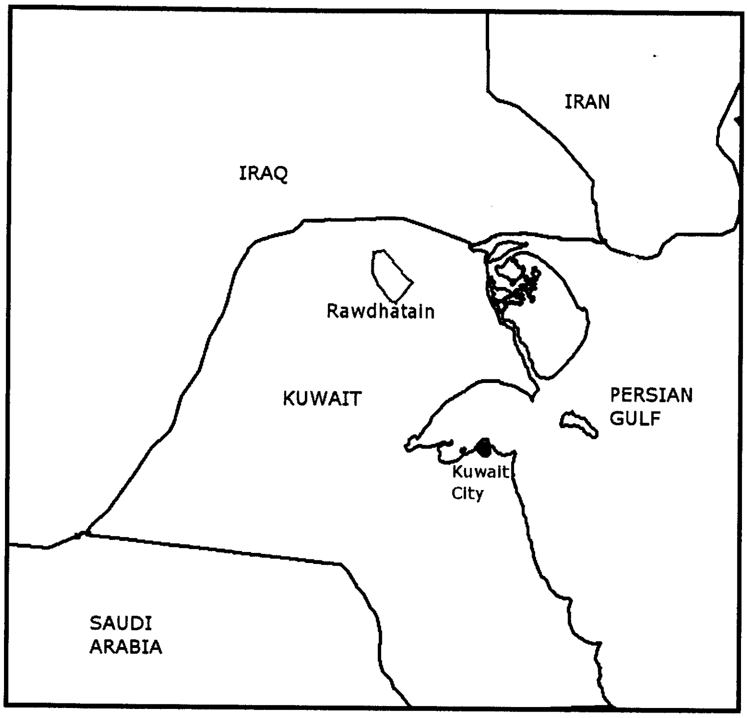

Figure 5-6 Regional map

When full, a $1km^3$ reservoir could provide enough water for the entire country for three years at the current usage rate. Building such a reservoir would also allow water to be imported from other countries without depending on other governments for water security. For example, water could be imported from Iran or Iraq, and stored in this reservoir. It could then be used to even cycles of demand to allow desalination plants to operate at maximum efficiency, to supply peaks in irrigation demand or for other uses. As long as around a year's supply is maintained in the reservoir, a sudden end to imported supply would not be a threat to water security. The design and construction of such a reservoir would be a major engineering challenge due to the scale of the project. Figure 5-7 shows the proposed area and the natural elevation relief. In this case, the natural topography could form the bottom and sides of the reservoir, with only the southeast end requiring some earth-movement to build up the wall at that point.

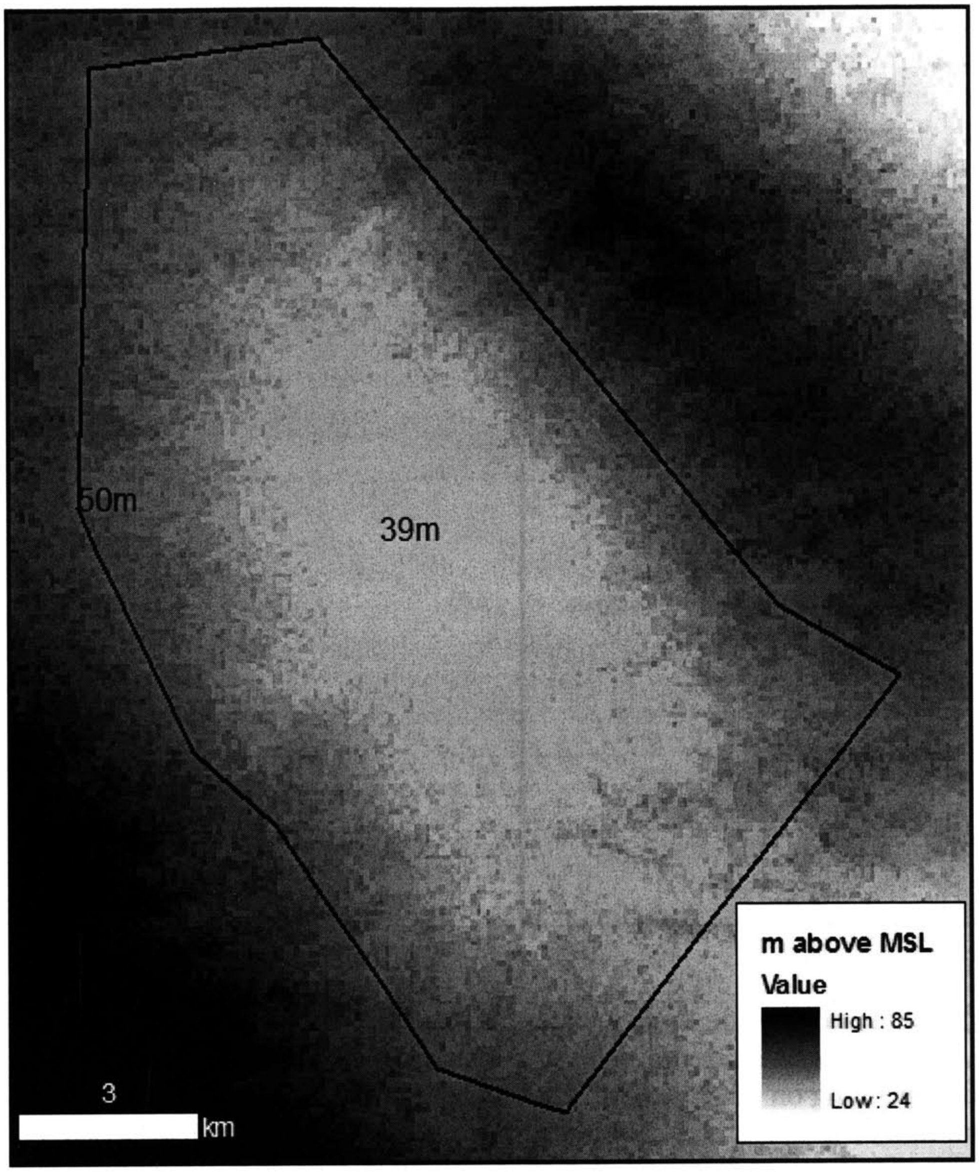

Figure 5-7 Elevation variation at Rawdhatain

If a reservoir were built in the proposed area in the Rawdhatain basin to a top elevation of 50m, the total volume would be 1km^3, with a surface area of 143km^2 and a maximum depth of 11m. Figure 5-8 shows the approximate relationship between reservoir volume and the top elevation of the reservoir. The bottom surface of the reservoir is at 39m above M.S.L.

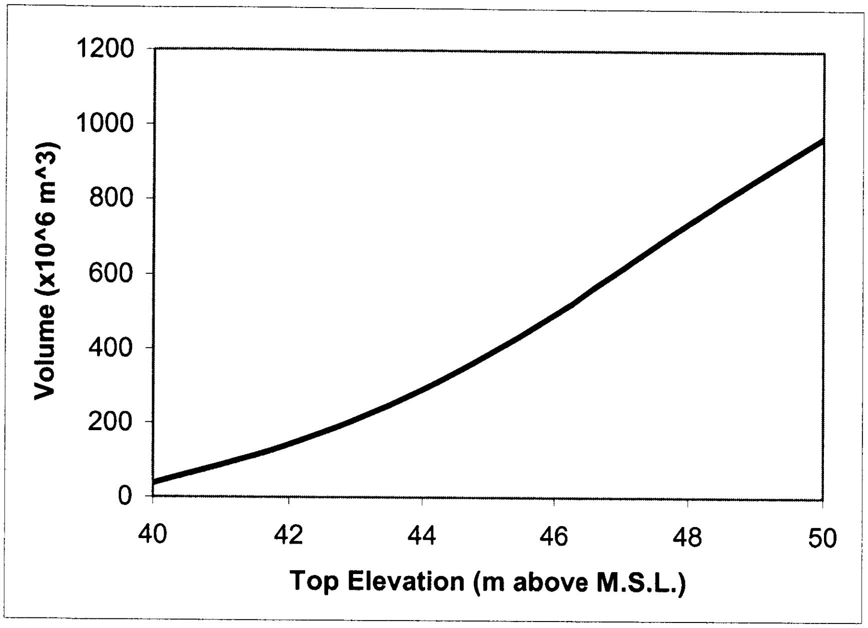

Figure 5-8 Storage volume of Rawdhatain basin

This location would be convenient for storing water imported from north of Kuwait, and like any storage stystem, it would reduce the political risk associated with such a scheme. On the other hand, it is not a very convenient location for seasonal storage of desalinated water or reclaimed wastewater from the Sulaibiya plant.

This reservoir could also be used to store water from a rainfall harvesting system constructed in the Rawdhatain drainage area. Individual wadis could easily be dammed at the edge of the reservoir, and this water could be stored in the protected reservoir. The construction of this reservoir would drastically reduce recharge into the Rawdhatain aquifer, causing the quality to decline significantly over time. The fact that much less water will be recharging the aquifer naturally makes it more advisable to capture the runoff for storage. Chapter 4 discusses the potential for capturing the runoff from this area.

5.3.2 Reservoir Practicality

As with aquifer storage, there are some complications to consider with building a large surface storage system in Kuwait. Table 5.1 summarizes the differences between these two options. Several issues must be considered regarding the constructability of such a massive structure. If the bottom of the reservoir is made of concrete, a second waterproof layer should be considered to prevent leakage. This is necessary because the concrete is porous, and the surface will have construction joints that would create leaks. In addition, with such a large surface, additional cracks would probably form over time due to expansion and contraction with temperature variation. Alternatively, it may be possible to pave the bottom surface with asphalt to minimize cracking, but the load bearing capacity would need to be investigated. A watertight cover above the water surface would be desirable to prevent excessive evaporation loss. The mechanics of sealing these waterproof membranes around the columns supporting the roof and over the entire area of the reservoir would be a significant challenge in itself.

Table 5.1 Comparison of aquifer and surface storage systems

Concern	Aquifer Storage	Surface Storage
Water Losses	medium - high	low - medium
Initial Cost	low - medium	very high
Operating/Maintenance Cost	medium	low
Vulnerability	low	medium - high

In addition to water loss through cracks in the floor, the air filling any empty volume of the reservoir will be saturated, so any air loss also constitutes a water loss. Due to the high average temperatures in Kuwait, this air will probably hold quite a bit of water, so efforts should be made to prevent these losses. In the summer, the average air temperature is around 44 C°, and saturated air would hold over 60 grams of water for every kilogram of air. The reservoir air may be slightly cooler than the outside temperature, but it would still be expected to hold significant water mass.

Another issue to consider with building one massive reservoir for strategic storage is its security. It would be a stable source in the case of mechanical failures or other such accident at desalination plants, but this type of incident would probably not require a cubic kilometer of reserve, which would be enough to supply the country for three years at current usage levels. However, in the case of sabotage, this reservoir would be a fairly easy target. Leaked water may be recoverable by pumping out of the surrounding sand, but water stored in aquifers would already have pump systems in place and would therefore be easier to access in this type of situation. In addition, if a surface reservoir is built in the north, transporting water to population centers during a crisis may also be a logistical concern, though this is also an issue for water stored in the Rawdhatain aquifer. In light of the construction and security concerns, the choice of what type of reservoir should be built is a complex policy question that requires careful consideration of a range of risks in addition to the usual cost considerations.

Chapter 6
Recommendations

6.1 Flux Increase

Kuwait has the potential to increase its water supply through several options, including additional desalination capacity, importation, wastewater reuse and rainfall harvesting. Further study is needed to quantitatively compare these options, and the final decision will also require economic and political analysis.

Desalination should continue to be considered as a key component in Kuwait's water supply infrastructure. However, it is very expensive, and due to the large energy requirements of Kuwait's desalination plants, the price will probably continue to increase with the price of energy. On the other hand, new desalination technology allows production of freshwater from seawater at a lower cost than is currently attained in Kuwait. As a result, it is possible that added desalination capacity could produce water at a significantly lower cost than the existing multistage flash facilities.

Importation has the potential to supply large volumes of water at a relatively low cost compared to desalination or wastewater reuse. The political implications must be considered, and as water becomes more and more scarce in the Middle East, and around the world, it may become more difficult to reach agreements to obtain imported water. In addition, there is significant risk associated with relying on another country for necessary water resources. However, ensuring that a large volume of water is stored for emergency use can greatly reduce this risk. A storage volume of at least one year's supply would allow for the construction of additional desalination capacity or for other arrangements to be made in the event that the imported water supply is interrupted.

The wastewater reuse system in Kuwait could operate much more efficiently by allocating water to more appropriate uses based on quality. Currently, RO treated water is planned to be used exclusively for irrigation and similar uses. However, based on previous experiences, this water is probably safe for indirect potable use. If storage systems are built, this water could be blended with stored desalinated or imported water to increase the potable water supply. It could also be used in industrial applications, such as cooling towers, that require low TDS content. Similarly, tertiary-treated wastewater could be used instead of RO water for most agricultural applications. Additional study of the product water quality from these facilities is required to verify that these applications are safe, but they should be acceptable based on experiences with similar treatment systems in other places. The quality of the treated product depends on the constituents initially present in the wastewater. If the quality is found to be unacceptable for indirect potable use, education campaigns could be used to improve the source water along with improving the facility to achieve better product quality.

Further research is needed to determine the feasibility of rainfall harvesting for Kuwait. The aggregate data used to model the rainfall harvesting system at Rawdhatain suggest that with average soil conditions and average rain events, no significant runoff is produced. However, both of these parameters vary widely in time and space in the natural environment. It is likely that spatial variation in soil properties is such that this type of system could collect runoff under natural conditions. If further study determines that the natural soil conditions are not conducive to rainfall collection, the soils could be modified by compaction or other means to improve the collection efficiency of a rainfall harvesting system.

In order to better understand the system, several components should be studied. First, the existing rainfall records for the Rawdhatain weather station should be analyzed to determine historical rainfall intensity and duration trends. If hourly data is not available for that station, hourly data for the nearest weather station should be analyzed to determine a profile for typical storms in the area. This could be used to produce a more accurate design storm that could be combined with aggregate precipitation data from the Rawdhatain station.

In addition, instrumentation and further study within the watershed should be carried out to better understand the surface hydrology in the Rawdhatain basin. A comprehensive soil survey should be completed in order to better understand the variation in soil properties around the watershed. In addition, a network of stations measuring precipitation, soil moisture, and atmospheric variables such as evaporation, temperature, humidity and wind speed would be extremely valuable for constructing an accurate model of the hydrologic system.

Rainfall harvesting has the advantage of being inexpensive compared to other methods of obtaining potable water, but in Kuwait it will have limited applicability due to the arid climate. It could easily be coupled with a storage system located in the watershed to supplement other supplies. However, the extreme seasonal and inter-annual variability in precipitation will make this system somewhat unreliable under even the best circumstances.

Based on experiences in other dry climates, it is possible that collection of urban runoff, either at the household scale or over large catchments, could be another practical addition to the water supply. The existing storm sewer system could be utilized to collect water from virtually all of the urban areas with high efficiency. This water would be much more contaminated than desert runoff, but the cost of treatment should still be significantly less than desalination or membrane treatment of wastewater. If the cost of water is increased for domestic use, individuals may be motivated to install rain barrels or more sophisticated rainfall collection systems. These could be used to store runoff for irrigating lawns in the dry season.

6.2 Storage

Some type of high-capacity water storage would be extremely valuable for Kuwait. By storing at least a year's supply of potable water, importation could become politically feasible. Without significant storage, the supplying nation could exert a great deal of political influence because Kuwait would be dependent on them for a necessary supply of water. In addition, pipelines are vulnerable to damage by accident or attack, which could cut off the supply at any time. With a large reserve of water, these scenarios do not pose insurmountable obstacles to water importation. Water storage could also allow for the indirect potable use of high-quality reclaimed wastewater. Direct consumption of this water is not socially acceptable, and would be a very difficult policy to implement. However, if studies are done to prove the exceptional quality of the RO product water, it is possible that blending it with other water reserves could be feasible. Water collected by rainfall harvesting could also be stored in such a system to supplement the reserve , since it will not be available on a predictable basis. Finally, storage capacity could be used to smooth the seasonal demand for desalinated water. This would allow desalination plants to operate at a nearly constant production rate throughout the year by storing excess in the winter for use when demand increases in the summer months.

Large volumes of water could be stored at Rawdhatain, either in the freshwater zone of the Kuwait Group aquifer, or in an enclosed reservoir constructed in the depression. This location has the advantage of being convenient to Iran and Iraq, where pipelines could be built to import water. It is also very convenient for the storage of rainwater that could be collected from the drainage networks at Rawdhatain. On the other hand, it is not very convenient to the city, where most of the demand would be for this water, or to the desalination and water recycling plants that could contribute seasonal supply.

An aquifer storage system will have a much lower initial cost than a surface reservoir, but it will have a higher operating and maintenance cost, depending on the volume of water to be stored. It is also much harder to predict the amount of water that will be lost due to groundwater flow and mixing with the native brackish water. A detailed groundwater model should be constructed that includes a description of the salinity distribution in order to estimate the amount of fresh water that could be recovered from such a system. Another advantage of aquifer storage is that the water supply is very well protected from contamination by either natural or human mechanisms.

A surface storage system will be somewhat difficult and very expensive to construct, but once it is built, it will have very little operating and maintenance cost. It will also be easier to predict the amount of water that will be lost to evaporation and potential leakage through the bottom of the reservoir than to predict losses in the aquifer. The evaporation losses will depend on how the cover is constructed and sealed, but they will be quite high if the reservoir is not covered. A surface reservoir will be somewhat more vulnerable to attacks that could introduce contamination or cause major leaks.

Further investigation must be done to obtain accurate cost estimates based on the desired storage volume. Energy and water balances should also be used to determine the expected water loss from each system. Ultimately, all of these elements must be weighed in order to determine the best system based on both technical and political considerations. There are a wide variety of viable options that should be considered for improving the sustainability of Kuwait's water supply. The construction of a large storage system will enhance any of the options chosen for flux increase, and should be a priority for Kuwait's water resource planning.

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Appendix A
Sample Input and Output Files from KINEROS2

A.1 Input Rainfall File for 10mm, 10hr, 90% Saturation Storm

! User-defined storm created in AGWA Fri Apr 28 09:09:37 2006
!** AGWA does not apply an area reduction factor to these data.

BEGIN RG1
N = 600
! Duration = 10
! Return period depth = 10

TIME	DEPTH	!TIME	DEPTH	! TIME	DEPTH	! TIME	DEPTH
! (min)	(mm)	! (min)	(mm)	! (min)	(mm)	! (min)	(mm)
0	0.00	37	0.16	74	0.35	111	0.55
1	0.00	38	0.17	75	0.35	112	0.56
2	0.01	39	0.17	76	0.36	113	0.57
3	0.01	40	0.18	77	0.36	114	0.57
4	0.02	41	0.18	78	0.37	115	0.58
5	0.02	42	0.19	79	0.37	116	0.58
6	0.03	43	0.19	80	0.38	117	0.59
7	0.03	44	0.20	81	0.38	118	0.60
8	0.03	45	0.20	82	0.39	119	0.60
9	0.04	46	0.21	83	0.39	120	0.61
10	0.04	47	0.21	84	0.40	121	0.62
11	0.05	48	0.22	85	0.41	122	0.62
12	0.05	49	0.22	86	0.41	123	0.63
13	0.06	50	0.23	87	0.42	124	0.63
14	0.06	51	0.23	88	0.42	125	0.64
15	0.06	52	0.24	89	0.43	126	0.65
16	0.07	53	0.24	90	0.43	127	0.65
17	0.07	54	0.25	91	0.44	128	0.66
18	0.08	55	0.25	92	0.44	129	0.67
19	0.08	56	0.26	93	0.45	130	0.67
20	0.09	57	0.26	94	0.46	131	0.68
21	0.09	58	0.27	95	0.46	132	0.69
22	0.10	59	0.27	96	0.47	133	0.69
23	0.10	60	0.28	97	0.47	134	0.70
24	0.10	61	0.28	98	0.48	135	0.71
25	0.11	62	0.29	99	0.48	136	0.71
26	0.11	63	0.29	100	0.49	137	0.72
27	0.12	64	0.30	101	0.50	138	0.73
28	0.12	65	0.30	102	0.50	139	0.73
29	0.13	66	0.31	103	0.51	140	0.74
30	0.13	67	0.31	104	0.51	141	0.75
31	0.14	68	0.32	105	0.52	142	0.75
32	0.14	69	0.32	106	0.52	143	0.76
33	0.15	70	0.33	107	0.53	144	0.77
34	0.15	71	0.33	108	0.54	145	0.77
35	0.15	72	0.34	109	0.54	146	0.78
36	0.16	73	0.34	110	0.55	147	0.79

! TIME	DEPTH
! (min)	(mm)
148	0.80
149	0.80
150	0.81
151	0.82
152	0.82
153	0.83
154	0.84
155	0.85
156	0.85
157	0.86
158	0.87
159	0.88
160	0.88
161	0.89
162	0.90
163	0.91
164	0.91
165	0.92
166	0.93
167	0.94
168	0.95
169	0.95
170	0.96
171	0.97
172	0.98
173	0.99
174	0.99
175	1.00
176	1.01
177	1.02
178	1.03
179	1.04
180	1.04
181	1.05
182	1.06
183	1.07
184	1.08
185	1.09
186	1.10
187	1.10
188	1.11
189	1.12
190	1.13
191	1.14
192	1.15
193	1.16
194	1.17
195	1.18
196	1.19
197	1.20
198	1.21
199	1.22
200	1.23
201	1.24

! TIME	DEPTH
! (min)	(mm)
202	1.25
203	1.26
204	1.27
205	1.28
206	1.29
207	1.30
208	1.31
209	1.32
210	1.33
211	1.34
212	1.35
213	1.36
214	1.37
215	1.38
216	1.39
217	1.41
218	1.42
219	1.43
220	1.44
221	1.45
222	1.46
223	1.48
224	1.49
225	1.50
226	1.51
227	1.53
228	1.54
229	1.55
230	1.56
231	1.58
232	1.59
233	1.60
234	1.62
235	1.63
236	1.64
237	1.66
238	1.67
239	1.69
240	1.70
241	1.72
242	1.73
243	1.75
244	1.76
245	1.78
246	1.79
247	1.81
248	1.83
249	1.84
250	1.86
251	1.88
252	1.89
253	1.91
254	1.93
255	1.95

! TIME	DEPTH
! (min)	(mm)
256	1.97
257	1.99
258	2.00
259	2.02
260	2.04
261	2.07
262	2.09
263	2.11
264	2.13
265	2.15
266	2.18
267	2.20
268	2.22
269	2.25
270	2.27
271	2.30
272	2.33
273	2.35
274	2.38
275	2.41
276	2.44
277	2.47
278	2.51
279	2.54
280	2.58
281	2.61
282	2.65
283	2.69
284	2.74
285	2.78
286	2.83
287	2.88
288	2.94
289	3.00
290	3.06
291	3.14
292	3.21
293	3.30
294	3.41
295	3.53
296	3.68
297	3.87
298	4.14
299	4.59
300	5.41
301	5.86
302	6.13
303	6.32
304	6.47
305	6.59
306	6.70
307	6.79
308	6.86
309	6.94

! TIME	DEPTH
! (min)	(mm)
310	7.00
311	7.06
312	7.12
313	7.17
314	7.22
315	7.26
316	7.31
317	7.35
318	7.39
319	7.42
320	7.46
321	7.49
322	7.53
323	7.56
324	7.59
325	7.62
326	7.65
327	7.67
328	7.70
329	7.73
330	7.75
331	7.78
332	7.80
333	7.82
334	7.85
335	7.87
336	7.89
337	7.91
338	7.93
339	7.96
340	7.98
341	8.00
342	8.01
343	8.03
344	8.05
345	8.07
346	8.09
347	8.11
348	8.12
349	8.14
350	8.16
351	8.17
352	8.19
353	8.21
354	8.22
355	8.24
356	8.25
357	8.27
358	8.28
359	8.30
360	8.31
361	8.33
362	8.34
363	8.36

! TIME ! (min)	DEPTH (mm)
364	8.37
365	8.38
366	8.40
367	8.41
368	8.42
369	8.44
370	8.45
371	8.46
372	8.47
373	8.49
374	8.50
375	8.51
376	8.52
377	8.54
378	8.55
379	8.56
380	8.57
381	8.58
382	8.59
383	8.61
384	8.62
385	8.63
386	8.64
387	8.65
388	8.66
389	8.67
390	8.68
391	8.69
392	8.70
393	8.71
394	8.72
395	8.73
396	8.74
397	8.75
398	8.76
399	8.77
400	8.78
401	8.79
402	8.80
403	8.81
404	8.82
405	8.83
406	8.84
407	8.85
408	8.86
409	8.87
410	8.88
411	8.89
412	8.90
413	8.90
414	8.91
415	8.92
416	8.93
417	8.94

! TIME ! (min)	DEPTH (mm)
418	8.95
419	8.96
420	8.96
421	8.97
422	8.98
423	8.99
424	9.00
425	9.01
426	9.01
427	9.02
428	9.03
429	9.04
430	9.05
431	9.05
432	9.06
433	9.07
434	9.08
435	9.09
436	9.09
437	9.10
438	9.11
439	9.12
440	9.12
441	9.13
442	9.14
443	9.15
444	9.15
445	9.16
446	9.17
447	9.18
448	9.18
449	9.19
450	9.20
451	9.20
452	9.21
453	9.22
454	9.23
455	9.23
456	9.24
457	9.25
458	9.25
459	9.26
460	9.27
461	9.27
462	9.28
463	9.29
464	9.29
465	9.30
466	9.31
467	9.31
468	9.32
469	9.33
470	9.33
471	9.34

! TIME ! (min)	DEPTH (mm)
472	9.35
473	9.35
474	9.36
475	9.37
476	9.37
477	9.38
478	9.38
479	9.39
480	9.40
481	9.40
482	9.41
483	9.42
484	9.42
485	9.43
486	9.43
487	9.44
488	9.45
489	9.45
490	9.46
491	9.46
492	9.47
493	9.48
494	9.48
495	9.49
496	9.49
497	9.50
498	9.50
499	9.51
500	9.52
501	9.52
502	9.53
503	9.53
504	9.54
505	9.54
506	9.55
507	9.56
508	9.56
509	9.57
510	9.57
511	9.58
512	9.58
513	9.59
514	9.59
515	9.60
516	9.61
517	9.61
518	9.62
519	9.62
520	9.63
521	9.63
522	9.64
523	9.64
524	9.65
525	9.65

! TIME ! (min)	DEPTH (mm)
526	9.66
527	9.66
528	9.67
529	9.67
530	9.68
531	9.68
532	9.69
533	9.69
534	9.70
535	9.70
536	9.71
537	9.71
538	9.72
539	9.72
540	9.73
541	9.73
542	9.74
543	9.74
544	9.75
545	9.75
546	9.76
547	9.76
548	9.77
549	9.77
550	9.78
551	9.78
552	9.79
553	9.79
554	9.80
555	9.80
556	9.81
557	9.81
558	9.82
559	9.82
560	9.83
561	9.83
562	9.84
563	9.84
564	9.85
565	9.85
566	9.85
567	9.86
568	9.86
569	9.87
570	9.87
571	9.88
572	9.88
573	9.89
574	9.89
575	9.90
576	9.90
577	9.90
578	9.91
579	9.91

```
! TIME  DEPTH
!   (min) (mm)
    580   9.92
     581   9.92
     582   9.93
     583   9.93
     584   9.94
     585   9.94
     586   9.94
     587   9.95
     588   9.95
     589   9.96
     590   9.96
     591   9.97
     592   9.97
     593   9.97
     594   9.98
     595   9.98
     596   9.99
     597   9.99
     598   10.00
     599   10.00

SA = 0.90
END
!duration: 600
```

A.2 Watershed Parameter Input File for Sub-basin 3

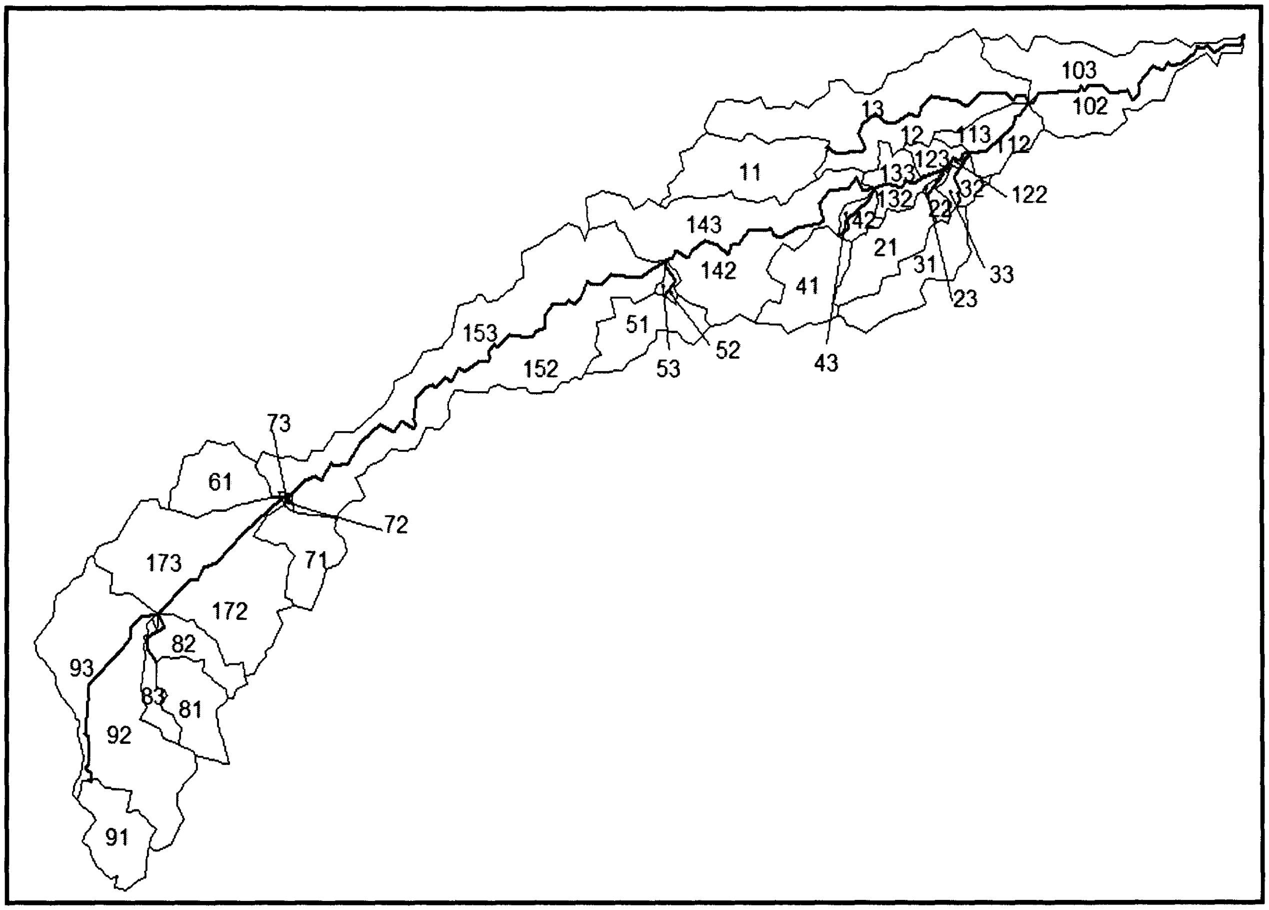

Figure A-1 Sub-basin 3 with plane elements labeled

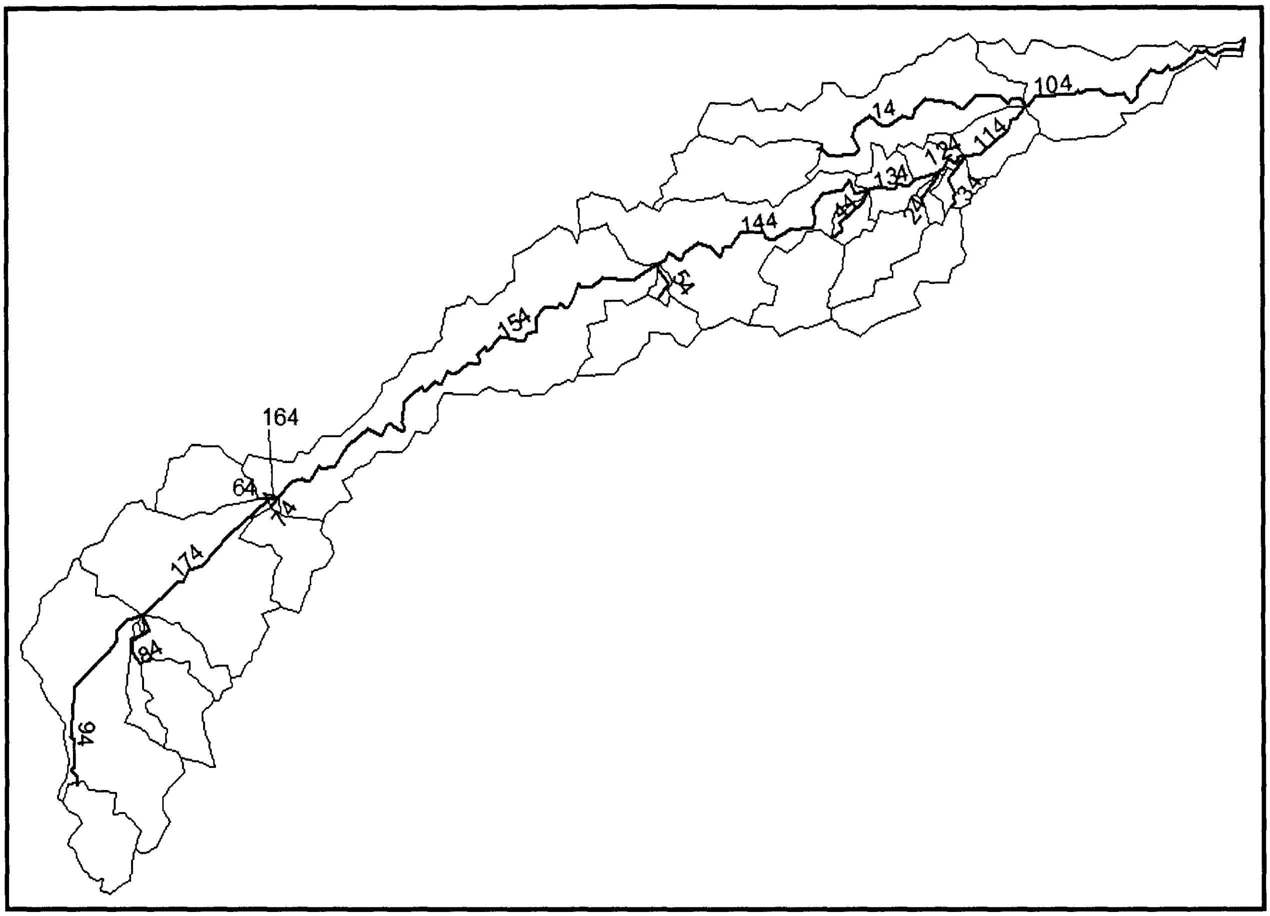

Figure A-2 Sub-basin 3 with channel elements labeled

Parameter File for "Kmin" values: Ks = 22.22mm/hr for planes, 8.4mm/hr for channels

```
! File Info
!  Watershed:        wSub3
!  LandCover:        Resampl_land
!  Soils:            Soil_utm_edit.shp
!  Number of Channels: 17
!  Number of Planes:  39
!  Contrib Source Area: 812 Acres
!  DEM GRid Size:     85.5641 m
!  Total Drainage Area: 32470 Acres (13140 ha)
!  AGWA Version:      beta
!  Creation Date:     04/30/2006 19:28
! End of File Info

BEGIN GLOBAL
 CLEN = 10, UNITS = METRIC
 DIAMS = 0.25, 0.033, 0.004 ! mm
 DENSITY = 2.65, 2.65, 2.65 ! g/cc
 TEMP = 33 !deg C
 NELE = 56
END GLOBAL
```

```
BEGIN PLANE
 ID = 81, LEN = 2378.7, WID = 1384.5
 SL = 0.014, MAN = 0.010, X = 723430.7, Y = 3294990.0
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 82, LEN = 1422.0, WID = 1591.9
 SL = 0.011, MAN = 0.010, X = 723561.6, Y = 3296386.3
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 83, LEN = 744.4, WID = 1591.9
 SL = 0.013, MAN = 0.010, X = 722324.0, Y = 3295787.4
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 84, PRINT = 1
 LAT =  82 83
 UP =  81
 LEN = 1591.86, SLOPE = 0.005, X = 722329.121, Y = 3296937.086
 WIDTH = 10.51, 13.55, DEPTH = 0.49, 0.55
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 91, LEN = 2297.5, WID = 1505.6
 SL = 0.011, MAN = 0.010, X = 721477.8, Y = 3291796.9
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 92, LEN = 1552.2, WID = 5362.6
 SL = 0.010, MAN = 0.010, X = 722108.5, Y = 3294437.4
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
```

```
END PLANE

BEGIN PLANE
 ID = 93, LEN = 1136.1, WID = 5362.6
 SL = 0.012, MAN = 0.010, X = 720378.6, Y = 3295836.8
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 94, PRINT = 1
 LAT =  92 93
 UP =  91
 LEN = 5362.64, SLOPE = 0.0020, X = 720724.410, Y = 3295704.007
 WIDTH = 10.70, 19.09, DEPTH = 0.50, 0.64
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 172, LEN = 1573.1, WID = 4539.8
 SL = 0.012, MAN = 0.010, X = 724321.8, Y = 3298183.1
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 173, LEN = 1502.4, WID = 4539.8
 SL = 0.012, MAN = 0.010, X = 723320.7, Y = 3298763.5
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 174, PRINT = 1
 LAT =  172 173
 UP =  84 94
 LEN = 4539.84, SLOPE = 0.0020, X = 724154.366, Y = 3298890.001
 WIDTH = 21.34, 24.97, DEPTH = 0.67, 0.72
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
```

```
 ID = 61, LEN = 2051.4, WID = 1635.5
 SL = 0.014, MAN = 0.010, X = 724160.9, Y = 3300900.8
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 64, PRINT = 1
 UP =  61
 LEN = 299.47, SLOPE = 0.0020, X = 725614.070, Y = 3300486.712
 WIDTH = 10.58, 10.58, DEPTH = 0.50, 0.50
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN CHANNEL
 ID = 164, PRINT = 1
 UP =  64 174
 LEN = 270.58, SLOPE = 0.0020, X = 725892.153, Y = 3300529.495
 WIDTH = 25.70, 25.70, DEPTH = 0.73, 0.73
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 71, LEN = 2144.0, WID = 1527.3
 SL = 0.013, MAN = 0.010, X = 726253.7, Y = 3298915.2
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 72, LEN = 186.2, WID = 368.0
 SL = 0.011, MAN = 0.010, X = 725951.8, Y = 3300322.3
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 73, LEN = 79.6, WID = 368.0
 SL = 0.002, MAN = 0.010, X = 725892.2, Y = 3300422.5
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
```

```
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 74, PRINT = 1
 LAT =  72 73
 UP =  71
 LEN = 368.02, SLOPE = 0.0020, X = 725913.544, Y = 3300422.539
 WIDTH = 10.49, 10.60, DEPTH = 0.49, 0.50
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 152, LEN = 764.2, WID = 14167.3
 SL = 0.010, MAN = 0.010, X = 730940.4, Y = 3303188.6
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 153, LEN = 808.7, WID = 14167.3
 SL = 0.009, MAN = 0.010, X = 730475.9, Y = 3303988.1
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 154, PRINT = 1
 LAT =  152 153
 UP =  164 74
 LEN = 14167.34, SLOPE = 0.0020, X = 730681.821, Y = 3303747.403
 WIDTH = 26.40, 30.34, DEPTH = 0.74, 0.78
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 51, LEN = 1571.4, WID = 2276.8
 SL = 0.009, MAN = 0.010, X = 735423.5, Y = 3304607.1
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE
```

```
BEGIN PLANE
 ID = 52, LEN = 190.8, WID = 1086.7
 SL = 0.009, MAN = 0.010, X = 736158.3, Y = 3305908.5
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 53, LEN = 150.7, WID = 1086.7
 SL = 0.008, MAN = 0.010, X = 735855.9, Y = 3306027.0
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 54, PRINT = 1
 LAT =  52 53
 UP =  51
 LEN = 1086.74, SLOPE = 0.0010, X = 736083.713, Y = 3306007.277
 WIDTH = 10.83, 11.21, DEPTH = 0.50, 0.51
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 142, LEN = 796.7, WID = 7640.3
 SL = 0.009, MAN = 0.010, X = 738598.4, Y = 3306696.8
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 143, LEN = 927.7, WID = 7640.3
 SL = 0.009, MAN = 0.010, X = 737570.3, Y = 3307634.3
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 144, PRINT = 1
 LAT =  142 143
 UP =  54 154
 LEN = 7640.32, SLOPE = 0.0020, X = 738706.032, Y = 3307149.686
 WIDTH = 30.95, 32.82, DEPTH = 0.79, 0.81
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
```

```
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 41, LEN = 2171.0, WID = 1886.4
 SL = 0.008, MAN = 0.010, X = 739487.8, Y = 3305957.3
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 42, LEN = 398.8, WID = 1730.9
 SL = 0.008, MAN = 0.010, X = 740968.3, Y = 3307638.0
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 43, LEN = 127.2, WID = 1730.9
 SL = 0.009, MAN = 0.010, X = 740667.8, Y = 3307738.3
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 44, PRINT = 1
 LAT =  42 43
 UP =  41
 LEN = 1730.87, SLOPE = 0.0030, X = 740798.787, Y = 3307702.162
 WIDTH = 11.36, 12.20, DEPTH = 0.51, 0.53
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 132, LEN = 486.4, WID = 1951.9
 SL = 0.009, MAN = 0.010, X = 742192.1, Y = 3308151.4
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
```

```
 ID = 133, LEN = 509.3, WID = 1951.9
 SL = 0.008, MAN = 0.010, X = 741772.2, Y = 3308941.2
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 134, PRINT = 1
 LAT =  132 133
 UP =  44 144
 LEN = 1951.94, SLOPE = 0.0020, X = 742180.328, Y = 3308505.142
 WIDTH = 33.48, 33.73, DEPTH = 0.82, 0.82
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 21, LEN = 2577.5, WID = 1308.4
 SL = 0.010, MAN = 0.010, X = 741618.0, Y = 3306728.7
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 22, LEN = 472.9, WID = 917.6
 SL = 0.006, MAN = 0.010, X = 743000.5, Y = 3308097.7
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 23, LEN = 60.5, WID = 917.6
 SL = 0.010, MAN = 0.010, X = 742889.6, Y = 3308422.8
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 24, PRINT = 1
 LAT =  22 23
 UP =  21
 LEN = 917.63, SLOPE = 0.0030, X = 742917.055, Y = 3308441.352
 WIDTH = 10.60, 11.13, DEPTH = 0.50, 0.51
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
```

```
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 122, LEN = 118.8, WID = 1053.6
 SL = 0.006, MAN = 0.010, X = 743432.8, Y = 3308964.2
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 123, LEN = 787.3, WID = 1053.6
 SL = 0.008, MAN = 0.010, X = 742957.7, Y = 3309093.5
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 124, PRINT = 1
 LAT =  122 123
 UP =  134 24
 LEN = 1053.62, SLOPE = 0.0020, X = 743414.134, Y = 3309116.621
 WIDTH = 34.21, 34.33, DEPTH = 0.82, 0.83
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 31, LEN = 3153.6, WID = 1235.0
 SL = 0.010, MAN = 0.010, X = 742129.3, Y = 3306238.5
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 32, LEN = 400.2, WID = 1612.6
 SL = 0.011, MAN = 0.010, X = 743898.9, Y = 3308536.4
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 33, LEN = 207.4, WID = 1612.6
```

```
 SL = 0.010, MAN = 0.010, X = 743369.5, Y = 3308408.0
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 34, PRINT = 1
 LAT =  32 33
 UP =  31
 LEN = 1612.55, SLOPE = 0.0030, X = 743421.412, Y = 3308552.490
 WIDTH = 11.16, 12.08, DEPTH = 0.51, 0.52
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 112, LEN = 704.2, WID = 2129.8
 SL = 0.011, MAN = 0.010, X = 744797.3, Y = 3309536.9
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 113, LEN = 599.7, WID = 2129.8
 SL = 0.010, MAN = 0.010, X = 744112.8, Y = 3309856.0
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 114, PRINT = 1
 LAT =  112 113
 UP =  124 34
 LEN = 2129.81, SLOPE = 0.0030, X = 744718.728, Y = 3309713.758
 WIDTH = 34.92, 35.25, DEPTH = 0.83, 0.83
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 11, LEN = 3200.3, WID = 1729.6
 SL = 0.008, MAN = 0.010, X = 737967.1, Y = 3308771.0
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
```

```
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 12, LEN = 516.3, WID = 7171.1
 SL = 0.009, MAN = 0.010, X = 742553.2, Y = 3309648.7
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 13, LEN = 1241.5, WID = 7171.1
 SL = 0.009, MAN = 0.010, X = 743388.9, Y = 3310790.8
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 14, PRINT = 1
 LAT =  12 13
 UP =  11
 LEN = 7171.11, SLOPE = 0.0020, X = 742457.010, Y = 3310180.077
 WIDTH = 12.64, 19.18, DEPTH = 0.53, 0.64
 MAN = 0.035, SS1 = 1.00, SS2 = 1.00
 WOOL = Yes
 CV = 0.00, KSAT = 8.4, G = 101
 DIST = 0.5450, POR = 0.4400, ROCK = 0.00
 FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

BEGIN PLANE
 ID = 102, LEN = 531.7, WID = 7388.4
 SL = 0.011, MAN = 0.010, X = 748683.5, Y = 3310927.5
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN PLANE
 ID = 103, LEN = 705.1, WID = 7388.4
 SL = 0.011, MAN = 0.010, X = 747591.8, Y = 3311374.7
 CV = 1.00, PRINT = 1
 KS = 22.22, G = 115.60, DIST = 0.30, POR = 0.459, ROCK = 0.23
 FR = 0.46, 0.31, 0.23, SPLASH = 128.29, COH = 0.008, SMAX = 0.93
 INTER = 0.00, CANOPY = 0, PAVE = 0.00
END PLANE

BEGIN CHANNEL
 ID = 104, PRINT = 3, FILE = c:\kuwav\agwa2\simulations\S3_20_5_90\\kmin.sim
 LAT =  102 103
```

UP = 14 114
LEN = 7388.44, SLOPE = 0.0030, X = 748267.159, Y = 3311004.562
WIDTH = 37.27, 38.21, DEPTH = 0.86, 0.86
MAN = 0.035, SS1 = 1.00, SS2 = 1.00
WOOL = Yes
CV = 0.00, KSAT = 8.4, G = 101
DIST = 0.5450, POR = 0.4400, ROCK = 0.00
FR = 0.9000, 0.0500, 0.0500, SP = 63.00, COH = 0.0050
END CHANNEL

A.3 Sample KINEROS2 Output File

Output file for Sub-basin 3, 10mm, 10hr, 90% saturation storm. Ks = 0.044cm/hr for plane elements, 0.0168cm/hr for channel elements.

KINEROS2 Version 3.2 (Dec 2003)

```
Title:

Parameter File Used....... s3_kc.par
Rainfall File Used........ 10_10_90_1min.pre

Length of Run, minutes.... 800
Time Step, minutes........ 1
Use Courant criteria?..... Y
Simulate Sed. Transport?.. Y
Multiplier file (if any).. N
Tabular Summary?.......... Y
API Initializing?......... N

Multipliers Used:

Saturated Conductivity... 1.0
Manning n................ 1.0
CV of Ksat............... 1.0
Capillary Drive Coeff.... 1.0
Intercepted Depth........ 1.0
Sediment Cohesion Coeff.. 1.0
Sediment Splash Coeff.... 1.0


 Plane  81:  based on length and parameter CLEN,
 the numerical increment of  169.9 m. is too large for
 realistic numerical solution of the flow equation, and may
 give  misleading results.

Plane Element   81

Contributing area = 329.3310 ha


                                        theta   rel.sat.
 surface initial water content =        0.3986  0.9000
 estimated wilting point water content = 0.1025  0.1088
 estimated field capacity =             0.1902  0.3430

Peak flow = 2.421263 cu m /s (2.646743 mm/hr) at 357.0 min

Peak sediment discharge = 5.196627 kg/s at  367.0 min

          Water balance                   Sediment balance
-----------------------------------      -----------------------
  Rain:  32933.10 cu m   9.999999 mm          In:       0.00 kg
Inflow:      0.00 cu m   0.000000 mm     Deposited:  -25204.23 kg
```

Infilt: 17777.12 cu m 5.397948 mm Suspended: 0.00 kg
Stored: 1.22 cu m 0.000371 mm Out: 25182.29 kg
Out: 14608.52 cu m 4.435816 mm Error: 0.09 %
Error: 1.66 %

Plane 82: based on length and parameter CLEN,
the numerical increment of 101.6 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 82

Contributing area = 226.3682 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 2.315336 cu m /s (3.682148 mm/hr) at 339.0 min

Peak sediment discharge = 2.572440 kg/s at 346.0 min

Water balance			Sediment balance	
Rain:	22636.82 cu m	9.999999 mm	In:	0.000 kg
Inflow:	0.00 cu m	0.000000 mm	Deposited:	-9753.706 kg
Infilt:	12184.24 cu m	5.382489 mm	Suspended:	0.000 kg
Stored:	0.07 cu m	0.000030 mm	Out:	9725.771 kg
Out:	10327.98 cu m	4.562470 mm	Error:	0.29 %
Error:	0.55 %			

Plane 83: based on length and parameter CLEN,
the numerical increment of 53.2 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 83

Contributing area = 118.5010 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 2.138844 cu m /s (6.497699 mm/hr) at 317.0 min

Peak sediment discharge = 2.764390 kg/s at 324.0 min

Water balance			Sediment balance	
Rain:	11850.10 cu m	10.00000 mm	In:	0.000 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-6246.393 kg

```
Infilt:   6099.63 cu m    5.14732 mm        Suspended:     0.000 kg
Stored:       3.87 cu m    0.00327 mm            Out:  6225.354 kg
  Out:   5593.07 cu m    4.71985 mm          Error:       0.34 %
 Error:      1.30 %
```

Channel 84: based on length and parameter CLEN,
the numerical increment of 113.7 m is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Channel Elem. 84

Contributing area = 674.2003 ha

```
                                          theta   rel.sat.
 surface initial water content =         0.3819   0.9000
 estimated wilting point water content = 0.0638   0.0179
 estimated field capacity =              0.1092   0.1437
```

Peak flow = 5.774152 cu m /s (3.083201 mm/hr) at 331.0 min

Peak sediment discharge = 17.08890 kg/s at 340.0 min

```
      Water balance              Sediment balance
 -------------------------    ------------------------
  Rain:      0.00 cu m          In:   41133.43 kg
 Inflow:  30529.70 cu m      Deposited:  -49537.17 kg
 Infilt:     69.42 cu m     Suspended:      57.59 kg
 Stored:     61.54 cu m         Out:   90605.80 kg
   Out:   30405.31 cu m       Error:       0.01 %
  Error:     -0.02 %
```

Plane 91: based on length and parameter CLEN,
the numerical increment of 164.1 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 91

Contributing area = 345.9116 ha

```
                                          theta   rel.sat.
 surface initial water content =         0.3986   0.9000
 estimated wilting point water content = 0.1025   0.1088
 estimated field capacity =              0.1902   0.3430
```

Peak flow = 2.352134 cu m /s (2.447933 mm/hr) at 363.0 min

Peak sediment discharge = 3.082487 kg/s at 370.0 min

```
          Water balance                         Sediment balance
 -------------------------------------     ------------------------
  Rain:  34591.16 cu m    10.00000 mm             In:       0.00 kg
 Inflow:      0.00 cu m    0.00000 mm       Deposited:  -16932.44 kg
```

Infilt: 18987.27 cu m 5.48905 mm Suspended: 0.00 kg
Stored: 0.74 cu m 0.00022 mm Out: 16906.44 kg
Out: 15185.75 cu m 4.39007 mm Error: 0.15 %
Error: 1.21 %

Plane 92: based on length and parameter CLEN,
the numerical increment of 110.9 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 92

Contributing area = 832.3828 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 7.613105 cu m /s (3.292618 mm/hr) at 345.0 min

Peak sediment discharge = 7.623106 kg/s at 351.0 min

Water balance			Sediment balance	
Rain:	83238.27 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-31710.30 kg
Infilt:	45245.40 cu m	5.43565 mm	Suspended:	0.00 kg
Stored:	0.78 cu m	0.00009 mm	Out:	31621.60 kg
Out:	37657.81 cu m	4.52410 mm	Error:	0.28 %
Error:	0.40 %			

Plane 93: based on length and parameter CLEN,
the numerical increment of 81.2 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 93

Contributing area = 609.2450 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 7.691439 cu m /s (4.544835 mm/hr) at 329.0 min

Peak sediment discharge = 9.772564 kg/s at 336.0 min

Water balance			Sediment balance	
Rain:	60924.50 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-29604.25 kg

Infilt:	31954.99 cu m	5.24501 mm	Suspended: 0.00 kg
Stored:	14.21 cu m	0.00233 mm	Out: 29491.44 kg
Out:	28210.39 cu m	4.63039 mm	Error: 0.38 %
Error:	1.22 %		

Channel 94: based on length and parameter CLEN,
the numerical increment of 383.0 m is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Channel Elem. 94

Contributing area = 1787.539 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 11.39872 cu m /s (2.295636 mm/hr) at 383.0 min

Peak sediment discharge = 15.93370 kg/s at 387.0 min

Water balance		Sediment balance	
Rain:	0.00 cu m	In:	78019.4 kg
Inflow:	81053.73 cu m	Deposited:	-26749.6 kg
Infilt:	415.49 cu m	Suspended:	1625.1 kg
Stored:	2158.02 cu m	Out:	102749.9 kg
Out:	78648.70 cu m	Error:	0.38 %
Error:	-0.21 %		

Plane 172: based on length and parameter CLEN,
the numerical increment of 112.4 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 172

Contributing area = 714.1559 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 6.971801 cu m /s (3.514426 mm/hr) at 341.0 min

Peak sediment discharge = 10.10341 kg/s at 332.0 min

Water balance			Sediment balance	
Rain:	71415.59 cu m	9.999999 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.000000 mm	Deposited:	-38166.30 kg

Infilt:	37735.72 cu m 5.283961 mm	Suspended:	0.00 kg
Stored:	29.85 cu m 0.004180 mm	Out:	38082.89 kg
Out:	32467.18 cu m 4.546231 mm	Error:	0.22 %
Error:	1.66 %		

Plane 173: based on length and parameter CLEN,
the numerical increment of 107.3 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 173

Contributing area = 682.0596 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 6.909448 cu m /s (3.646897 mm/hr) at 340.0 min

Peak sediment discharge = 9.010261 kg/s at 347.0 min

Water balance			Sediment balance	
Rain:	68205.95 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-34602.39 kg
Infilt:	37345.29 cu m	5.47537 mm	Suspended:	0.00 kg
Stored:	1.39 cu m	0.00020 mm	Out:	34484.37 kg
Out:	31097.18 cu m	4.55931 mm	Error:	0.34 %
Error:	-0.35 %			

Channel 174: based on length and parameter CLEN,
the numerical increment of 324.3 m is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Channel Elem. 174

Contributing area = 3857.955 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 17.32975 cu m /s (1.617103 mm/hr) at 427.0 min

Peak sediment discharge = 34.75182 kg/s at 428.0 min

Water balance		Sediment balance	
Rain:	0.0 cu m	In:	265922.8 kg
Inflow:	172628.5 cu m	Deposited:	-9698.6 kg

Infilt:	672.7 cu m	Suspended:	7114.4 kg
Stored:	7566.7 cu m	Out:	268275.7 kg
Out:	164370.1 cu m	Error:	0.08 %
Error:	0.01 %		

Plane 61: based on length and parameter CLEN,
the numerical increment of 146.5 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 61

Contributing area = 335.5064 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 2.800225 cu m /s (3.004655 mm/hr) at 350.0 min

Peak sediment discharge = 5.483071 kg/s at 356.0 min

Water balance			Sediment balance	
Rain:	33550.64 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-24481.73 kg
Infilt:	18012.50 cu m	5.36875 mm	Suspended:	0.00 kg
Stored:	10.98 cu m	0.00327 mm	Out:	24438.73 kg
Out:	15054.79 cu m	4.48719 mm	Error:	0.18 %
Error:	1.41 %			

Channel Elem. 64

Contributing area = 335.5064 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 2.791869 cu m /s (2.995689 mm/hr) at 354.3 min

Peak sediment discharge = 5.123752 kg/s at 350.7 min

Water balance		Sediment balance	
Rain:	0.00 cu m	In:	24436.59 kg
Inflow:	15054.73 cu m	Deposited:	1194.46 kg
Infilt:	12.57 cu m	Suspended:	0.05 kg
Stored:	1.71 cu m	Out:	23228.14 kg
Out:	15072.51 cu m	Error:	0.06 %
Error:	-0.21 %		

Channel Elem. 164

Contributing area = 4193.461 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 17.98918 cu m /s (1.544333 mm/hr) at 394.2 min

Peak sediment discharge = 35.95527 kg/s at 430.6 min

Water balance		Sediment balance	
Rain:	0.0 cu m	In:	291502.2 kg
Inflow:	179480.3 cu m	Deposited:	-3186.8 kg
Infilt:	45.7 cu m	Suspended:	638.4 kg
Stored:	669.3 cu m	Out:	293993.2 kg
Out:	178856.8 cu m	Error:	0.02 %
Error:	-0.05 %		

Plane 71: based on length and parameter CLEN,
the numerical increment of 153.1 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 71

Contributing area = 327.4531 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 2.550051 cu m /s (2.803510 mm/hr) at 353.0 min

Peak sediment discharge = 4.830949 kg/s at 362.0 min

Water balance			Sediment balance	
Rain:	32745.31 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-21416.76 kg
Infilt:	17884.89 cu m	5.46182 mm	Suspended:	0.00 kg
Stored:	1.85 cu m	0.00056 mm	Out:	21379.00 kg
Out:	14602.97 cu m	4.45956 mm	Error:	0.18 %
Error:	0.78 %			

Plane Element 72

Contributing area = 6.852160 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 0.2942422 cu m /s (15.45895 mm/hr) at 304.0 min

Peak sediment discharge = 0.2325732 kg/s at 304.0 min

Water balance			Sediment balance	
Rain:	685.2160 cu m	10.00000 mm	In:	0.0000 kg
Inflow:	0.0000 cu m	0.00000 mm	Deposited:	-208.0591 kg
Infilt:	352.3257 cu m	5.14182 mm	Suspended:	0.0000 kg
Stored:	0.0000 cu m	0.00000 mm	Out:	207.9873 kg
Out:	331.6729 cu m	4.84041 mm	Error:	0.03 %
Error:	0.18 %			

Plane Element 73

Contributing area = 2.929280 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 0.1256148 cu m /s (15.43769 mm/hr) at 304.0 min

Peak sediment discharge = 0.0279667 kg/s at 304.0 min

Water balance			Sediment balance	
Rain:	292.9280 cu m	10.00000 mm	In:	0.00000 kg
Inflow:	0.0000 cu m	0.00000 mm	Deposited:	-26.64286 kg
Infilt:	150.6343 cu m	5.14237 mm	Suspended:	0.00000 kg
Stored:	0.0000 cu m	0.00000 mm	Out:	26.50294 kg
Out:	141.7846 cu m	4.84025 mm	Error:	0.53 %
Error:	0.17 %			

Channel Elem. 74

Contributing area = 337.2346 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 2.558788 cu m /s (2.731522 mm/hr) at 359.8 min

Peak sediment discharge = 4.022919 kg/s at 371.5 min

Water balance Sediment balance

Water balance		Sediment balance	
Rain:	0.00 cu m	In:	21611.60 kg
Inflow:	15077.56 cu m	Deposited:	354.45 kg
Infilt:	15.50 cu m	Suspended:	0.14 kg
Stored:	2.95 cu m	Out:	21267.82 kg
Out:	15072.02 cu m	Error:	-0.05 %
Error:	-0.09 %		

Plane 152: based on length and parameter CLEN, the numerical increment of 54.6 m. is too large for realistic numerical solution of the flow equation, and may give misleading results.

Plane Element 152

Contributing area = 1082.665 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 17.30617 cu m /s (5.754522 mm/hr) at 322.0 min

Peak sediment discharge = 14.39792 kg/s at 327.0 min

Water balance			Sediment balance	
Rain:	108266.5 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.0 cu m	0.00000 mm	Deposited:	-36374.64 kg
Infilt:	56470.1 cu m	5.21585 mm	Suspended:	0.00 kg
Stored:	36.0 cu m	0.00332 mm	Out:	36226.93 kg
Out:	50836.3 cu m	4.69548 mm	Error:	0.41 %
Error:	0.85 %			

Plane 153: based on length and parameter CLEN, the numerical increment of 57.8 m. is too large for realistic numerical solution of the flow equation, and may give misleading results.

Plane Element 153

Contributing area = 1145.710 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 16.86701 cu m /s (5.299880 mm/hr) at 324.0 min

Peak sediment discharge = 11.61342 kg/s at 330.0 min

Water balance Sediment balance

Rain:	114571.0 cu m	10.00000 mm	In: 0.00 kg
Inflow:	0.0 cu m	0.00000 mm	Deposited: -32477.17 kg
Infilt:	59088.1 cu m	5.15734 mm	Suspended: 0.00 kg
Stored:	43.7 cu m	0.00382 mm	Out: 32284.72 kg
Out:	53588.6 cu m	4.67733 mm	Error: 0.59 %
Error:	1.62 %		

Channel 154: based on length and parameter CLEN, the numerical increment of 1012.0 m is too large for realistic numerical solution of the flow equation, and may give misleading results.

Channel Elem. 154

Contributing area = 6759.070 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 18.42146 cu m /s (0.9811594 mm/hr) at 572.0 min

Peak sediment discharge = 33.98930 kg/s at 584.0 min

Water balance		Sediment balance	
Rain:	0.0 cu m	In:	383774.0 kg
Inflow:	298397.0 cu m	Deposited:	-42995.4 kg
Infilt:	2872.4 cu m	Suspended:	89585.8 kg
Stored:	78266.1 cu m	Out:	331682.9 kg
Out:	217981.0 cu m	Error:	1.29 %
Error:	-0.24 %		

Plane 51: based on length and parameter CLEN, the numerical increment of 112.2 m. is too large for realistic numerical solution of the flow equation, and may give misleading results.

Plane Element 51

Contributing area = 357.7764 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 3.107124 cu m /s (3.126435 mm/hr) at 347.0 min

Peak sediment discharge = 2.566077 kg/s at 354.0 min

Water balance Sediment balance

Water balance			Sediment balance	
Rain:	35777.64 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-11277.31 kg
Infilt:	19366.96 cu m	5.41315 mm	Suspended:	0.00 kg
Stored:	2.05 cu m	0.00057 mm	Out:	11241.85 kg
Out:	16124.16 cu m	4.50677 mm	Error:	0.31 %
Error:	0.80 %			

Plane Element 52

Contributing area = 20.73424 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 0.8289406 cu m /s (14.39255 mm/hr) at 304.5 min

Peak sediment discharge = 0.5000398 kg/s at 304.5 min

Water balance			Sediment balance	
Rain:	2073.424 cu m	10.00000 mm	In:	0.0000 kg
Inflow:	0.000 cu m	0.00000 mm	Deposited:	-506.0495 kg
Infilt:	1029.167 cu m	4.96361 mm	Suspended:	0.0000 kg
Stored:	0.981 cu m	0.00473 mm	Out:	502.4850 kg
Out:	1003.076 cu m	4.83778 mm	Error:	0.70 %
Error:	1.94 %			

Plane Element 53

Contributing area = 16.37657 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 0.7225794 cu m /s (15.88420 mm/hr) at 304.0 min

Peak sediment discharge = 0.3889253 kg/s at 304.0 min

Water balance			Sediment balance	
Rain:	1637.657 cu m	10.00000 mm	In:	0.0000 kg
Inflow:	0.000 cu m	0.00000 mm	Deposited:	-360.5854 kg
Infilt:	842.424 cu m	5.14408 mm	Suspended:	0.0000 kg
Stored:	0.000 cu m	0.00000 mm	Out:	359.6130 kg
Out:	793.165 cu m	4.84329 mm	Error:	0.27 %
Error:	0.13 %			

Channel 54: based on length and parameter CLEN,

the numerical increment of 77.6 m is too large for realistic numerical solution of the flow equation, and may give misleading results.

Channel Elem. 54

Contributing area = 394.8872 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 3.102712 cu m /s (2.828596 mm/hr) at 368.0 min

Peak sediment discharge = 1.952368 kg/s at 370.0 min

Water balance		Sediment balance	
Rain:	0.00 cu m	In:	12103.93 kg
Inflow:	17923.72 cu m	Deposited:	1786.86 kg
Infilt:	55.43 cu m	Suspended:	10.35 kg
Stored:	64.36 cu m	Out:	10277.33 kg
Out:	17818.10 cu m	Error:	0.24 %
Error:	-0.08 %		

Plane 142: based on length and parameter CLEN, the numerical increment of 56.9 m. is too large for realistic numerical solution of the flow equation, and may give misleading results.

Plane Element 142

Contributing area = 608.7027 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 9.063037 cu m /s (5.360077 mm/hr) at 323.0 min

Peak sediment discharge = 6.247384 kg/s at 330.0 min

Water balance			Sediment balance	
Rain:	60870.27 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-17241.08 kg
Infilt:	31298.33 cu m	5.14181 mm	Suspended:	0.00 kg
Stored:	24.98 cu m	0.00410 mm	Out:	17148.02 kg
Out:	28494.87 cu m	4.68125 mm	Error:	0.54 %
Error:	1.73 %			

Plane 143: based on length and parameter CLEN,

the numerical increment of 66.3 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 143

Contributing area = 708.7906 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 9.371232 cu m /s (4.759718 mm/hr) at 328.0 min

Peak sediment discharge = 6.548470 kg/s at 335.0 min

Water balance			Sediment balance	
Rain:	70879.05 cu m	9.999999 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.000000 mm	Deposited:	-20350.06 kg
Infilt:	36846.68 cu m	5.198528 mm	Suspended:	0.00 kg
Stored:	1.86 cu m	0.000262 mm	Out:	20242.85 kg
Out:	32936.67 cu m	4.646883 mm	Error:	0.53 %
Error:	1.54 %			

Channel 144: based on length and parameter CLEN,
the numerical increment of 545.7 m is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Channel Elem. 144

Contributing area = 8471.450 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 17.58935 cu m /s (0.7474715 mm/hr) at 672.0 min

Peak sediment discharge = 28.69549 kg/s at 690.0 min

Water balance		Sediment balance	
Rain:	0.0 cu m	In:	379350.9 kg
Inflow:	297531.8 cu m	Deposited:	-18508.0 kg
Infilt:	1662.6 cu m	Suspended:	121595.4 kg
Stored:	86014.7 cu m	Out:	273782.3 kg
Out:	209479.0 cu m	Error:	0.62 %
Error:	0.13 %		

Plane 41: based on length and parameter CLEN,

the numerical increment of 155.1 m. is too large for realistic numerical solution of the flow equation, and may give misleading results.

Plane Element 41

Contributing area = 409.5374 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 2.533267 cu m /s (2.226845 mm/hr) at 369.0 min

Peak sediment discharge = 2.043011 kg/s at 378.0 min

Water balance			Sediment balance	
Rain:	40953.74 cu m	9.999999 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.000000 mm	Deposited:	-11718.79 kg
Infilt:	22938.60 cu m	5.601099 mm	Suspended:	0.00 kg
Stored:	0.45 cu m	0.000111 mm	Out:	11656.94 kg
Out:	17749.86 cu m	4.334123 mm	Error:	0.53 %
Error:	0.65 %			

Plane Element 42

Contributing area = 69.02830 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 1.649034 cu m /s (8.600129 mm/hr) at 311.0 min

Peak sediment discharge = 0.8717275 kg/s at 310.0 min

Water balance			Sediment balance	
Rain:	6902.829 cu m	10.00000 mm	In:	0.000 kg
Inflow:	0.000 cu m	0.00000 mm	Deposited:	-1574.936 kg
Infilt:	3495.458 cu m	5.06381 mm	Suspended:	0.000 kg
Stored:	3.606 cu m	0.00522 mm	Out:	1566.824 kg
Out:	3294.444 cu m	4.77260 mm	Error:	0.52 %
Error:	1.58 %			

Plane Element 43

Contributing area = 22.01705 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000

estimated wilting point water content = 0.1025 0.1088
estimated field capacity = 0.1902 0.3430

Peak flow = 1.100446 cu m /s (17.99336 mm/hr) at 303.0 min

Peak sediment discharge = 0.6713018 kg/s at 303.2 min

Water balance			Sediment balance	
Rain:	2201.705 cu m	10.00000 mm	In:	0.0000 kg
Inflow:	0.000 cu m	0.00000 mm	Deposited:	-526.1325 kg
Infilt:	1107.479 cu m	5.03010 mm	Suspended:	0.0000 kg
Stored:	0.723 cu m	0.00329 mm	Out:	522.0557 kg
Out:	1069.073 cu m	4.85566 mm	Error:	0.77 %
Error:	1.11 %			

Channel 44: based on length and parameter CLEN,
the numerical increment of 123.6 m is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Channel Elem. 44

Contributing area = 500.5828 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 2.863536 cu m /s (2.059346 mm/hr) at 339.0 min

Peak sediment discharge = 4.111588 kg/s at 394.0 min

Water balance		Sediment balance	
Rain:	0.00 cu m	In:	13746.43 kg
Inflow:	22114.64 cu m	Deposited:	-15781.81 kg
Infilt:	82.12 cu m	Suspended:	53.83 kg
Stored:	121.05 cu m	Out:	29467.06 kg
Out:	21921.29 cu m	Error:	0.02 %
Error:	-0.04 %		

Plane 132: based on length and parameter CLEN,
the numerical increment of 34.7 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 132

Contributing area = 94.94042 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000

estimated wilting point water content = 0.1025 0.1088
estimated field capacity = 0.1902 0.3430

Peak flow = 2.052848 cu m /s (7.784096 mm/hr) at 313.0 min

Peak sediment discharge = 1.293478 kg/s at 312.0 min

Water balance			Sediment balance	
Rain:	9494.042 cu m	10.00000 mm	In:	0.000 kg
Inflow:	0.000 cu m	0.00000 mm	Deposited:	-2555.091 kg
Infilt:	4899.088 cu m	5.16017 mm	Suspended:	0.000 kg
Stored:	0.462 cu m	0.00049 mm	Out:	2542.662 kg
Out:	4514.848 cu m	4.75545 mm	Error:	0.49 %
Error:	0.84 %			

Plane 133: based on length and parameter CLEN,
the numerical increment of 36.4 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 133

Contributing area = 99.41027 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 1.990489 cu m /s (7.208268 mm/hr) at 314.0 min

Peak sediment discharge = 1.063637 kg/s at 314.0 min

Water balance			Sediment balance	
Rain:	9941.026 cu m	9.999999 mm	In:	0.000 kg
Inflow:	0.000 cu m	0.000000 mm	Deposited:	-2334.691 kg
Infilt:	5247.147 cu m	5.278275 mm	Suspended:	0.000 kg
Stored:	0.415 cu m	0.000417 mm	Out:	2323.588 kg
Out:	4716.025 cu m	4.744002 mm	Error:	0.48 %
Error:	-0.23 %			

Channel 134: based on length and parameter CLEN,
the numerical increment of 139.4 m is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Channel Elem. 134

Contributing area = 9166.385 ha

theta rel.sat.

surface initial water content = 0.3819 0.9000
estimated wilting point water content = 0.0638 0.0179
estimated field capacity = 0.1092 0.1437

Peak flow = 17.52310 cu m /s (0.6882011 mm/hr) at 696.0 min

Peak sediment discharge = 28.03535 kg/s at 714.0 min

Water balance		Sediment balance	
Rain:	0.0 cu m	In:	308115.4 kg
Inflow:	241194.5 cu m	Deposited:	-6797.2 kg
Infilt:	428.7 cu m	Suspended:	42480.3 kg
Stored:	27842.0 cu m	Out:	272210.5 kg
Out:	212335.9 cu m	Error:	0.07 %
Error:	0.24 %		

Plane 21: based on length and parameter CLEN,
the numerical increment of 184.1 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 21

Contributing area = 337.2401 ha

theta rel.sat.
surface initial water content = 0.3986 0.9000
estimated wilting point water content = 0.1025 0.1088
estimated field capacity = 0.1902 0.3430

Peak flow = 1.968610 cu m /s (2.101469 mm/hr) at 373.0 min

Peak sediment discharge = 2.360112 kg/s at 384.0 min

Water balance			Sediment balance	
Rain:	33724.01 cu m	9.999999 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.000000 mm	Deposited:	-14219.72 kg
Infilt:	19015.73 cu m	5.638632 mm	Suspended:	0.00 kg
Stored:	0.80 cu m	0.000237 mm	Out:	14176.49 kg
Out:	14497.99 cu m	4.299012 mm	Error:	0.30 %
Error:	0.62 %			

Plane 22: based on length and parameter CLEN,
the numerical increment of 33.8 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 22

Contributing area = 43.39330 ha

theta rel.sat.

surface initial water content = 0.3986 0.9000
estimated wilting point water content = 0.1025 0.1088
estimated field capacity = 0.1902 0.3430

Peak flow = 0.8248998 cu m /s (6.843543 mm/hr) at 316.0 min

Peak sediment discharge = 0.3042211 kg/s at 314.0 min

Water balance			Sediment balance	
Rain:	4339.330 cu m	9.999999 mm	In:	0.0000 kg
Inflow:	0.000 cu m	0.000000 mm	Deposited:	-724.4120 kg
Infilt:	2245.134 cu m	5.173917 mm	Suspended:	0.0000 kg
Stored:	1.771 cu m	0.004082 mm	Out:	719.2847 kg
Out:	2054.120 cu m	4.733727 mm	Error:	0.71 %
Error:	0.88 %			

Plane Element 23

Contributing area = 5.551480 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 0.3977272 cu m /s (25.79164 mm/hr) at 301.2 min

Peak sediment discharge = 0.2982337 kg/s at 301.4 min

Water balance			Sediment balance	
Rain:	555.1479 cu m	10.00000 mm	In:	0.0000 kg
Inflow:	0.0000 cu m	0.00000 mm	Deposited:	-149.0549 kg
Infilt:	273.9124 cu m	4.93404 mm	Suspended:	0.0000 kg
Stored:	0.2581 cu m	0.00465 mm	Out:	148.0900 kg
Out:	271.8668 cu m	4.89719 mm	Error:	0.65 %
Error:	1.64 %			

Channel 24: based on length and parameter CLEN, the numerical increment of 65.5 m is too large for realistic numerical solution of the flow equation, and may give misleading results.

Channel Elem. 24

Contributing area = 386.1849 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 2.245172 cu m /s (2.092940 mm/hr) at 329.0 min

Peak sediment discharge = 3.195452 kg/s at 386.0 min

Water balance		Sediment balance	
Rain:	0.00 cu m	In:	15044.10 kg
Inflow:	16824.73 cu m	Deposited:	-7606.85 kg
Infilt:	37.84 cu m	Suspended:	11.60 kg
Stored:	25.70 cu m	Out:	22636.81 kg
Out:	16764.93 cu m	Error:	0.01 %
Error:	-0.02 %		

Plane Element 122

Contributing area = 12.51677 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 0.5798666 cu m /s (16.67779 mm/hr) at 303.5 min

Peak sediment discharge = 0.2547284 kg/s at 303.0 min

Water balance			Sediment balance	
Rain:	1251.677 cu m	10.00000 mm	In:	0.0000 kg
Inflow:	0.000 cu m	0.00000 mm	Deposited:	-231.3277 kg
Infilt:	641.074 cu m	5.12172 mm	Suspended:	0.0000 kg
Stored:	0.000 cu m	0.00000 mm	Out:	229.9155 kg
Out:	606.492 cu m	4.84544 mm	Error:	0.61 %
Error:	0.33 %			

Plane 123: based on length and parameter CLEN, the numerical increment of 56.2 m. is too large for realistic numerical solution of the flow equation, and may give misleading results.

Plane Element 123

Contributing area = 82.94993 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 1.191090 cu m /s (5.169293 mm/hr) at 325.0 min

Peak sediment discharge = 0.6635588 kg/s at 332.0 min

Water balance			Sediment balance	
Rain:	8294.992 cu m	10.00000 mm	In:	0.000 kg
Inflow:	0.000 cu m	0.00000 mm	Deposited:	-1988.905 kg
Infilt:	4354.965 cu m	5.25011 mm	Suspended:	0.000 kg
Stored:	2.674 cu m	0.00322 mm	Out:	1978.033 kg
Out:	3872.938 cu m	4.66901 mm	Error:	0.55 %
Error:	0.78 %			

Channel 124: based on length and parameter CLEN, the numerical increment of 75.3 m is too large for realistic numerical solution of the flow equation, and may give misleading results.

Channel Elem. 124

Contributing area = 9648.036 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 17.49355 cu m /s (0.6527420 mm/hr) at 709.0 min

Peak sediment discharge = 27.75189 kg/s at 727.5 min

Water balance		Sediment balance	
Rain:	0.0 cu m	In:	297053.8 kg
Inflow:	234226.8 cu m	Deposited:	-4565.7 kg
Infilt:	233.8 cu m	Suspended:	25121.6 kg
Stored:	16113.8 cu m	Out:	276470.0 kg
Out:	217266.9 cu m	Error:	0.01 %
Error:	0.26 %		

Plane 31: based on length and parameter CLEN, the numerical increment of 225.3 m. is too large for realistic numerical solution of the flow equation, and may give misleading results.

Plane Element 31

Contributing area = 389.4696 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 1.859583 cu m /s (1.718876 mm/hr) at 387.0 min

Peak sediment discharge = 2.027349 kg/s at 396.0 min

```
        Water balance                    Sediment balance
--------------------------------------   ------------------------
 Rain:  38946.96 cu m   10.00000 mm          In:      0.00 kg
Inflow:     0.00 cu m   0.00000 mm    Deposited: -15748.60 kg
Infilt: 22243.66 cu m   5.71127 mm    Suspended:      0.00 kg
Stored:    13.42 cu m   0.00345 mm         Out:  15706.27 kg
  Out:  16239.89 cu m   4.16975 mm        Error:      0.27 %
 Error:     1.16 %
```

Plane Element 32

Contributing area = 64.53625 ha

```
                                       theta   rel.sat.
 surface initial water content =        0.3986  0.9000
 estimated wilting point water content = 0.1025  0.1088
 estimated field capacity =            0.1902  0.3430
```

Peak flow = 1.721786 cu m /s (9.604571 mm/hr) at 309.0 min

Peak sediment discharge = 1.488909 kg/s at 309.0 min

```
        Water balance                    Sediment balance
--------------------------------------   ------------------------
 Rain:  6453.625 cu m   10.00000 mm          In:     0.000 kg
Inflow:    0.000 cu m   0.00000 mm    Deposited: -2286.619 kg
Infilt: 3309.530 cu m   5.12817 mm    Suspended:     0.000 kg
Stored:    0.321 cu m   0.00050 mm         Out:  2277.726 kg
  Out:  3090.244 cu m   4.78838 mm        Error:     0.39 %
 Error:     0.83 %
```

Plane Element 33

Contributing area = 33.44532 ha

```
                                       theta   rel.sat.
 surface initial water content =        0.3986  0.9000
 estimated wilting point water content = 0.1025  0.1088
 estimated field capacity =            0.1902  0.3430
```

Peak flow = 1.314109 cu m /s (14.14486 mm/hr) at 304.5 min

Peak sediment discharge = 0.9129270 kg/s at 305.0 min

```
        Water balance                    Sediment balance
--------------------------------------   ------------------------
 Rain:  3344.532 cu m   10.00000 mm          In:    0.0000 kg
Inflow:    0.000 cu m   0.00000 mm    Deposited: -914.7480 kg
Infilt: 1666.248 cu m   4.98201 mm    Suspended:    0.0000 kg
Stored:    0.123 cu m   0.00037 mm         Out:  909.2374 kg
  Out:  1617.217 cu m   4.83541 mm        Error:     0.60 %
 Error:     1.82 %
```

Channel 34: based on length and parameter CLEN, the numerical increment of 115.2 m is too large for realistic numerical solution of the flow equation, and may give misleading results.

Channel Elem. 34

Contributing area = 487.4511 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 2.490829 cu m /s (1.839565 mm/hr) at 336.0 min

Peak sediment discharge = 3.167242 kg/s at 340.0 min

Water balance		Sediment balance	
Rain:	0.00 cu m	In:	18894.26 kg
Inflow:	20950.22 cu m	Deposited:	-10244.46 kg
Infilt:	73.07 cu m	Suspended:	82.41 kg
Stored:	124.26 cu m	Out:	29047.31 kg
Out:	20760.41 cu m	Error:	0.03 %
Error:	-0.04 %		

Plane 112: based on length and parameter CLEN, the numerical increment of 50.3 m. is too large for realistic numerical solution of the flow equation, and may give misleading results.

Plane Element 112

Contributing area = 149.9805 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 2.651961 cu m /s (6.365534 mm/hr) at 318.0 min

Peak sediment discharge = 2.461680 kg/s at 325.0 min

Water balance			Sediment balance	
Rain:	14998.05 cu m	9.999999 mm	In:	0.000 kg
Inflow:	0.00 cu m	0.000000 mm	Deposited:	-5849.432 kg
Infilt:	7881.22 cu m	5.254826 mm	Suspended:	0.000 kg
Stored:	0.00 cu m	0.000000 mm	Out:	5833.664 kg
Out:	7074.88 cu m	4.717199 mm	Error:	0.27 %
Error:	0.28 %			

Plane 113: based on length and parameter CLEN,
the numerical increment of 42.8 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 113

Contributing area = 127.7241 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 2.459847 cu m /s (6.933265 mm/hr) at 316.0 min

Peak sediment discharge = 1.884724 kg/s at 314.0 min

Water balance			Sediment balance	
Rain:	12772.41 cu m	10.00000 mm	In:	0.000 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-4148.258 kg
Infilt:	6600.22 cu m	5.16756 mm	Suspended:	0.000 kg
Stored:	5.54 cu m	0.00434 mm	Out:	4131.918 kg
Out:	6050.44 cu m	4.73711 mm	Error:	0.39 %
Error:	0.91 %			

Channel 114: based on length and parameter CLEN,
the numerical increment of 152.1 m is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Channel Elem. 114

Contributing area = 10413.19 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 17.25262 cu m /s (0.5964496 mm/hr) at 737.0 min

Peak sediment discharge = 39.24409 kg/s at 752.0 min

Water balance		Sediment balance	
Rain:	0.0 cu m	In:	315488.0 kg
Inflow:	251846.9 cu m	Deposited:	-169418.1 kg
Infilt:	435.7 cu m	Suspended:	63519.1 kg
Stored:	30838.4 cu m	Out:	420070.4 kg
Out:	219851.5 cu m	Error:	0.27 %
Error:	0.29 %		

Plane 11: based on length and parameter CLEN,
the numerical increment of 228.6 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 11

Contributing area = 553.5239 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 2.335140 cu m /s (1.518725 mm/hr) at 398.0 min

Peak sediment discharge = 1.673819 kg/s at 408.0 min

Water balance			Sediment balance	
Rain:	55352.39 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-15193.11 kg
Infilt:	32181.86 cu m	5.81400 mm	Suspended:	0.00 kg
Stored:	27.29 cu m	0.00493 mm	Out:	15139.50 kg
Out:	22617.24 cu m	4.08605 mm	Error:	0.35 %
Error:	0.95 %			

Plane 12: based on length and parameter CLEN,
the numerical increment of 36.9 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 12

Contributing area = 370.2439 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 7.663119 cu m /s (7.451096 mm/hr) at 314.0 min

Peak sediment discharge = 4.843482 kg/s at 313.0 min

Water balance			Sediment balance	
Rain:	37024.39 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-10029.14 kg
Infilt:	19263.29 cu m	5.20287 mm	Suspended:	0.00 kg
Stored:	0.00 cu m	0.00000 mm	Out:	9970.90 kg
Out:	17569.60 cu m	4.74541 mm	Error:	0.58 %
Error:	0.52 %			

Plane 13: based on length and parameter CLEN,
the numerical increment of 88.7 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 13

Contributing area = 890.2921 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 9.331118 cu m /s (3.773146 mm/hr) at 339.0 min

Peak sediment discharge = 7.003525 kg/s at 345.0 min

Water balance			Sediment balance	
Rain:	89029.21 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-26375.17 kg
Infilt:	47425.83 cu m	5.32700 mm	Suspended:	0.00 kg
Stored:	21.12 cu m	0.00237 mm	Out:	26229.71 kg
Out:	40668.91 cu m	4.56804 mm	Error:	0.55 %
Error:	1.03 %			

Channel 14: based on length and parameter CLEN,
the numerical increment of 512.2 m is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Channel Elem. 14

Contributing area = 1814.060 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 7.391282 cu m /s (1.466799 mm/hr) at 415.0 min

Peak sediment discharge = 8.889252 kg/s at 419.0 min

Water balance		Sediment balance	
Rain:	0.00 cu m	In:	51340.09 kg
Inflow:	80855.93 cu m	Deposited:	-28758.62 kg
Infilt:	617.49 cu m	Suspended:	3715.61 kg
Stored:	5617.85 cu m	Out:	75948.07 kg
Out:	74931.89 cu m	Error:	0.54 %
Error:	-0.39 %		

Plane 102: based on length and parameter CLEN,
the numerical increment of 38.0 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 102

Contributing area = 392.8412 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 8.566743 cu m /s (7.850570 mm/hr) at 312.0 min

Peak sediment discharge = 7.698836 kg/s at 312.0 min

Water balance			Sediment balance	
Rain:	39284.12 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-14575.07 kg
Infilt:	20250.37 cu m	5.15485 mm	Suspended:	0.00 kg
Stored:	1.97 cu m	0.00050 mm	Out:	14521.86 kg
Out:	18688.72 cu m	4.75732 mm	Error:	0.37 %
Error:	0.87 %			

Plane 103: based on length and parameter CLEN,
the numerical increment of 50.4 m. is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Plane Element 103

Contributing area = 520.9561 ha

	theta	rel.sat.
surface initial water content =	0.3986	0.9000
estimated wilting point water content =	0.1025	0.1088
estimated field capacity =	0.1902	0.3430

Peak flow = 9.202649 cu m /s (6.359373 mm/hr) at 318.0 min

Peak sediment discharge = 8.559267 kg/s at 325.0 min

Water balance			Sediment balance	
Rain:	52095.61 cu m	10.00000 mm	In:	0.00 kg
Inflow:	0.00 cu m	0.00000 mm	Deposited:	-20324.39 kg
Infilt:	27372.88 cu m	5.25435 mm	Suspended:	0.00 kg
Stored:	0.00 cu m	0.00000 mm	Out:	20270.54 kg
Out:	24573.23 cu m	4.71695 mm	Error:	0.26 %
Error:	0.29 %			

Channel 104: based on length and parameter CLEN,
the numerical increment of 527.7 m is too large for
realistic numerical solution of the flow equation, and may
give misleading results.

Channel Elem. 104

Contributing area = 13141.05 ha

	theta	rel.sat.
surface initial water content =	0.3819	0.9000
estimated wilting point water content =	0.0638	0.0179
estimated field capacity =	0.1092	0.1437

Peak flow = 15.32541 cu m /s (0.4198408 mm/hr) at 519.0 min

Peak sediment discharge = 38.90087 kg/s at 525.0 min

Water balance		Sediment balance	
Rain:	0.0 cu m	In:	530810.8 kg
Inflow:	338852.3 cu m	Deposited:	-202523.8 kg
Infilt:	1639.5 cu m	Suspended:	281265.6 kg
Stored:	116763.0 cu m	Out:	458196.3 kg
Out:	219788.0 cu m	Error:	-0.84 %
Error:	0.20 %		

56 elements Processed

Event Volume Summary:

Rainfall	10.00000 mm	1314105. cu m
Plane infiltration	5.33508	701085.
Channel infiltration	0.07130	9370.
Storage	2.83468	372506.
Outflow	1.67253	219788.

Error (Volume in - Volume out - Storage) < 1 percent

Time step was adjusted to meet Courant condition

Total watershed area = 13141.05 ha

Sediment yield = 34.86756 kg/ha

Sediment yield by particle class:

Particle size (mm)	0.250	0.033	0.004
Yield (kg/ha)	26.63894	4.87393	3.35470
% of total yield	76.40	13.98	9.62

Appendix B
Reservoir Program Code

```
Imports System
Imports System.IO
Public Class FrmInputs
    Inherits System.Windows.Forms.Form
    Public Volumes() As Double
    Public Areas() As Double
    Public num As Integer


#Region " Windows Form Designer generated code "

    Public Sub New()
        MyBase.New()

        'This call is required by the Windows Form Designer.
        InitializeComponent()

        'Add any initialization after the InitializeComponent() call

    End Sub

    'Form overrides dispose to clean up the component list.
    Protected Overloads Overrides Sub Dispose(ByVal disposing As Boolean)
        If disposing Then
            If Not (components Is Nothing) Then
                components.Dispose()
            End If
        End If
        MyBase.Dispose(disposing)
    End Sub

    'Required by the Windows Form Designer
    Private components As System.ComponentModel.IContainer

    'NOTE: The following procedure is required by the Windows Form Designer
    'It can be modified using the Windows Form Designer.
    'Do not modify it using the code editor.
    Friend WithEvents Label1 As System.Windows.Forms.Label
    Friend WithEvents Label2 As System.Windows.Forms.Label
    Friend WithEvents Label3 As System.Windows.Forms.Label
    Friend WithEvents Label4 As System.Windows.Forms.Label
    Friend WithEvents TxtCellArea As System.Windows.Forms.TextBox
    Friend WithEvents TxtVolMax As System.Windows.Forms.TextBox
    Friend WithEvents TxtEvapRate As System.Windows.Forms.TextBox
    Friend WithEvents TxtInfRate As System.Windows.Forms.TextBox
    Friend WithEvents Label5 As System.Windows.Forms.Label
    Friend WithEvents Label6 As System.Windows.Forms.Label
    Friend WithEvents TxtTimeStep As System.Windows.Forms.TextBox
    Friend WithEvents TxtInjRate As System.Windows.Forms.TextBox
    Friend WithEvents BtnReadAreaVol As System.Windows.Forms.Button
    Friend WithEvents Label7 As System.Windows.Forms.Label
    Friend WithEvents txtFileName As System.Windows.Forms.TextBox
    Friend WithEvents BtnDrain As System.Windows.Forms.Button
```

```
    <System.Diagnostics.DebuggerStepThrough()> Private Sub
InitializeComponent()
        Me.Label1 = New System.Windows.Forms.Label
        Me.Label2 = New System.Windows.Forms.Label
        Me.Label3 = New System.Windows.Forms.Label
        Me.Label4 = New System.Windows.Forms.Label
        Me.TxtCellArea = New System.Windows.Forms.TextBox
        Me.TxtVolMax = New System.Windows.Forms.TextBox
        Me.TxtEvapRate = New System.Windows.Forms.TextBox
        Me.TxtInfRate = New System.Windows.Forms.TextBox
        Me.BtnReadAreaVol = New System.Windows.Forms.Button
        Me.Label5 = New System.Windows.Forms.Label
        Me.TxtInjRate = New System.Windows.Forms.TextBox
        Me.Label6 = New System.Windows.Forms.Label
        Me.TxtTimeStep = New System.Windows.Forms.TextBox
        Me.Label7 = New System.Windows.Forms.Label
        Me.txtFileName = New System.Windows.Forms.TextBox
        Me.BtnDrain = New System.Windows.Forms.Button
        Me.SuspendLayout()
        '
        'Label1
        '
        Me.Label1.Font = New System.Drawing.Font("Microsoft Sans Serif",
8.25!, System.Drawing.FontStyle.Bold, System.Drawing.GraphicsUnit.Point,
CType(0, Byte))
        Me.Label1.Location = New System.Drawing.Point(48, 96)
        Me.Label1.Name = "Label1"
        Me.Label1.Size = New System.Drawing.Size(88, 16)
        Me.Label1.TabIndex = 0
        Me.Label1.Text = "Cell Area (m^2)"
        '
        'Label2
        '
        Me.Label2.Font = New System.Drawing.Font("Microsoft Sans Serif",
8.25!, System.Drawing.FontStyle.Bold, System.Drawing.GraphicsUnit.Point,
CType(0, Byte))
        Me.Label2.Location = New System.Drawing.Point(48, 136)
        Me.Label2.Name = "Label2"
        Me.Label2.Size = New System.Drawing.Size(120, 16)
        Me.Label2.TabIndex = 1
        Me.Label2.Text = "Runoff Volume (m^3)"
        '
        'Label3
        '
        Me.Label3.Font = New System.Drawing.Font("Microsoft Sans Serif",
8.25!, System.Drawing.FontStyle.Bold, System.Drawing.GraphicsUnit.Point,
CType(0, Byte))
        Me.Label3.Location = New System.Drawing.Point(48, 176)
        Me.Label3.Name = "Label3"
        Me.Label3.Size = New System.Drawing.Size(136, 16)
        Me.Label3.TabIndex = 2
        Me.Label3.Text = "Evaporation Rate (m/hr)"
        '
        'Label4
        '
```

```
        Me.Label4.Font = New System.Drawing.Font("Microsoft Sans Serif",
8.25!, System.Drawing.FontStyle.Bold, System.Drawing.GraphicsUnit.Point,
CType(0, Byte))
        Me.Label4.Location = New System.Drawing.Point(48, 216)
        Me.Label4.Name = "Label4"
        Me.Label4.Size = New System.Drawing.Size(120, 16)
        Me.Label4.TabIndex = 3
        Me.Label4.Text = "Infiltration Rate (m/hr)"
        '
        'TxtCellArea
        '
        Me.TxtCellArea.Location = New System.Drawing.Point(184, 96)
        Me.TxtCellArea.Name = "TxtCellArea"
        Me.TxtCellArea.Size = New System.Drawing.Size(96, 20)
        Me.TxtCellArea.TabIndex = 2
        Me.TxtCellArea.Text = "8100"
        '
        'TxtVolMax
        '
        Me.TxtVolMax.Location = New System.Drawing.Point(184, 136)
        Me.TxtVolMax.Name = "TxtVolMax"
        Me.TxtVolMax.Size = New System.Drawing.Size(96, 20)
        Me.TxtVolMax.TabIndex = 3
        Me.TxtVolMax.Text = ""
        '
        'TxtEvapRate
        '
        Me.TxtEvapRate.Location = New System.Drawing.Point(184, 176)
        Me.TxtEvapRate.Name = "TxtEvapRate"
        Me.TxtEvapRate.Size = New System.Drawing.Size(96, 20)
        Me.TxtEvapRate.TabIndex = 4
        Me.TxtEvapRate.Text = ""
        '
        'TxtInfRate
        '
        Me.TxtInfRate.Location = New System.Drawing.Point(184, 216)
        Me.TxtInfRate.Name = "TxtInfRate"
        Me.TxtInfRate.Size = New System.Drawing.Size(96, 20)
        Me.TxtInfRate.TabIndex = 5
        Me.TxtInfRate.Text = ""
        '
        'BtnReadAreaVol
        '
        Me.BtnReadAreaVol.Font = New System.Drawing.Font("Microsoft Sans
Serif", 8.25!, System.Drawing.FontStyle.Bold,
System.Drawing.GraphicsUnit.Point, CType(0, Byte))
        Me.BtnReadAreaVol.Location = New System.Drawing.Point(104, 48)
        Me.BtnReadAreaVol.Name = "BtnReadAreaVol"
        Me.BtnReadAreaVol.Size = New System.Drawing.Size(152, 23)
        Me.BtnReadAreaVol.TabIndex = 1
        Me.BtnReadAreaVol.Text = "Read Area Volume File"
        '
        'Label5
        '
        Me.Label5.Font = New System.Drawing.Font("Microsoft Sans Serif",
8.25!, System.Drawing.FontStyle.Bold, System.Drawing.GraphicsUnit.Point,
CType(0, Byte))
```

```
        Me.Label5.Location = New System.Drawing.Point(48, 256)
        Me.Label5.Name = "Label5"
        Me.Label5.Size = New System.Drawing.Size(128, 16)
        Me.Label5.TabIndex = 5
        Me.Label5.Text = "Injection Rate (m^3/hr)"
        '
        'TxtInjRate
        '
        Me.TxtInjRate.Location = New System.Drawing.Point(184, 256)
        Me.TxtInjRate.Name = "TxtInjRate"
        Me.TxtInjRate.Size = New System.Drawing.Size(96, 20)
        Me.TxtInjRate.TabIndex = 6
        Me.TxtInjRate.Text = ""
        '
        'Label6
        '
        Me.Label6.Font = New System.Drawing.Font("Microsoft Sans Serif",
8.25!, System.Drawing.FontStyle.Bold, System.Drawing.GraphicsUnit.Point,
CType(0, Byte))
        Me.Label6.Location = New System.Drawing.Point(48, 296)
        Me.Label6.Name = "Label6"
        Me.Label6.Size = New System.Drawing.Size(112, 16)
        Me.Label6.TabIndex = 6
        Me.Label6.Text = "Time Step Size (hr)"
        '
        'TxtTimeStep
        '
        Me.TxtTimeStep.Location = New System.Drawing.Point(184, 296)
        Me.TxtTimeStep.Name = "TxtTimeStep"
        Me.TxtTimeStep.Size = New System.Drawing.Size(96, 20)
        Me.TxtTimeStep.TabIndex = 7
        Me.TxtTimeStep.Text = ""
        '
        'Label7
        '
        Me.Label7.Font = New System.Drawing.Font("Microsoft Sans Serif",
8.25!, System.Drawing.FontStyle.Bold, System.Drawing.GraphicsUnit.Point,
CType(0, Byte))
        Me.Label7.Location = New System.Drawing.Point(16, 16)
        Me.Label7.Name = "Label7"
        Me.Label7.Size = New System.Drawing.Size(160, 16)
        Me.Label7.TabIndex = 9
        Me.Label7.Text = "Location of Area-Volume File"
        '
        'txtFileName
        '
        Me.txtFileName.Location = New System.Drawing.Point(184, 16)
        Me.txtFileName.Name = "txtFileName"
        Me.txtFileName.Size = New System.Drawing.Size(152, 20)
        Me.txtFileName.TabIndex = 0
        Me.txtFileName.Text = "C:\UserTemp\AreaVolume.txt"
        '
        'BtnDrain
        '
        Me.BtnDrain.Font = New System.Drawing.Font("Microsoft Sans Serif",
8.25!, System.Drawing.FontStyle.Bold, System.Drawing.GraphicsUnit.Point,
CType(0, Byte))
```

```
        Me.BtnDrain.Location = New System.Drawing.Point(72, 336)
        Me.BtnDrain.Name = "BtnDrain"
        Me.BtnDrain.Size = New System.Drawing.Size(176, 23)
        Me.BtnDrain.TabIndex = 8
        Me.BtnDrain.Text = "Calculate Reservoir Drainage"
        '
        'FrmInputs
        '
        Me.AutoScaleBaseSize = New System.Drawing.Size(5, 13)
        Me.ClientSize = New System.Drawing.Size(344, 374)
        Me.Controls.Add(Me.BtnDrain)
        Me.Controls.Add(Me.txtFileName)
        Me.Controls.Add(Me.TxtTimeStep)
        Me.Controls.Add(Me.TxtInjRate)
        Me.Controls.Add(Me.TxtInfRate)
        Me.Controls.Add(Me.TxtEvapRate)
        Me.Controls.Add(Me.TxtVolMax)
        Me.Controls.Add(Me.TxtCellArea)
        Me.Controls.Add(Me.Label7)
        Me.Controls.Add(Me.Label6)
        Me.Controls.Add(Me.Label5)
        Me.Controls.Add(Me.BtnReadAreaVol)
        Me.Controls.Add(Me.Label4)
        Me.Controls.Add(Me.Label3)
        Me.Controls.Add(Me.Label2)
        Me.Controls.Add(Me.Label1)
        Me.Name = "FrmInputs"
        Me.Text = "Input Parameters"
        Me.ResumeLayout(False)

    End Sub

#End Region

    Private Sub Label1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs)

    End Sub

    Private Sub TextBox1_TextChanged(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles TxtInfRate.TextChanged

    End Sub

    Private Sub TxtCellArea_TextChanged(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles TxtCellArea.TextChanged

    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles BtnReadAreaVol.Click

        ' Get the number of numbers.
        Dim num As Integer = Integer.Parse(Me.txtFileName.Text)

        ' Size the array.
        Dim AreaVol(num - 1) As Double
```

```
        ' Read the numbers.
        Dim stream_reader As New StreamReader(Me.txtFileName.Text)
        For i As Integer = 0 To num - 1
            AreaVol(i) = _
                Double.Parse(stream_reader.ReadLine())
        Next i
        stream_reader.Close()

        For i As Integer = 0 To num - 1 Step 2
            Areas(i) = AreaVol(i / 2)
            Volumes(i) = AreaVol(i / 2 + 1)
        Next
        MsgBox("Area - Volume File Read Sucessfully")

    End Sub

    Private Sub BtnDrain_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles BtnDrain.Click
        Dim InjRate As Double
        Dim InfRate As Double
        Dim EvapRate As Double
        Dim TimeStep As Double
        Dim StartVolume As Double
        Dim Volume As Double
        Dim Area As Double
        Dim Index As Integer
        Dim InjVol As Double = 0
        Dim InfVol As Double = 0
        Dim EvapVol As Double = 0

        InjRate = Me.TxtInjRate.Text
        InfRate = Me.TxtInfRate.Text
        EvapRate = Me.TxtEvapRate.Text
        TimeStep = Me.TxtTimeStep.Text
        StartVolume = Me.TxtVolMax.Text

        Volume = StartVolume
        Dim Empty As Boolean
        Empty = False
        While Empty = False
            Volume = Volume - InjRate * TimeStep - InfRate * Area * TimeStep
- EvapRate * Area * TimeStep
            InjVol = InjVol + InjRate * TimeStep
            InfVol = InfVol + InfRate * Area * TimeStep
            EvapVol = EvapRate * Area * TimeStep

            For i As Integer = 0 To num - 2
                If Math.Abs(Volumes(i) - Volume) < Math.Abs(Volumes(i + 1) -
Volume) Then
                    Index = i
                Else : Index = i + 1
                End If
            Next
            Area = Areas(Index)
            If Volume < Volumes(0) Then
                Empty = True
```

```
            End If
        End While

        'Dim msg As String
        'Dim title As String
        'msg = "Volume Injected: " InjVol "  Volume Infiltrated: " infvol "
Volume Evaporated: "   ' Define message.
        'title = "Results"    ' Define title.
        '' Display message.
        'MsgBox(msg, MsgBoxStyle.OKOnly, title)

    End Sub
End Class
```

Appendix C
Area-Volume Relationships for Sub-Basin Outlets

Table C.1 Area-volume relationship for sub-basin 1 outlet

Top Elev. (m above MSL)	Height	Area (m^2)	Volume (m^3)	1mm Runoff (m^3)
51	1	5.64E+05	1.17E+06	6.11E+05
53	3	1.55E+06	3.89E+06	6.11E+05
55	5	2.24E+06	8.13E+06	6.11E+05

Table C.2 Area-volume relationship for sub-basin 2 outlet

Top Elev. (m above MSL)	Height	Area (m^2)	Volume (m^3)	1mm Runoff (m^3)
49	1	4.39E+04	4.39E+04	1.41E+05
50	2	9.52E+04	1.68E+05	1.41E+05
51	3	1.24E+05	2.93E+05	1.41E+05
52	4	1.83E+05	4.76E+05	1.41E+05
53	5	3.51E+05	9.01E+05	1.41E+05

Table C.3 Area-volume relationship for sub-basin 3 outlet

Top Elev. (m above MSL)	Height	Area (m^2)	Volume (m^3)	1mm Runoff (m^3)
50	1	2.20E+04	2.20E+04	1.31E+05
51	2	1.17E+05	1.39E+05	1.31E+05
52	3	1.61E+05	3.00E+05	1.31E+05

Table C.4 Area-volume relationship for sub-basin 4 outlet

Top Elev. (m above MSL)	Height	Area (m^2)	Volume (m^3)	1mm Runoff (m^3)
52	1	1.54E+05	2.49E+05	9.13E+04
53	2	1.98E+05	4.54E+05	9.13E+04
54	3	3.66E+05	8.93E+05	9.13E+04

Table C.5 Area-volume relationship for sub-basin 5 outlet

Top Elev. (m above MSL)	Height	Area (m^2)	Volume (m^3)	1mm Runoff (m^3)
50	1	9.52E+04	1.10E+05	1.66E+05
51	2	1.90E+05	3.29E+05	1.66E+05
52	3	4.17E+05	7.47E+05	1.66E+05