Application of a hydrological model in a data-poor arid region catchment: a case study of Wadi Ham, United Arab Emirates

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Application of a hydrological model in a data-poor arid region catchment: a case study of Wadi Ham, United Arab Emirates

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Abstract

Many arid region Wadi catchments are facing increasing water scarcity due to the unsustainable human practises such as the over expansion of irrigated agriculture and over exploitation of their groundwater aquifers.

The "Soil and Water Assessment Tool" (SWAT) model, which is a comprehensive conceptual, semi-distributed watershed scale model, was selected after a review of the hydrological processes occurring in arid region catchments to simulate the hydrological processes of the Wadi Ham catchment in northeast United Arab Emirates.

A sensitivity analysis conducted for SWAT for the total runoff, maximum runoff and days of runoff showed that a DEM resolution of no more than 100 m should be used for proper representation of such mountainous arid catchments. The appropriate size of defined sub-basins was found to be about 18 km^2. The sensitivity analysis also demonstrated that the most sensitive parameters that affect the ephemeral streamflow are mainly related to the soil and channel properties of the catchment soil depth, soil available water capacity, soil bulk density, soil clay percentage, soil curve number, baseflow recession constant and channel effective hydraulic conductivity.

SWAT simulated the ephemeral streamflow in Wadi Ham acceptably. For the calibration period of 1981 and 1982, the performance statistics for DRMS, PBIAS, NSE and PEM were 1.10 m^3/s, 27.12%, 0.78 and 0.80 respectively. During the validation period between 1983 and 1988, the DRMS, PBIAS, NSE and PEM were 0.93 m^3/s, -27.30%, 0.57 and 0.70 respectively. SWAT showed very plausible behaviour for reservoir sedimentation, plant growth, irrigation abstraction and groundwater recharge via the transmission losses mechanism. However, SWAT was not able to adequately simulate the recharge from the bottom of the recharge dam reservoir due to an inappropriate maximum effective hydraulic conductivity defined by the model.

Two management scenarios were simulated. The first scenario related to the construction of an additional dam upstream and its effect on sedimentation rate in the main reservoir. The second scenario found that the recharge volumes could be enhanced through the construction of a discharge inlet point into the main stream channel for the treated wastewater from the principal town upstream of the catchment.

The successful simulation of Wadi Ham represents the first use of SWAT in a truly arid climate. This research has therefore established the feasibility of using SWAT as a tool for integrated catchment modelling in arid region data-poor Wadi catchments and to support improved water resources management in this water stressed environment.

Dedication

To my mother, for always being there for me.

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Introduction

1.1 General background

The arid regions of the world are experiencing severe pressures on their natural resources (UNEP, 1999). Water scarcity is one of the most serious threats to food production, human health and ecosystem stability in the world and in particular the arid regions. In general usage, scarcity is a “situation where there is insufficient water to satisfy normal requirements” (Winpenny, 2003). According to UNEP (1999) the arid region water resources are under increasing pressure. Some arid countries already have chronic water shortages, experiencing growing water scarcity, deteriorating water quality, and sectoral conflicts over water allocation. Seckler et al., (1998) estimated that a quarter of the world’s population live in regions that will experience severe water scarcity within the Twenty-first century. More than one billion people living in arid regions will face water scarcity by the year 2025 (Seckler et al., 1999).

1.2 The arid zones

The world’s arid zones are mainly located in the tropics and sub-tropics (Figure. 1.1). Aridity is found principally in regions with persistent anticyclonic conditions, resulting from the presence of dry descending air (FAO, 1989).

The arid zones can be classified into several sub classes according to the degree of aridity assessed by a relationship between rainfall and reference water demand (Table 1.1). UNESCO classified the arid zones of the world based on the value of the ratio of annual precipitation to annual potential evapotranspiration calculated by the standard Penman method. The classification provides a standardised and simple relationship between rainfall and reference crop water demand (De Pauw et al., 2000).

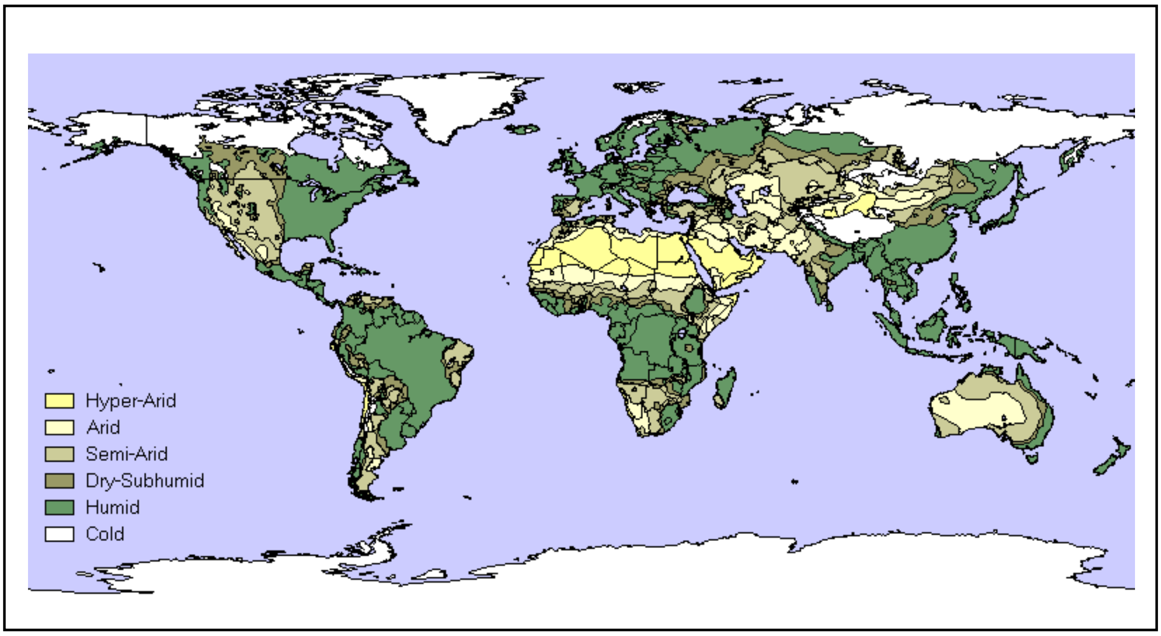


Figure 1.1 Arid zone distribution map.
(Source: http://ialcworld.org/soils/surveys/global.html).

Table1.1 UNESCO classification of arid zones of the world (after De Pauw et al., 2000).

Zone	P^a/PET^b ratio	Characteristics
Hyper-arid zone	<0.03	Very low and irregular rain which may fall in any season Interannual variability of rainfall can reach 100% Almost no perennial vegetation, except some bushes in river beds; annual plants can grow in good years Agriculture and grazing are generally impossible
Arid zone	$0.03<P/\mathrm{PET}<0.2$	Annual rainfall of 80–150 mm up to 200–350 mm Interannual rainfall variability 50–100% Scattered vegetation including bushes, small woody, succulent, thorny or leafless shrubs Very light pastoral use possible, but not rainfed agriculture
Semi-arid zone	$0.2<P/\mathrm{PET}<0.5$	Mean annual rainfall from 300–400 to 700–800 mm in summer rainfall regimes, and from 200–250 to 450–500 mm in winter rainfall regimes. Interannual rainfall variability 25–50% Steppe zone with some savannas and tropical scrub Sometimes good grazing areas and rainfed agriculture is possible, although with great yield fluctuations due to great rainfall variability
Semi-humid zone	$0.5<P/\mathrm{PET}<0.75$	Interannual rainfall variability is less than 25% Includes tropical savanna, maquis and chaparral, steppes, etc. Agriculture is the normal use

[a] P: annual rainfall.
[b] PET: annual potential evapotranspiration.

According to the previous classification, arid zones are characterised by high but variable degrees of aridity, reflecting low ratios between precipitation and potential evapotranspiration, and by sparse, unevenly distributed, or temporally variable vegetation cover (Middelton and Thomas, 1997).

The natural resources of arid regions, particularly soil and water, are limited and often in a delicate environmental balance (Williams and Balling, 1996; Thomas and Middelton, 1994). The most obvious features of their climate are the lack of water and high evaporation rates. The distinctive hydro-climatic features of arid zone can be summarised as:

- High levels of incident radiation with high diurnal and seasonal temperature variation.
- Low humidity, except in close proximity to the sea.
- Sporadic rainfall of high temporal and spatial variability
- High potential evapotranspiration rates.
- Variable short duration runoff events in ephemeral drainage systems.
- High infiltration rates in channel alluvium.
- High sediment transport rates.
- Large groundwater and soil moisture storage change.

In this research work the consideration will be given mainly to the mountainous arid zones, where according to the previous classification the P/PET is $0.03<P/PET<0.2$, and to the Arabian Gulf region in particular.

1.3 Water demands and supply in arid region

There are strong signs that the balance between supply and demand of water is deteriorating and becoming critical in large areas of the arid and semi-arid regions (Mwendera, 2003; Tao and Wei, 1997 and Sadik and Barghouti, 1993). The reasons behind such scarcity could be natural causes i.e. drought cycles (UNEP, 1992) or human impacts i.e. modification in land use and management (Al Alawiand and Abdul Razzak, 1993).

As an example from the typical arid region of the Arabian Peninsula, the seven Gulf Co-operation Council (GCC) countries witness a clear imbalance between the available water resources and water demands. The high population growth, improvements in the standard of living, agriculture land expansion strategies and industrial development are the main reasons behind increasing water demands (Abdulrazzak, 1997). The total water demands of these GCC countries are around 22000 million m^3/year, of which non-renewable groundwater resources satisfy nearly 75% of these demands, while the remaining 25% of the demands is supplied by the renewable water resources found mainly in Wadi catchments (that are associated with the mountainous region in Arabian Peninsula), desalination and recycled treated wastewater (Al-Zubari, 1998). According to Table 1.2 the total water demands in GCC countries by the year 2020 will reach 28000 million m^3, an overall annual increase of 0.8% per annum in total water demand.

As a result of the clear imbalance between the available water resources and the rising water demands in the GCC countries, the intensive use of groundwater from both shallow and deep aquifers in excess of the natural renewability has led to falling water tables (Rasheeduddin, 2001), water quality deterioration (Rizk and Alsharhan, 1999) and sea water intrusion in the coastal zone (Victor R. and Al-Farsi A. A., 2001).

Table 1.2 Estimated and projected future total water demands in the GCC countries in million m^3/year (after Al-Zubari, 1998).

Demands / resources	**Estimated 1990**	**Projected 2020**	**% Expected annual increase**
Water Demands			
Domestic	3,400	6,100	2
Agriculture	18,000	21,000	1.7
Industrial	350	750	2.6
Total	21,850	27,850	0.8
Water resources / sources			
Fossil groundwater	16,400	20,200	0.7
Renewable groundwater and Surface water	3,000	4,000	1
Desalinated water	2,100	3,000	1.2
Reused water	250	650	3.3
Total	21,750	27,850	0.8

1.4 Alternative sources of water supplies in arid region

In order to reduce the rising disparity between supply and demand of water resources in the arid countries, an integrated water conservation and management approach policy should be practiced. Table 1.2 illustrated the important role of the alternative water resources in decreasing the disparity between supply and demand of water resources in arid GCC countries. These alternative resources can be developed from water desalination, wastewater reuse and water harvesting on catchment and field scales.

1.4.1 Desalination

Desalination can provide a consistent and independent source of water in many arid countries. The high construction and operational costs of the desalination plants limits their use to arid high-income countries and to a lesser extent in some industrial countries and arid islands (Dabbagh and Al-saqabi, 1989).

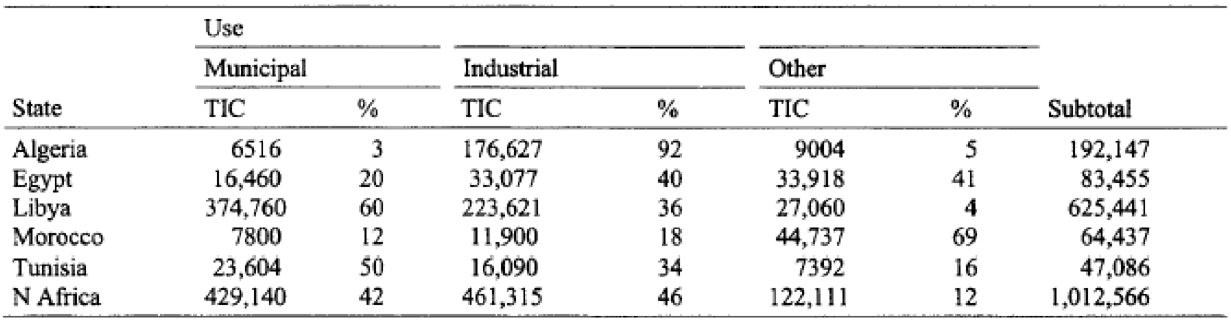
As a reliable solution to the severe shortage in freshwater resources, the GCC countries have constructed a large number of desalination plants since the early 1970’s, mainly to secure drinking and domestic water demands. According to Al-Rashed and Sherif (2000) the combined capacities of all desalination plants in the GCC countries reached 2.14 billion m^3 in 1997, while the total volume of desalinated water produced during the same year reached about 1.7 billion m^3. Abdulrazzak (1997) concluded that desalinated water would continue to become the main source of water for domestic requirements for most of the GCC countries as shown in Table 1.3.

Table 1.3 Desalination Schemes in GCC countries (modified from Abdulrazzak 1997).

	1990				2000			
Country	**Installed desalination capacity (Mcm)**	**Desalination production (Mcm)**	**Domestic/ industrial demand (Mcm)**	**Desalination/ demand ratio (%)**	**Planned desalination capacity (Mcm)**	**Total desalination capacity (Mcm)**	**Domestic/ industrial demand (Mcm)**	**Desalination/ demand ratio(%)**
Bahrain	75	56	103	54	66	141	155	91
Kuwait	318	240	303	79	110	428	530	81
Oman	55	32	86	37	13	68	147	46
Qatar	112	83	85	98	104	216	140	>100
Saudi Arabia	950	795	1,700	47	339	1,289	2,900	44
UA E	502	342	540	63	270	772	832	93
Total	*2017*	*1548*	*2817*	-	*902*	*2914*	*4669*	-

Abufayed et al., (2002) found that desalination also provides an alternate source of reliable and readily available water to the North Africa states to meet the chronic water shortages facing the region (Table 1.4). The recent development in desalination technologies have made desalination more competitive compared with new hard-to-find conventional water resources.

Table 1.4 Desalinated water uses in the North African countries (after Abufayed et al, 2002).



	Use						
	Municipal		Industrial		Other		
State	TIC	%	TIC	%	TIC	%	Subtotal
Algeria	6516	3	176,627	92	9004	5	192,147
Egypt	16,460	20	33,077	40	33,918	41	83,455
Libya	374,760	60	223,621	36	27,060	4	625,441
Morocco	7800	12	11,900	18	44,737	69	64,437
Tunisia	23,604	50	16,090	34	7392	16	47,086
N Africa	429,140	42	461,315	46	122,111	12	1,012,566

TIC = total installed capacity (m^3/d)

Many researchers believe that solar still desalination systems can provide technically feasible and suitable future water sources for arid areas (Chaibi, 2000 and El-Kady and El-Shibini, 2001). In Egypt where irrigated agriculture consumes about 80% of the Nile's water, solar desalination systems are considered to be an attractive water source in remote areas where either seawater or brackish groundwater are available. Such a system is described by El-Kady and El-Shibini (2001). They proposed a simple integrated system of a solar still desalination and drip irrigation as agriculture irrigation sources.

Generally desalination of sea and brackish groundwater is becoming an essential domestic water supply source for many arid countries, and is considered to be a promising component of future irrigation water sources in such countries. However, the cost factors have limited the use of desalination to municipal and industrial applications.

1.4.2 Treated wastewater

In many areas where the available supply of fresh water has become inadequate to meet the increasing demand, the wastewater is considered as a resource that must be reused. Much reuse of wastewater occurs in the arid and semi-arid regions such as the GCC countries (Abdulrazzak, 1997) and western and south-western states of the United States (Cheremisinoff, 2002).

The GCC countries reuse about 25% of the available treated wastewater mainly for irrigation of non-cash crops, landscape irrigation and industrial cooling, while in Qatar it is used for fodder crop irrigation (Abdulrazzak, 1997). As an approach towards the establishment of total water cycle management and water reuse in arid countries Al-Zubari (1998) found that at present the GCC countries recycle about 35% of their total treated wastewater, which contributes 2.2% of their total water supply, used mainly for landscaping, fodder crops irrigation and some industrial uses. He suggested that if 50% of domestic water supplies are treated and recycled in agriculture, recycled water has the potential to meet 11% of GCC countries’ total water demands, could satisfy 14% of the agricultural sector demand and could reduce fossil groundwater withdrawal by 15% by the year 2020.

1.4.3 Rainwater harvesting and rainfall enhancement

Water harvesting in general is capturing and storing rainfall for different uses. Rainwater harvesting techniques have been used in a number of arid and semi-arid environments (Boers, 1994). The water harvesting techniques for agriculture can be generally categorised under three basic categories:

- within-field catchment systems i.e. semi-circular bunds for range and fodder crops;
- long slope catchment techniques i.e. contour stone bunds for crops, and;
- floodwater harvesting i.e. water spreading bunds for crops (Critchley, 1991).

The on farm techniques of rainwater harvesting such as tillage methods, mulching tillage and other on farm rainwater collecting systems (Rockstrom et al., 2000, Shangguan et al., 2001 and Shangguan, 2002) have led to significant yield and water use efficiency increases in rainfed and dry land agriculture.

The use of rainfall enhancement by cloud seeding techniques for semi-arid to arid regions in some countries such as Australia indicates a positive effect on rainfall duration, extension and intensity on the targeted area (Goodrich, 1994). Many countries in the Arabian Gulf (i.e. UAE, Saudi Arabia and Oman) have ongoing studies and attempt to develop such methods to enhance their natural water resources (RAP, 2004).

1.4.4 Artificial recharge and recharge dams

Artificial recharge of groundwater using surface infiltration or injection wells can play an important role in integrated water management in some arid countries (Bouwer, 1997).

Dams play a role in sustainable management of scarce water resources particularly in arid and semi-arid regions. Recharge dams are used to increase the volume of groundwater recharge from flash runoff events (Table 1.5), which would otherwise be lost to the sea from coastal drainage basins or by evaporation from inland drainage basins. Abdulrazzak (1997) appreciates the role of recharge dams in groundwater augmentation in the Arabian Peninsula but he points out the need to increase the efficiency of recharge dams through better dam operation and silt and clay removal from the reservoir bed.

Table 1.5 Calculated monthly potential recharge in 1985/1986 from a recharge dam in Saudi Arabia using a reservoir water budget model (after Al-Muttair and Al-Turbak, 1989).

Month	**Recharge volume (m^3)**
November, 1985	268660
December	25113
January, 1986	18623
February	36798
March	335139
April	305325
May	20874
June	4329
July	1719
August	181
September	83
October	0
Total	***1016844***

Another promising resource in the Arabian Gulf is recharge of the available excess wastewater. According to Ishaq and Khan (1997), wastewater recharge is one of the most available and promising water reuse and reclamation processes for Saudi Arabia, offering the potential to replenish the depleting water tables arising from over extraction. They have concluded that alluvial aquifers and the outcrops of the principal aquifers could be suitable sites for recharge that can be withdrawn mainly as irrigation water.

1.5 Water resources management in arid regions

From the above review, it can be seen that arid regions such as the Arabian Gulf states have developed a serious water resources problem due to their increasing population and the expansion in agricultural land use. Most of the efforts made to date have involved the development of new non conventional water resources (e.g. desalination and wastewater treatment) to reduce the gap between the increased demand and the supply on the domestic level, and by introducing recharge facilities to support the irrigation water demand at the catchment level. For better management outcomes, it can be proposed to integrate all of the previous solutions, especially in the catchments where agriculture exists.

Sustainable water resources development in general (Kobori, 1997), should take into account (a) meeting human requirements in the present and in the future, (b) ensuring water security and conflict resolution and (c) satisfying the ecosystem requirements The UN Agenda 21 recommendations identify some general programme areas, as summarised by Prinz and Singh (2000), for the fresh water resources sector for action research and local implementation:

(a) Integrated water resources development and management that is based on the perception of water as an integral part of the ecosystem including the integration of land and water related aspects carried out at the level of catchment.

(b) Water resources assessment to identify potential sources of fresh water supply, human activities that affect those resources, conflicts between supply and demand and to provide data bases for rational water resources utilisation.

(c) Protection of water resources, water quality and aquatic ecosystems based on holistic fresh water management and balanced consideration of the needs of people and the environment.

(d) Drinking water supply and sanitation which includes community management of services backed by measures to strengthen local institutions, and sound financial practices achieved through better management of existing assets and widespread use of appropriate technology in implementing and sustaining water and sanitation programmes.

(e) Implementing strategies and actions to ensure the continued supply of affordable water for present and future needs in urban environments and to reverse current trends of resources degradation and depletion.

(f) Water for sustainable food production and rural development depends on efficient water use and conservation practices consisting primarily of irrigation development and management, water management for rainfed areas, water for aquatic and terrestrial ecosystems. In the agriculture sector and due to rising demand of irrigation water resources, multiple use of water should be given priority.

(g) Impact of climate change on regional water resources and the relationship between water supplies and increasing water demands.

Agricultural activities are the most vital and water demanding sector in the world and particularly in the arid regions. Irrigated agriculture consumes over 70% of the total water supplies of the world. Efficient irrigation water use and conservation methods in the agriculture sector of the arid regions are fundamental for sustainable development. As an example of agricultural irrigation water use in an arid region, Table 1.6 shows that the irrigation water use in arid regions of China is 93% of the total water use.

The need for water conservation and management alternatives to the current practices are highly crucial to the conservation of irrigation water resources in arid regions. Ethan and Umar (2001) proposed feasible water conservation options for arid and semi-arid agricultural areas of Northern Nigeria, which consisted of rainfall water harvesting for irrigation, crop residue mulches to minimise direct evaporation and surface crust formation, occasional shallow cultivation especially after each rainfall to minimise direct evaporation losses from the sub-soil and finally encouragement for the adoption of the drip irrigation system which offers greater efficiency of water application. Such management approaches are essential in the agricultural sector, since water is the major limiting factor in arid land agriculture.

Table 1.6 Annual water utilisation in the Arid Regions of China (after Tao and Wei, 1997).

Province	**Agricultural irrigation (10^8 m³)**	**Range-land irrigation (10^8 m³)**	**Industrial water use (10^8 m³)**	**City use (10^8 m³)**	**Country side use (10^8 m³)**
Xinjiang	387.98	9.50	7.49	0.43	2.05
Hexi Corridor Region, Gansu	63.81	3.95	2.01	0.09	0.69
Qinhai	5.07	2.33	-	0.05	0.46
Inner Mongolia	5.35	-	0.23	0.06	0.57
Yellow River	120.00	2.00	8.00	1.00	2.60
Total	582.21	17.78	18.18	1.63	6.37
Percentage	**93.0**	**2.8**	**2.9**	**0.3**	**1.0**

Arid region countries that depend on groundwater resources should formulate clear strategies to ensure the continued sustainable supply and to avoid the depletion of their sensitive groundwater resources. Al-Rashed and Sherif (2000) suggested an integrated water resources management outline for the sustainability of the hydrogeological system in the arid GCC countries which consisted of a comprehensive policy for groundwater pumping to ensure the sustainability of their hydrogeological systems, which included:

- Limiting expensive desalinated water for the purposes of drinking and domestic uses
- Treatment and recycling of wastewater to a greater extent.
- Construction of detention or recharge dams in the major Wadi catchments of the region.
- Application of different schemes for the artificial recharge of groundwater according to the nature of the hydrogeological systems under consideration.

To establish management approaches for analysing the uses, depletion and productivity of water in the basin, the integrated water resources management approach which includes the watershed and its associated groundwater aquifers is the most appropriate unit for planning water resources development and management (Prinz and Singh, 2000).

1.6 Wadi catchment simulation

A Wadi can be defined as a channel which is dry except in the rainy season (UNESCO, 2002). The development of water resources in Wadi catchments is challenged by many constraints. Hydrologically, Wadi systems are characterized by extreme temporal changes from droughts to heavy floods. The resultant high rates of erosion and sedimentation processes can negatively affect the efficiency of the constructed water resources augmentation facility within a catchment (UNEP, 1998). Other constraints can be the degradation of groundwater resources in both their quantity and quality in many Wadi systems (Al Alawi and Abdul Razzak, 1993).

Many Wadi catchments experience deficient management practices, such as the expansion of agriculture land, the cultivation of highly water demanding crops (such as alfalfa) in such an arid climate, the extensive use of agricultural chemicals and low efficiency surface irrigation systems which allow high losses through evaporation. Such practices can drive the Wadi catchment to a very critical level in regard of the available water resources.

The application of watershed hydrological models has become a principle tool for water resources assessment (Singh and Woolhiser, 2002) and for the prediction of the impact of land management practices on water resources (Föhrer et al., 2005), contaminants (Diluzio and Arnold, 2004) and sediment yields (Noman and Tahir, 2002) within watersheds. Traditionally, modelling of arid region Wadi catchments has suffered from the lack or limitation of the necessary hydrological and meteorological observations (Pilgrim et al., 1988). Very few models were developed specifically for arid Wadi catchment modelling (e.g. El-Hames and Richads, 1994), and their unique associated hydrological features.

The proposed research is aiming at better understanding the water resources in an arid Wadi catchment by using an available comprehensive watershed scale model and available datasets. The use of such a modelling approach will improve the understanding of the relationships between different water cycle elements in the catchment (i e: evapotranspiration, rainfall-runoff, sedimentation and recharge) and the effects of management practices (i.e. recharge dams and groundwater abstraction) on the water balance of the catchment.

1.7 The aim

Assessment of the feasibility of using an available hydrological watershed model for integrated catchment management in the arid, data poor Arabian Gulf region, using a case study from Wadi Ham catchment, United Arab Emirates (UAE).

1.8 The objectives

1- To provide information and guidance on the choice of model for Wadi catchment modelling.
2- To provide guidance on the derivation of model parameters in a data poor region.
3- To provide a critical assessment of the performance of the selected model for the case study catchment.

4- To apply example scenarios of alternative water management practice on the selected case study catchment to demonstrate the potential use of the selected model for better management of water resources.
5- To discuss the use of the selected model for modelling other arid, data poor region, catchments.

2

Hydrological processes and modelling in the arid zone

The hydrology of arid regions is considerably different from that in more humid regions. The arid regions have their own distinctive characteristics that control the hydrological processes. Some of these important features are discussed in more detail in the following section, including (where appropriate) modelling approaches that have been used.

2.1 Rainfall

Rainfall is the most important environmental factor limiting the development of the arid regions. A single arid region location can receive precipitation of different origins. For example, the eastern arid coast of Saudi Arabia located on the Arabian Gulf, receives four different types of winter precipitation. In addition to the dominant Mediterranean depressions, convection cells, cyclonic depressions in front of the Zagros Mountains and high currents transport air masses from equatorial areas in Sudan and Ethiopia in a north-eastern direction across the Arabian Peninsula to provide rainfall for the area (Barth and Steinkohl, 2004).

Precipitation of arid zones that results from depressions and convective cloud mechanisms produce storms, which are typically of short duration and relatively high intensity. Table 2.1 shows examples of extreme rainfall events for ten stations in arid zones around the world. However, low intensity frontal-type rains are also sometimes experienced, usually in the winter season (Jones et al., 1981).

Rainfall distribution in arid regions is characterised by high spatio-temporal variability. It varies from one year to another and between the seasons of summer and winter. The difference between the lowest and highest annual rainfall recorded in different years can be significant, although it is usually within a range of ± 50% of the mean annual rainfall (FAO, 1989).

Table 2.1 Examples of extreme rainfall events in arid zones (after Tooth, 2000).

Location	Year of event	Mean annual precipitation (mm)	Storm event precipitation (mm)
Chicama, Peru	1925	4	394
Aozou, central Sahara	1934	30	370 / 3 days
Swakopmund, Namibia	1934	15	50
Lima, Peru	1925	46	1524
Sharjah, UAE	1957	107	74 / 50 min
Tamanrasset, central Sahara	1950	27	44 / 3 h
Mt. Dare, central Australia	1967	126	149 / 1 day
Bisra, Algeria	1969	148	210 / 2 days
El Djem, Tunisia	1969	275	319 / 3 days
Alice Springs, central Australia	1988	275	205 / 1 day

In terms of the long term temporal variability associated with rainfall occurrence in some arid regions, Hess (1995) analyzed rainfall records of four stations from the North East arid zone of Nigeria. The analysis showed significant decline in annual rainfall over the period from 1961 to 1990 by an average of 8 mm/year. The reduction in rainfall was due to a reduction of 6 to 25 days in the number of rain-days during the rainy season. No shortening of the season or reduction in mean rainfall per rain-day was detected.

The spatial variability of rainfall events in arid regions is highly evident. In general, greater spatial variation of rainfall occurs in arid regions than in more humid regions (Pilgrim et al., 1988). The annual rainfall volume at nearby stations can vary significantly. According to Jones et al. (1981) during a storm, it is common for appreciable amounts of rainfall to be observed at a single raingauge site while all neighbouring raingauges record little or no rainfall. A study from Wadi Yiba (2869 km^2) in southwest Saudi Arabia by Wheater et al. (1991) showed that for an 8 to 10 km inter-gauge spacing and on 51% of raindays, only one or two raingauges out of 20 experienced rainfall. The sub-daily rainfall showed an even more variable behaviour than the daily distribution.

In term of the effects of elevation, Wheater (2002) reported that no clear relationships between elevation and rainfall intensity or duration of rainfall were observed in studies in Wadi catchments in Saudi Arabia and Yemen. However, a strong relationship was identified between the frequency of rain days and elevation. He concluded that once rainfall occurred, its point properties were similar over the catchment but occurrence was more likely at the higher elevations (Wheater, 2002).

Rainfall is a basic hydrological parameter and a major input to all hydrological models. Accurate spatial and temporal representation of rainfall events over a catchment is an important requirement for achieving good model results.

2.2 Evapotranspiration

Evapotranspiration (ET) is defined as the sum of the amount of water returned to the atmosphere through the processes of evaporation and transpiration (Hansen et al., 1980). The evaporation component of ET is comprised of the direct evaporative loss from the soil surface, standing water, and intercepted water by leaves or roofs etc. Transpiration is that water used by the vegetation and subsequently lost to the atmosphere through the leaf stomata (Hansen et al., 1980).

As a related concept to ET, the potential evapotranspiration (PET) is considered to be the maximum ET rate possible for a given set of meteorological and physical soil and vegetation parameters if the soil/vegetation mass had an unlimited supply of water available (Dingman 1994). The important controlling factors (Fontenot, 2004) are:

- meteorological - solar radiation, air temperature, humidity, and wind speed;
- vegetation - leaf shape, plant growth stage, leaf albedo, crop height and stomatal resistance;
- soil- heat capacity, soil albedo, and soil chemistry.

The actual crop ET can be measured (directly or indirectly) or estimated. Rana and Katerji (2000) reviewed several methods, of a variety of approaches, for the measurement and estimation of actual evapotranspiration in the field under a Mediterranean (arid and semi-arid) climate:

- hydrological approaches- soil water balance and weighing lysimeter methods;
- micrometeorological approaches- energy balance:Bowen ratio, aerodynamic and eddy covariance methods;
- plant physiology approaches- sap flow and chambers system methods;
- analytical approach, Penman–Monteith model;
- and, empirical approaches, crop coefficient and soil water balance modelling methods.

They have concluded that some methods are more suitable than others in terms of convenience, accuracy or cost for the measurement of ET at a particular spatial scale and over a particular time scale (Table 2.2). The ET measurement methods are based on concepts which can be critical under semi-arid and arid environments for several reasons:

- representativeness e. g. weighing lysimeter: where the data are not always representative of conditions of the whole field but represent only the ET of just one point in the field. Soil, elevation and vegetation density differences between the lysimeter and outside vegetation can severely affect the ET measurements.

- instrumentation (e g. Bowen ratio): where accuracy difficulties related to continuous recording using differential psychrometry, and the calibration of thermometers in order to detect temperature differences of 0.05–0.2°C is observed.
- microclimate e. g. chamber systems: where modification of the microclimate during the measurement period occurs. For example, the rapid increase in air temperature inside the chambers could alter the biological control of the leaf transpiration process, and reduced wind speed has direct consequences on ET measurement accuracy.
- hypothesis of applicability e. g. the simplified aerodynamic method: where the accuracy depends on the number of measurement levels of wind speed and temperature profiles. The commonly used simplified version of the method is based on the measurement of wind speed and temperature at two levels only. Thus, aerodynamic method does not work with enough accuracy on tall crops.

The more operational methods for actual ET estimation are the analytical modelling methods of ET (i.e. Penman, 1948), methods based on soil water balance modelling (i.e. water reservoir model) and finally the methods in which actual crop ET is deduced from the evapotranspiration of a reference (i.e. ETo is the water consumed by a standard crop). According to Rana and Katerji (2000), the accuracy of ET estimation methods is proportional to the degree of empiricism in the model or sub-models.

It can be seen from the previous review that the ET measurement methods can have their own limitations under arid climate regimes. The more operational and practical modelling approaches for ET are the ET estimation methods, for a catchment, where ET can be estimated according to the available climatologic and vegetation dataset. The following section reviews modelling approaches of ET estimation under arid region conditions.

Table 2.2 Summary of the advantages and disadvantages of seven ET measurement methods (after Rana and Katerji, 2000).

Measurement method	Advantages	Disadvantages
Soil water balance	Soil moisture simple to be evaluated with gravimetric method (Not expensive if the gravimetric method is used)	Large spatial variability / Difficult to be applied when drainage and capillary rising are important / Difficult to measure soil moisture in cracked soils
Weighing lysimeter	Direct method	Fixed / Difficult maintenance / It could be not representative of the plot area / Expensive
Energy balance/ Bowen ratio	Simple sensors to be installed / Suitable also for tall crops / It can be used when the fetch is 20:1 / Not very expensive if psychrometers are used	Difficult to have correct measurement of the wet temperature if psychrometers are used / The sensors need to be inverted to reduce bias / Difficult maintenance
Aerodynamic	Simple sensors to be installed / It does not need humidity measurements / Not very expensive	needs to be corrected for stability / Not suitable for tall crops
Eddy covariance	Direct method with fast hygrometer	Delicate sensors / Difficult software for data acquisition / Hygrometer very delicate and expensive
Sap flow	Suitable for small plots / It takes into account the variability among plants	Difficult scaling-up / The gauges need to be replaced every 1–2 weeks / The soil evaporation is neglected
Chamber method	Suitable for small plots / It can be used also for detecting emissions of different gases	modifies the microclimate / Difficult scaling-up

2.3 Modelling approaches of ET

Knowledge of evapotranspiration is an essential requirement for numerous water planning activities and hydrological investigations. A large number of methods have been developed world wide to estimate evapotranspiration, empirically through field experiments (e.g. Jensen and Haise, 1963) or by incorporating theoretical approaches that involve a combination of the energy budget and mass transfer methods (e.g. Penman, 1948 and Hargreaves and Samani 1985).

The concept of reference evapotranspiration (ETo) has been developed in order to eliminate all the vegetation and soil specific characteristics that could affect the estimation of evapotranspiration, and to leave only climatological factors to be considered as affecting the evaporative demand of the atmosphere (Fontenot, 2004). Reference evapotranspiration (ETo) is defined by Allen et al. (1998) as the rate of potential evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground and with adequate water.

Commonly grass and alfalfa were used as two reference ET surfaces based on the availability of relevant data. FAO recommended short clipped grass as the primary reference surface to be use on a world wide scale (Pereira et al., 1999). Alternatively, alfalfa has been used more in arid regions (Wright and Jensen 1972, 1978; Allen et al., 1989; Jensen et al., 1990 and Abo-Ghobar and Mohammad 1995). Although, the reference ET ratio between the two references types (ETr (alfalfa)/ETo (grass)) changes with climate and possibly with the time of the year, a general ratio to predict or convert between the two reference surfaces (ETr/ETo) is 1.1 for humid and sub-humid, and 1.2 to 1.25 for semi-arid and arid climates respectively (Allen, 1999).

In the southern arid region of Saudi Arabia, five methods for the estimation of alfalfa reference evapotranspiration, ETr, for four areas (located at the coast and inland) were evaluated by Al-Ghobari (2000). The methods were FAO-Penman, Jensen-Haise, Blaney & Criddle, pan evaporation, and calibrated

FAO-Penman under local conditions (Penman-SA). Comparison was made between the estimated ETr and the measured ETr of alfalfa grown in lysimeters in the Riyadh area. The results indicated that no one method provided the best results under all conditions (Figure 2.1). However, it was found that the ETr estimated by the different methods was closely correlated with the ETr measured. The calibrated Penman-SA method gave the estimates closest to the values measured in comparison to the uncalibrated methods.

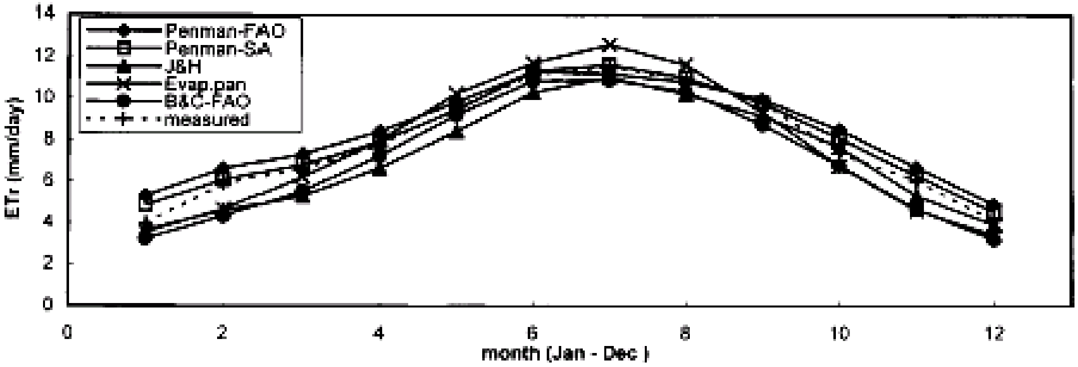


Figure 2.1 Average monthly Potential Evapo-transpiration for alfalfa (ETr) calculated by different methods for Riyadh in Saudi Arabia (Al-Ghobari, 2000).

In another attempt to study the performance of different estimation methods under arid region conditions, Shahin (1998) studied the performance of four methods for the estimation of reference evapotranspiration using data from fourteen meteorological stations in the Arabian Peninsula. The results obtained showed that values estimated by the FAO-Blaney-Criddle and FAO-Penman methods are 10% larger than grass evapotranspiration estimated by FAO-Penman-Monteith method. Conversely, values estimated with the Hargreaves method were, on average, 6% less than from the FAO-Penman-Monteith method. He also observed that the Hargreaves method considerably underestimated ETo for the coastal stations compared to the other methods. He related the underestimation to the small difference between the mean maximum temperature and mean minimum temperature values, used in the equation, for coastal areas.

Allen et al. (1998) recommends the FAO-56 Penman-Monteith method for grass evapotranspiration, ETo, as the single standard method that has a strong likelihood to correctly predict ETo in a wide range of locations and climates and which has provision for its application in data-short situations. This strong recommendation is based on the performance of the model and its incorporation of plant physiological and aerodynamic micrometeorological factors for the estimation of reference evapotranspiration. On the other hand Smith et al., (1996) stated that among the temperature methods for the estimation of ETo which require calibration for the local conditions, the 1985 Hargreaves method (Hargreaves and Samani, 1985), could be a possible exception that showed reasonable ETo estimation results with global validity. They presented a table after Jensen et al. (1990) with the performance of various ETo methods. The performance of the Hargreaves method in the arid locations indicates an underestimation of 9%, while Penman-Monteith underestimated by only 1% from 11-lysimeter data locations. As a general observation, it seems that the Hargreaves method has a tendency to underestimate ETo under high wind conditions (u_2 > 3 m/s) and to overestimate under conditions of high relative humidity (Allen et al., 1998). Generally the Hargreaves method has shown reasonable ETo results with world wide validity including arid regions (George et al., 2002; Xu and Singh, 2002 and Shahin, 1998).

As a conclusion, the FAO-56 Penman-Monteith is the recommended method for the estimation of ETo in the arid regions. Alternatively, and to get best results from limited datasets available in some arid regions, the 1985 Hargreaves method could be an acceptable temperature method for the calculation of ETo (Jensen et al., 1997; Stefano and Ferro, 1997). Another possible alternative can be the calibration of the Hargreaves method for local conditions based on FAO-56 Penman-Monteith estimation under data-short situations as recommended by Allen et al. (1998).

2.4 Surface Runoff

Typically surface runoff can be defined as that part of the precipitation which flows on the ground surface (UNESCO, 2002). In arid lands surface runoff originates and occurs sporadically as short, isolated flow periods separated by longer periods of low or nil flow. Continued flow is rare, and prolonged base flows occur only in channels fed from outside the region or by discharging groundwater (Jones et al., 1981). The short duration, ephemeral characteristics of surface runoff in arid catchments originate because of some distinctive features associated with, and controlling, its routing, which can be summarised as following:

1- The variability of rainfall intensity in both space and time over the catchment.
2- The influence of soil type and properties (e.g. infiltration capacity) in runoff production.
3- Sparse plant cover and relative absence of organic matter and litter on the ground surface.
4- The absence of base-flow.
5- The water table is usually below the streambed and detached from surface drainage systems so that transmission losses are an important process associated with channel stream flow. However, a temporary saturated hydraulic connection may occur in flood events.

The runoff in arid and semi-arid areas can be described as flashy, in terms of the duration of flow, since large amounts of surface runoff move into the ephemeral channels (Figure 2.2) in a short period of time (Smith and Ward 1998).

The flash flood hydrograph has a short duration and steep rising and falling limbs. The steep rise results from high rainfall intensity and sometimes from the catchment topography such as steepness of the channels draining the distinct runoff generating zones. The short duration of the hydrograph reflects the high rate of infiltration into the channel bed sediments, and the absence of base flow (Sharma and Murthy 1996; El-Hames and Richards, 1994). Sometimes, a multi peaked flash flow can be generated at water diversion sites in the lower reaches (Figure 2.3).

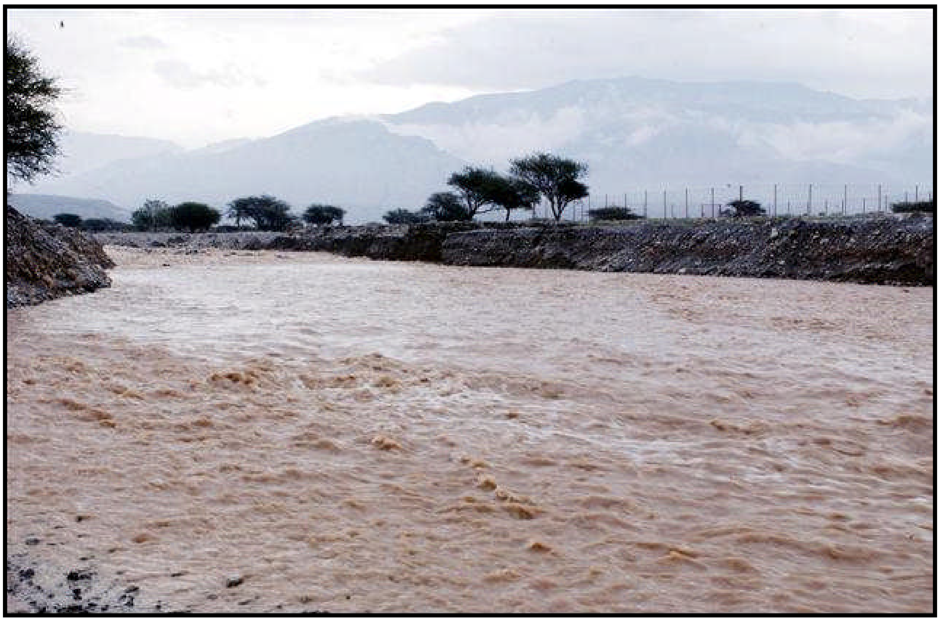


Figure 2.2 Surface runoff in ephemeral channel.

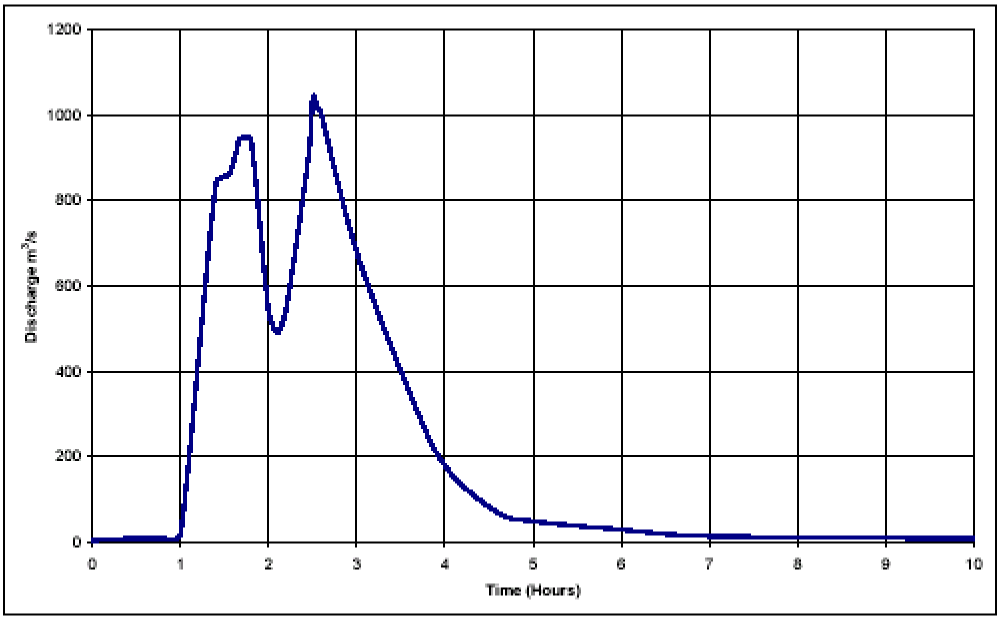


Figure 2.3 Multi peak flash flood hydrograph from Wadi Rima catchment in Yemen (WHO, 2004).

Rambla de la Viuda catchment (1289 km^2) in Spain is a good example of the hydrological behaviour of semi-arid ephemeral streams. Camrasa Belmonte and Beltran (2001) describe the causes of the dominant flash flood events as the intense, heavy and irregularly distributed rainfall and the characteristics of the drainage basin i.e. steep slopes, sparse vegetation, thin soil layers and highly fractured limestone rocks. Despite the large volumes of discharge during flood events, their analysis showed that the hydrological losses of evapotranspiration, infiltration and transmission losses significantly affected the runoff processes. For instance in 1962, rainfall totalled 519.43 x 10^6 m^3 while the discharge was only 85.98 x 10^6 m^3, giving an overall runoff coefficient estimated at only 16.6%.

Partial-area runoff is another hydrological phenomenon which occurs under arid catchment conditions. According to Pilgrim et al. (1988) the predominant runoff mechanism in arid catchments is Hortonian overland flow where the rainfall intensity exceeds the potential rate of infiltration. He reported several views that appointed the partial-area runoff in arid catchments to the spatial differences in infiltration capacity where the lower infiltration capacity areas, in valley bottoms and along stream channels caused by coarser more compacted rock rubble and fine material washed into the valley bottoms by previous events, to be the cause for such phenomenon.

Shaw (1989) described a high magnitude flood storm event in 1981 in Wadi Adai (380 km^2) in Oman that was caused by the eastward penetration of a depression over the Mediterranean Sea with an association of a secondary low pressure system developed over the Arabian Gulf. The storm rainfall over the Wadi catchment was estimated at 89 mm. With an overall runoff coefficient of 56%, the hydrograph showed a peak of 1163 m^3/s. Such high magnitude floods which are generated on arid smooth or steep sloping drainage basins may have the potential to cause extensive damage (Smith and Ward 1998; Shehata and Amin 1997).

2.5 Rainfall-runoff modelling approaches

Arid zone catchments and especially the sloping regions with their stream network and plain lands with their primitive stream network require a rainfall-runoff modelling approach that takes into account the previously discussed distinctive features that dominate their hydrological behaviour.

Obviously a large range of modeling approaches have been applied throughout the arid regions of the world. As an overview, runoff models can be considered as deterministic, which simulate the processes in the catchment to convert the precipitation into a unique value of runoff, or stochastic models which consider the chance of occurrence and probability of hydrological variables. Another description is empirical, conceptual or physically-based models, which depends on the emphasis given to the physical processes acting on the inputs to produce the output runoff. Models may also be lumped, semi-distributed or distributed, based on the representation (if any) of the spatial distribution in the hydrological variables within the catchment (Ward and Robinson, 1990).

Al-Qurashi and Herbertson (1999) used an empirical modelling approach to study the rainfall-runoff relationship for Wadi Ahin (900 km^2) in Oman. A simple linear regression correlation was employed to determine the relationship between rainfall and total runoff for selected events. The correlation obtained for four studied events was poor (r = 0.85, 0.50, 0.46 and 0.74) as the rainfall-runoff relationships were found to vary from summer to winter, with the summer events tending to yield a greater percentage of runoff due to the higher rainfall intensities and the negligible interception capacities. The evapotranspiration and transmission losses were found to vary considerably from event to event. The relationships showed that evapotranspiration and transmission losses are high and vary from less than 8 mm to around 20 mm (Al-Qurashi and Herbertson, 1999).

In another empirical approach, Sharma (2000) developed a series of regression models for rainfall-runoff relationships based on the drainage catchment areas for the Jamnagar district in the arid Gujarat region of India. The study aimed to predict peak flows and water yield for the management of water resources in the district. The total runoff tended to decrease with increasing area of the drainage catchment. Using 30 years of observation data, the runoff coefficient (a ratio of runoff to rainfall) was found to vary from 0.07 to 0.29. The larger catchments with their longer flow streams and longer opportunity for rainfall infiltration had the lowest runoff coefficient. Although used frequently, such empirical methods have significant limitations when used in arid regions because they only determine flood magnitudes without considering the time of occurrence of floods or the recurrence interval of the flood discharge (El-Hames and Richards, 1994).

Flood frequency methods provide reasonable information about flood magnitudes and their frequency but they can’t provide a comprehensive physical description of flood hydrograph. In particular, flood frequency methods cannot define the continuous response of runoff in flood hydrographs (El-Hames and Richards, 1994).

As cited in El-Hames and Richards (1994), Lane (1982) used the lumped conceptual model based on the Curve Number (CN) method of the USA Soil Conservation Service (SCS, 1972) in a number of small arid catchments in south-western USA to estimate the runoff volume. Lane (1982) reported satisfactory results obtained from applying the CN method and argued the superiority of the method to other methods in terms of data requirements due to its one parameter model, and availability of values of runoff Curve Number (CNs) for many soil types. The lumped conceptual models such as the CN method, the unit hydrograph and Geomorphological Instantaneous Unit Hydrograph (GIUH) must be applied with great care especially in large arid catchments because of high spatial variability of rainfall and soil characteristics within the catchment (El-Hames and Richards, 1994).

Semi-distributed and physically based models have the ability to forecast the spatial pattern of hydrological conditions within a catchment. However, most of the common semi-distributed or distributed physically based models such as

SHE, IHDM4, SWMM and TOPMODEL have a major component that makes them less relevant to arid regions, which is their emphasis on delayed or base flow, and on quick flow generated by subsurface flow, which is also treated as a factor contributing to surface flow as a result of lateral flow creating zones of soil saturation where saturation overland flow is generated (El-Hames and Richads, 1994). Any development of physically-based models for rainfall-runoff modelling suitable for arid catchments should account for some specific hydrological components included in the analysis, which are the determination of excess rainfall by calculating the infiltration rate, accumulation of flow generated on hillslopes in stream networks and routing it to the channel outlet taking into account the transmission loss into channel bed. A model structured as described above was developed by El-Hames (1993) and applied to storm events in catchments in Saudi Arabia (Wadi Tabalah 170 km^2) for which it showed considerable potential and reasonable simulation results that can be achieved with a minimum of calibration for arid region catchments.

The comparative performance of simple and more complex models has also been tested. For example, Hughes and Beater (1989) tested the comparative performance of single event lumped and semi-distributed models in catchments with different physical characteristics within semi-arid region models. The two models (OSE1) and (OSE2) operated as a lumped format and as a semi-distributed format, respectively. In the lumped model one rainfall input and one set of parameters were applied to the whole catchment, while in the semi-distributed version a series of user defined sub-catchments had their own rainfall input and set of model parameters. The results of modelling 174 rainfall-runoff events from 16 medium sized catchments in USA and South Africa showed that the simpler model appeared to perform as well as the more complex one when the spatial variability of rainfall was small.

Hernandez et al. (2000) modelled the runoff response to land cover and rainfall spatial variability in a small semi-arid watershed using two contrasting hydrological models. The first model was an event-based model (KINERO) with a one-minute time step and the second was a continuous model (SWAT) with daily time step. The inputs to the models were derived from GIS theme layers of USGS digital elevation models, the State Soil Geographic Database (STATSGO) and the Landsat-based North American Landscape Characterization classification (NALC) in conjunction with available literature and look up tables. Rainfall from a network of 10 raingauges and historical stream flow data were used to calibrate runoff depth from 1966 to 1974. The simulation results showed that both models were able to characterize the runoff response of the watershed due to changes in land cover.

Dual modeling approaches have also been developed. For example, (El-Hames and Richards (1998) utilised both the kinematic wave theory and the full solution of the St Venant equations in order to account for flood routing over slopes and down Wadi channels, respectively. An infiltration method based on the Crank-Nicholson numerical scheme to solve Richards' equation was coupled with the above flood routing techniques. The complete model has been tested in an arid region catchment (200 km^2), and performed well for runoff prediction in such a medium-sized catchment and for transmission loss simulation in arid Wadis. Data were obtained by dividing the catchment into a number of roughly homogeneous units. Rainfall data were collected on an hourly basis by five rain gauges scattered over an area of about 560 km^{2,} where only one of these rain gauges was inside the catchment area. The soil profile data employed in simulation were derived from well logging data. However, the model requires a very long CPU time to complete a simulation Thus they have recommended that the model cannot be practically used on personal computers.

Some hydrological modelling experience has shown different simulation performances according to flood size such as the results of Martin-Vide et al (1999). They studied a typical ephemeral stream (30 km^2) in the Spanish Mediterranean using a conventional distributed hydrological rainfall-runoff model (HEC-1) which is most commonly used in hydrological analysis in Spain. The model showed the capability to reproduce the measured hydrographs of major floods and to lesser extent the minor events.

2.6 Groundwater recharge

Groundwater recharge is the process by which water is added to the zone of saturation of an aquifer, either directly into a formation, or indirectly by way of another formation (UNESCO, 2002). Groundwater recharge may occur naturally from precipitation, rivers, channels, reservoirs and lakes or by man-made activities such as irrigation and urban developments. In terms of the sources of recharge to groundwater in semi-arid and arid areas, it has been distinguished by De Vries and Simmers (2002) (conceptually simplified from Lerner 1990) (Figure 2.4) into:

- Direct recharge: water added to the groundwater reservoir in excess of soil-moisture deficits and evapotranspiration by direct vertical percolation through the unsaturated zone i.e. recharge from precipitation or irrigation occurs fairly uniformly over large areas.
- Indirect recharge: percolation to the water table through the beds of surface-water courses i.e. streams and lakes.
- Localized recharge: an intermediate form of groundwater recharge resulting from the horizontal (near-) surface concentration of water in the absence of well defined channels i.e. joints or rivulets.

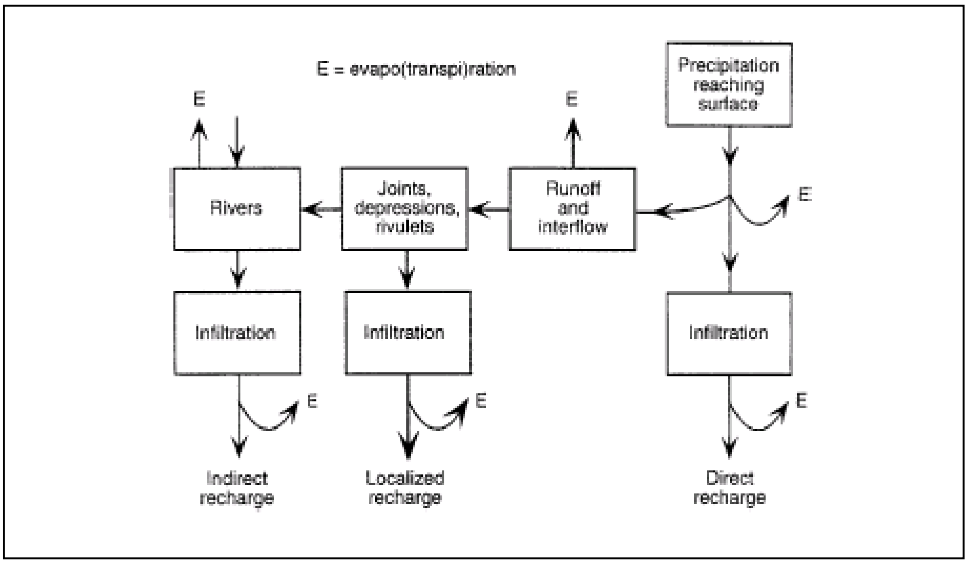


Figure 2.4 Groundwater recharge mechanisms in semi-arid regions as expressed by Lerner (1997) (After De Varies and Simmers 2002).

In many locations, all the previous mechanisms occur to some extent even in the most arid areas. But as the aridity increases, the direct recharge is expected to become less important than indirect and localized recharge, in terms of total recharge to an aquifer (De Vries and Simmers, 2002 and Lerner, 1990).

The estimation methods of groundwater recharge can be subdivided into three different types, based on the hydrologic zone they are modelling or monitoring: specifically, surface water, unsaturated zone, and saturated zone. Within each zone, methods can be classified as well into:

- physical methods, such as those based on the application of Darcy's law;
- tracer methods, such as chloride mass-balance approach, or;
- numerical modelling approaches such as watershed rainfall/runoff modelling approaches.

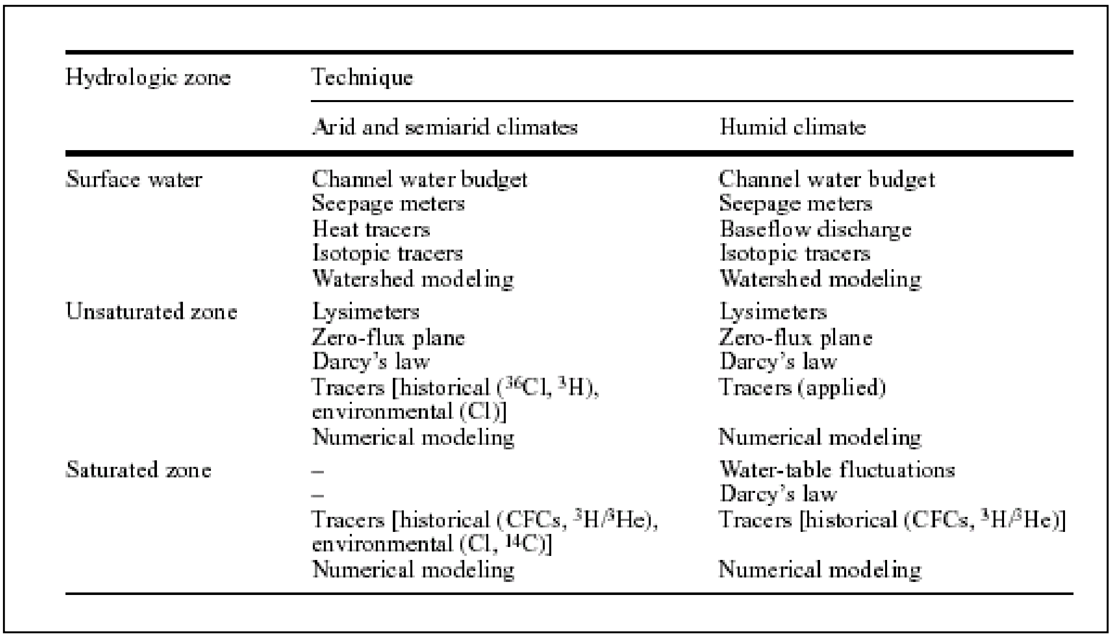
Methods based on surface-water and unsaturated-zone modelling or monitoring provide estimates of potential recharge, whereas methods based on groundwater modelling provide estimates of actual recharge to the aquifer.

Scanlon et al. (2002) summarised different methods that can be used in groundwater recharge studies (Table 2.4). They have concluded that choosing appropriate techniques for a specific site is highly dependent on a number of aspects:

- available background information i.e. climate, geomorphology, hydrology etc.;
- sources and mechanisms of recharge i.e. gaining or losing streams;
- the required accuracy of recharge estimates i.e. actual or potential recharge, and;
- the limitation of time and expense.

The natural groundwater recharge is limited by the availability of water at the land surface, which is controlled by climatic factors of precipitation and evapotranspiration, and by the surface geomorphic features. For example, the mountainous alluvial valley aquifers of the arid region are dominated by recharge focused in the channels of the ephemeral streams. The local rainstorm will be concentrated into alluvial channels by flow that originates from the surrounding higher lands. The alluvial fans at the base of mountains fronts will obtain recharge from streams draining from the adjoining mountains (Scanlon, 2002 and Jones et al., 1981). In experience from Wadi Tabalah in Saudi Arabia, Sorman and Abdulrazzak (1993) showed rises in the groundwater table due to transmission losses and they have estimated that an average of 75% of stream bed infiltration reached the water table.

Table 2.3 Methods of groundwater recharge estimation for arid and humid regions (After Scanlon et al., 2002).



Hydrologic zone	Technique	
	Arid and semiarid climates	Humid climate
Surface water	Channel water budget	Channel water budget
	Seepage meters	Seepage meters
	Heat tracers	Baseflow discharge
	Isotopic tracers	Isotopic tracers
	Watershed modeling	Watershed modeling
Unsaturated zone	Lysimeters	Lysimeters
	Zero-flux plane	Zero-flux plane
	Darcy's law	Darcy's law
	Tracers [historical (^{36}Cl, ^{3}H), environmental (Cl)]	Tracers (applied)
	Numerical modeling	Numerical modeling
Saturated zone	–	Water-table fluctuations
	–	Darcy's law
	Tracers [historical (CFCs, ^{3}H/^{3}He), environmental (Cl, ^{14}C)]	Tracers [historical (CFCs, ^{3}H/^{3}He)]
	Numerical modeling	Numerical modeling

Transmission losses from surface runoff via infiltration through the ephemeral stream channel bed are the most important recharge mechanism to the underlying aquifer system in Wadi catchments (Sorman et al., 1997 and Sorman and Abdulrazzak, 1993).

2.7 Transmission losses in arid stream channels

Transmission losses in ephemeral stream channels of arid region can be defined as the volume of channel flow reduced due to evaporation and infiltration through the bed, banks and possibly the flood plain (Walters, 1990). It is a common phenomenon in most arid region streams throughout the world (Shentsis et al., 1999 and Sorman et al., 1997).

The potential for infiltration of flood water over any channel reach is controlled by:

- The potential depth of water table below the channel bed and the storage coefficient of the unsaturated alluvium.
- The area of the channel bed occupied by the flood water.
- The surface infiltration capacity and the vertical permeability of the channel alluvium.
- The water temperature.
- The moisture content of the unsaturated zone.
- The nature of the sediment load.
- Volume of floodwater.

Generally it can be assumed (Sharma, 2000) that the runoff coefficient decreases due to transmission losses with increasing area of the drainage basin, since the larger the basin, the longer the flow paths and the longer the opportunity time for streamwater infiltration. However, it is likely that reach transmission loss upper limit can be constrained by the channel characteristics and possible causes such as air entrapment that could restrict infiltration rates, effects of bed mobilisation and pore blockage by the heavy sediment loads transmitted under flood flow conditions (Wheater, 2002).

As an example of transmission losses in an arid catchment, Al-Qurashi and Herbertson (1999) determined the transmission losses between two runoff gauging stations, located 42 km apart, in Wadi Ahin, Oman. The total volume of losses between the two stations was found to be in the range of 88-95% for high floods and about 100% for small floods. A very strong correlation (r = 0.999) was found between total loss and the flow volume passing the upstream station.

2.8 Transmission losses modelling approaches

A range of modeling approaches have been used to study the effects of transmission losses on runoff and aquifer recharge. Generally the methods used to assess the transmission losses vary between simple empirical regression equations to more complex physically based approaches. El-Hames and Richads (1994) have reviewed some methods that have been developed to aid the estimation of transmission losses from channel flow in arid regions and have the following comments:

- Smith (1972) coupled the kinematic wave model with an algebraic infiltration formula. The method was recommended for initially dry channels with infiltrating beds.
- Jordan (1977) studied streamflow transmission losses by applying simple assumptions and empirical formulae, and found that the transmission loss per mile for medium to large sized streams averaged about 2% of the flow volume at the beginning of the mile.
- Lane (1982) used differential equations with empirical and statistical techniques and the SCS (US Soil Conservation Service, 1972) method to study transmission losses in 14 channel reaches in Arizona and Texas. His model was recommended, as cited in El-Hames and Richads (1994), for use in small semi-arid watersheds of up to a few tens of square kilometers.
- Walters (1990) studied the relationship between transmission loss and channel geometry and the input flood volume in southern Saudi Arabia. Three regression equations were developed for prediction of transmission losses for large to small flood events with the best estimated standard error of 0.91. These equations were not recommended as extrapolation tools,

since they do not account for difference in any of the physical variables that should affect transmission loss.

- Sorman and Abdulrazzak (1993) included the effect of tributary flow on the transmission loss processes. They concluded that good estimation of the initial moisture condition is a key factor on which the success of any transmission loss prediction depends.

In another approach a hydrological-lithostratigraphical model was developed by Shentsis (1999) to assess transmission losses and groundwater recharge from runoff events in an arid watershed where hydrological and meteorological data are not sufficient. The model consisted of a water balance equation and a function which relates transmission losses to total inflow for a Wadi reach between hydrometric stations. The loss function relies on a hydrological-lithostratigraphical analogy and the concept that the distribution of rainfall is reflected by the relative runoff at different sites. The application of the model to another arid reach whose lateral inflow was directly estimated, results in a good agreement between the loss function for this reach and that for the studied one.

Based upon the above studies, it is considered that a modelling approach to assess runoff and recharge of alluvial aquifers in arid regions should take into account the transmission losses in stream channels. The transmission loss modelling approach should account for catchment size, soil (channel bed) properties, and water table depth below the channel bed. Generally physically based approaches combining hydraulic channel-routing procedures with an infiltration model can lead to better transmission loss prediction in arid region stream channels.

2.9 Erosion and Sedimentation

The extreme climate of heavy and very variable rainfall, high wind velocities, high diurnal temperature range, excessive weathering processes and the sparse vegetation cover, together with human activities i.e. rock and aggregate mining, give a high potential for erosion in arid region catchments.

Generally, large quantities of sediment are transported during flood events (Jones, 1981), both as suspended load and as bedload, in arid drainage basins (Tooth, 2000). The quantity of sediment reflects the ready mobilisation and delivery of material from sparsely or unevenly vegetated hillslopes to the river channel systems, and the availability of transportable material on the river channel beds (Tooth, 2000). The availability of large amounts of erodible material ready to be transported means that sediment transport is usually governed by the transport capacity of the event runoff rather than being supply-limited (Sharma et al., 1996).

The eroded material from the hillslopes and channel system is transported within the channel system and settles out through sedimentation within the channel system, the reservoir or by deposition in alluvial fans. In some Wadi systems, erosion of the original loess substrate has been so extreme that the underlying rock has been exposed. The loss of the loess substrate affects the soil nutrients, plant community structure and plant quality (Ward et al., 2001).

Sedimentation within arid region reservoirs (Table 2.5) is important to the design and operation of dams and structures (such as check dams and weirs) which are intended to detain flash floods, for use as temporary irrigation resources and to enhance the groundwater recharge potential of such areas. The sedimentation reduces the reservoir capacity and the infiltration rate from the reservoir bottom.

Table 2.4 Measured sedimentation rates for two rainy seasons in two Wadi dam reservoirs in Jordan valley during 2001/2002 and 2002/2003 (modified from Al-Kharabsheh et al., 2003).

Dam	Reservoir area (m^2)	Sedimentation mean thickness(cm)		Mean of sedimentation volume (m^3)	
		2001/2002	2002/2003	2001/2002	2002/2003
Dafali-C.	1100	35.29	44.09	388.19	484.99
Dafali-S.	1000	27.76	43.22	277.6	432.2

The rate of reservoir sedimentation depends on a number of climatic, geographic and human factors such as agricultural practices and urbanization in addition to the size, shape and operational method of the reservoir. For example, some reservoirs such as Burrinijuck reservoir in Australia have experienced declining rates of sedimentation. This results from the tributary channels becoming progressively less important sources of sediment as they equilibrate after their initial highly erosive stage following land use change (Srikathan and Wasson, 1993). Sekhar and Rao (2002) found that the soil being eroded from the catchment area of the Sriramsagar reservoir in India was more than the value adopted in the primary design of reservoir. Based on an analysis using remote sensing and GIS, the construction of additional check dams was proposed so that the soil erosion might be kept within the design value of the reservoir.

2.10 Erosion modelling approaches

Soil erosion modelling can be defined as the process of mathematically describing soil particle detachment, transport and deposition on a land surface (Nearing et al., 1994). Basically three types of soil erosion models can be identified:

- empirical models that are based on statistical relationships;
- conceptual lumped models, and;
- physically-based models which represent a synthesis of individual components with their interactions on the spatio-temporal scale that affects the erosion processes within the catchment.

A range of modelling approaches have been undertaken to simulate erosion and sediment transport at the catchment scale in arid regions. The empirical modelling approach based on the Universal Soil Loss Equation (USLE) has been used widely in catchment erosion studies. It appears that the USLE approach is weak in simulating the erosion that results from extreme events when sediment discharge from scouring and channel processes are important, leading to an under estimation of the erosion rate (Jetten and De Roo, 1998).

Since the USLE was primarily developed for croplands on hillslopes, Coronato and Del Valle (1993) reported that including gully erosion calculations in the USLE can be an important factor to improve the USLE when it is applied to arid rangelands.

The modified USLE (MUSLE) was developed to estimate erosion and sediment yield on an individual storm basis. The MUSLE replaced the rainfall energy factor from the USLE with a runoff erosivity factor, and included experience from different landscapes including semi-arid regions (Williams, 1995). In 1987 the US Department of Agriculture (USDA) revised the USLE and a new version was released as the Revised USLE (RUSLE). In the RUSLE the effect of slopes up to 60% were tabulated, the rainfall erosivity factor was modified to include both rainfall and runoff erosivity factors. The crop factor was separated into several sub-factors accounting for previous land use, crop canopy, surface cover and roughness (Lal, 2001). Since the RUSLE has a better representation of natural areas of rangelands, it has been implemented in some semi-arid to arid areas (Essa, 2004 and Renard, 1994) with satisfactory results on an average annual basis.

Sharma and Murthy (1993) developed a soil erosion model for arid zone drainage basins which takes into account the different hydrological processes that dominate in the uplands, where the sediment movement follows the principle of continuity of mass, and in the channel phases, where the sediment transport capacity is reduced by transmission losses of flood flows resulting in deposition of sediment. The combination of a physically based model of sediment transport in the upland phase and instantaneous unit sediment graph model in the channel phase produced a close accord between the calculated and observed sediment transport rates at the outlet of the catchment.

The use of Geographic Information Systems (GIS) and remote sensing in hydrological and erosion modelling offers significant potential for better representation and modelling of catchments. Since erosion can be influenced by many factors such as rainfall distribution, and soil, topographical and land use-related factors which all vary in both space and time, the use of GIS offers considerable potential for improved modelling and estimation of erosion and sediment yield (De Roo, 1998 and Moore et al., 1993). In general the use of GIS-based methods to calculate the spatiotemporal variation in catchment erosion and sediment yield has been found to provide satisfactory estimates (Kothyari et al., 2002; Jain & Kothyari, 2000 and Kothyari and Jain, 1997).

On the other hand, it has been found that even spatially distributed and physically based erosion models such as ANSWERS may not necessarily produce better results than much simpler and partly lumped erosion models with representative elements. The disappointing results obtained from spatially distributed models are related to the uncertainty involved in estimating and measuring the large number of input variables at a catchment scale (Jetten, 2003 and De Roo, 1998).

2.11 Summary

The scarcity of available data constitutes probably the greatest problem in arid zone hydrological modelling (Pilgrim et al., 1988 and Jones et al., 1981). As a basic hydrological input to all hydrological models, the accurate spatial and temporal representation of rainfall over a catchment is an important requirement for achieving good model results.

In the estimation of the evapotranspiration, the FAO-56 Penman-Monteith is the recommended method for the estimation of ETo in arid regions. Alternatively, in the case of limited data availability, the Hargreaves method could be an acceptable temperature-based method for the calculation of ETo under arid region conditions.

Rainfall-runoff modelling is a primary technique in operational hydrology. The development of rainfall-runoff models suitable for arid region catchments must account for some specific hydrological components, which are the determinations of:

- infiltration-excess rainfall,
- partial-area runoff,
- accumulation of flow generated on hillslopes in stream networks,
- transmission losses and
- routing to the channel outlet.

These suggest that some form of distributed or semi-distributed model is desirable for arid catchments. Thus, utilizing physically based semi-distributed models in unguaged or poorly gauged catchments is an important alternative to calibrating empirical models in gauged catchments.

Transmission losses from surface runoff via infiltration through the ephemeral stream channel bed are an important groundwater recharge mechanism to the underlying aquifer system in the mountainous Wadi catchments. In general, physically based approaches appear to lead to better transmission loss predictions in arid region stream channels.

The reservoir is an integral component of many water resource systems in arid catchments. Prediction of sedimentation rates is important for long term operation of dams and structures intended to detain flash floods or as a recharge augmentation facility. The use of GIS-based methods to calculate the spatio-temporal variation in catchment erosion and sediment yield can provide satisfactory estimates.

3

Description of the United Arab Emirates (UAE) and Wadi Ham catchment

3.1 Introduction

The United Arab Emirates (UAE) is a federation of the seven emirates of Abu Dhabi, Dubai, Sharjah, Ajman, Umm al-Qaiwain, Ras al-Khaimah and Fujairah. Comprising an area of 83,600 square kilometres (including islands), the country lies between latitudes 22 º- 26.5 º N and longitudes 51 º-56.5 º E at the south east of the Arabian Peninsula. The UAE has some 700 kilometres of coastline, including 100 kilometres on the Gulf of Oman (Figure 3.1). The population of the UAE according to the 1995 census was about 2.41 million and estimated in 2005 to be about 4.32 million (UAE INTERACT, 2005).

Figure 3.1 Location map of UAE (Source: www.uaeinteract.com).

3.2 Climatic Conditions

The UAE is located in the sub-tropical arid zone and is exposed to oceanic influences from the Arabian Gulf and the Indian Ocean (Satchell, 1979). A hot desert climate with high temperatures and infrequent low rainfall is dominant. Generally two seasons are identified, which are a long dry summer with very high temperatures between April and November and a winter season of mild to warm temperatures and slight rainfall between December and March (UAEU, 1993).

Annual rainfall in UAE is highly variable between one year and the next (Figure 3.2). The country-average annual rainfall is around 119 mm/year (UAEU, 1993). Spatially, rainfall distribution is low in the west and south and increases towards the north and east of the UAE (UAEU, 1993). Hence, the East coast on the Gulf of Oman has a higher rainfall than the west coast on the Arabian Gulf. The mountain region has the highest mean annual rainfall amount which is around 157 mm/year (Boer, 1997).

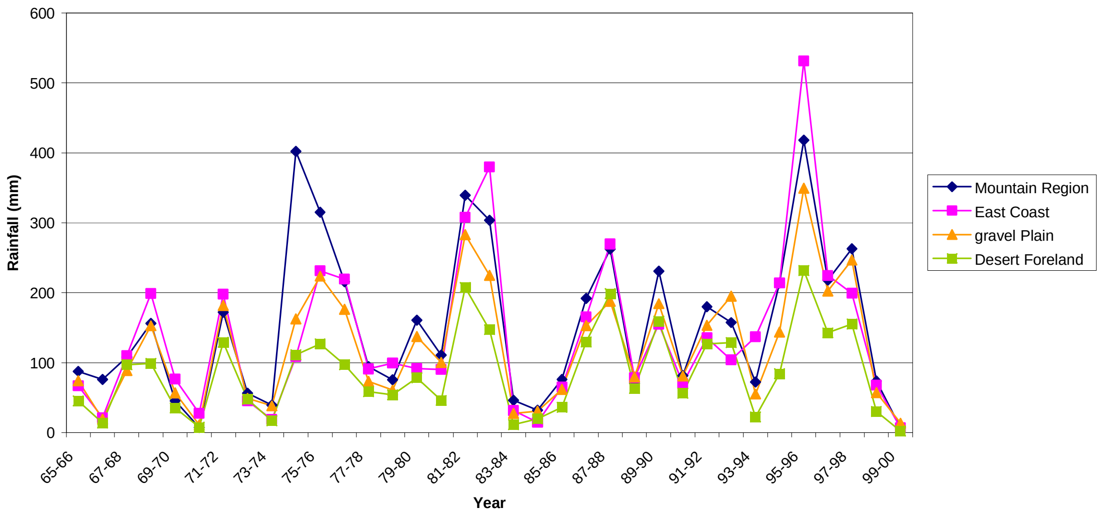


Figure 3. 2 Average annual rainfall (mm) for the UAE for the period 1965-66 to 1999-2000 (MAF, 2001b).

The mean annual temperatures are uniform throughout the country with a slight variation in the mountain region to the east of the country where the mean temperature is 25°C. The mean maximum temperature in summer lies between 41°C and 45°C. July is the hottest month of the year daytime peak temperatures can reach 50°C (UAEU, 1993). The temperatures tend to change seasonally within different regions of the country. According to Boer (1997) the monthly mean temperature of the central desert in the summer exceeds 35°C, but the mountains and the coastal region remains at less than 33°C. The coastal areas can be slightly warmer (less than 20°C) than the terrestrial and eastern mountains region in the winter season. In spring, the mountains and gulf coast regions are cooler (less than 27°C) than the southern terrestrial and east coast regions that can reach 27°C - 28°C or higher. In autumn temperatures all over the country generally remain similar between 27°C to 29°C (Boer, 1997).

Relative humidity is high and reaches more than 90%. Humidity throughout all seasons is higher closer to the Arabian Gulf and the Gulf of Oman coastal zones, and lower in the south, southwest and the eastern mountain zones (Boer, 1997). For instance, the mean annual relative humidity for the coastal Abu Dhabi area is more than 60%, while the equivalent value for the Al-Ain area located southwards of the mountain is less than 45% (UAEU, 1993).

The mean annual wind speed is less than 10 knots with a tendency for winds to be stronger between March and August, predominantly from the north-west and south or south-west (UAEU, 1993). The strength of wind in the regions decreases in the following sequence: coast of the Gulf of Oman, the mountain region, the Arabian Gulf coast, the desert foreland and the interior areas (UAEU, 1993).

The skies over the country are relatively cloud free all year around, with the most extensive cloud cover occurring in March (UAEU, 1993). The average annual sunshine hours are 10 hr/day with a mean maximum of 11.5 hr/day in May and mean minimum of 8.4 hr/day in March (UAEU, 1993).

The mean annual Pan evaporation is about 8.2 mm/day. The evaporation rate peak occurs in July at more than 13 mm/day, while in December and January it is about 4 mm/day (UAEU, 1993).

3.3 Geomorphology

The UAE can be divided into three principal geomorphic regions according to their prevailing surface features (UAEU, 1993). These are the eastern mountain-gravel plains (Bajada) region, the internal sand dunes region and the coastal-marine region. Figure 3.3 shows these regions in detail as represented by Rizk and Alsharhan (2000).

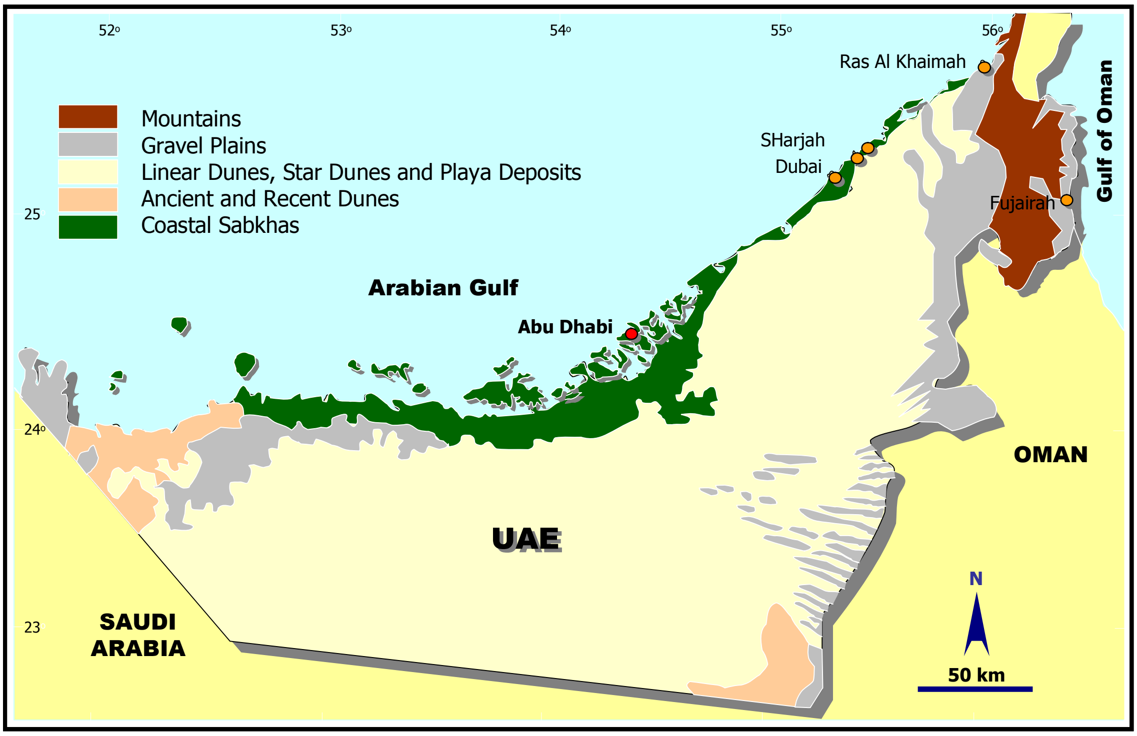


Figure 3.3 The principal geomorphic regions in the UAE.

The eastern mountain-gravel plains region is part of the Oman Mountains. In UAE the mountains extend for 150 km from Ras Al- Khaimah emirate in the north to Al-Ain city in the south. The average width is 10 km in the north, 38 km in the middle and 27 km in the south. The mountains are characterized by steep slopes and rise up to a height of 1000 metres with mountain peaks exceeding 1500 metres above sea level.

The mountains can be divided into three structural zones (UAEU, 1993). The first is the Diba zone in the middle which comprises a broad and relatively low lying region of south-west trending faults and complexly folded limestones. This zone separates the northern mountains of carbonate rocks from the southern mountains of mostly metamorphic and igneous rocks. The second structural zone is the Wadi Ham line that comprises NNW trending faults. The third structural zone is the Wadi Hatta zone of WNW trending faults in the south of the mountains, which has structural characteristics similar to the Diba zone.

The mountains are dissected into sharp ridges and blocks by many Wadi catchments. Two drainage systems can be distinguished on the mountains slopes (Figure 3.4). The first drainage system drains to the Gulf of Oman in the east. The second drainage system drains towards the north-eastern sand dune region and the Arabian Gulf. Bajada (Gravel plains) is “a depositional plain composed of coalescing series of alluvial fans at the footslopes of mountain ranges” (UAEU. 1993). The eastern gravel plain is a narrow strip and merges with the coastal plain in some places. It is 70 kilometres long and between 4 kilometres to 10 kilometres wide, and is bounded by the Gulf of Oman. The western gravel plain extends for 200 kilometres and is about 20 kilometres wide, and occupies the area between the mountains to the east and the sand dune region to the west. The surface of the gravel plains is either flat or undulating. The grain size of the gravels gradually decreases away from the mountains.

Sand dunes are the largest geomorphic region that covers 80% of the total area of the UAE (UAEU, 1993). The different types of sand dunes in UAE are an extension of the Sand Sea of *Rub al Khali*, which extends beyond the borders of the UAE into Saudi Arabia and Oman. In this region all types of dunes occur, including linear, barchan, barchanoid, transvers, and star type dunes. The dunes range in altitude from several metres in the north along the coast to 200 metres above sea level in the *Liwa* area in the south part of UAE (Rizk and Alsharhan, 2000).

The coastal-marine region lies along the coasts of both the Arabian Gulf in the west and the Gulf of Oman in the east. This region has a general height of 40 metres above sea level. The western Arabian Gulf coast line of the UAE is an area of tidal flats and salt marshes (*sabkhas*) that extend for about 600 kilometres (UAEU, 1993).

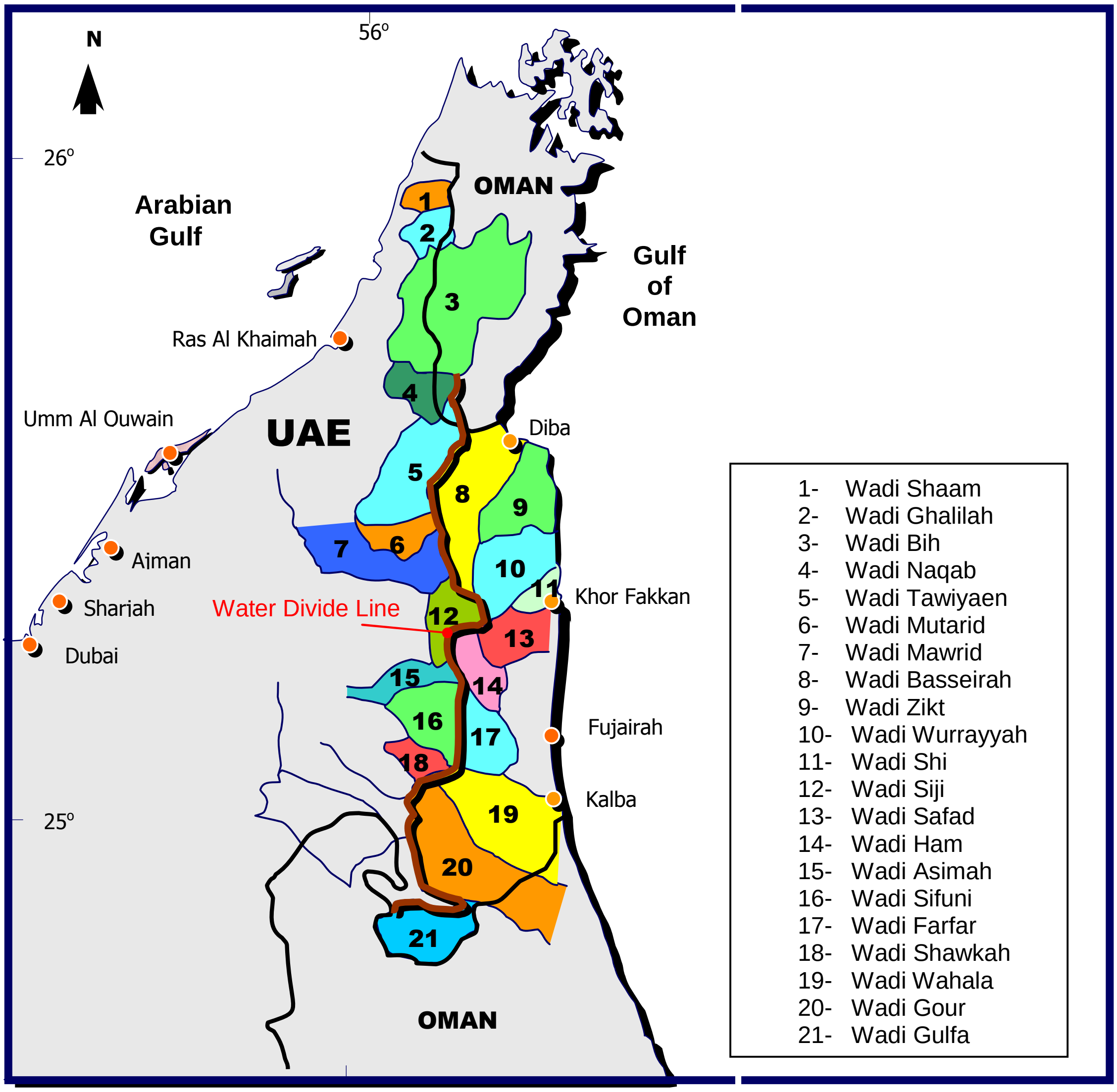


Figure 3.4 The main Wadi catchments in the north east of UAE.

3.4 Land use and agricultural development

According to the UAE atlas (UAEU, 1993), the majority of the country is desert in the form of sandy plains and extensive dune fields. The land use in such desert environments traditionally consisted of cultivated oases, with date palm trees and grazing areas for camels, goats and sheep flocks.

The agricultural practices were concentrated on the lowland oases, coastal plains and mountainous Wadi catchments. The climatic factors and the availability of groundwater in the aforementioned regions made them more suitable for the production of a wide variety of agricultural crops. Prior to the establishment of the UAE in 1971, the small population of the area was mostly concerned with producing enough food for their own consumption. After the foundation of the UAE, the government has given high priority to the growth of the agricultural sector. The two main reasons behind this interest were firstly, to achieve some level of self-sufficiency as a principle food security policy and secondly as part of the efforts to reduce economic dependency on the oil industry (UAEU, 1993).

Since the 1970's, the UAE has achieved remarkable expansion in its agriculture area (Figure 3.5). There were 7759 farms in the UAE and the cultivated area was 10,867 ha in 1977. At the end of 2000 the number of farms had risen to 35,584 and the cultivated area was 244,613 ha, out of which 197,574 ha was under modern irrigation systems of drip irrigation for vegetable crops, bubbler irrigation for trees and sprinkler systems for fodder crops (MAF, 2001a). In 2003, and in spite of the naturally harsh climate and environment, the agriculture sector made a 3.7% contribution to GDP (The Economist Intelligence Unit Limited (EIU), 2004).

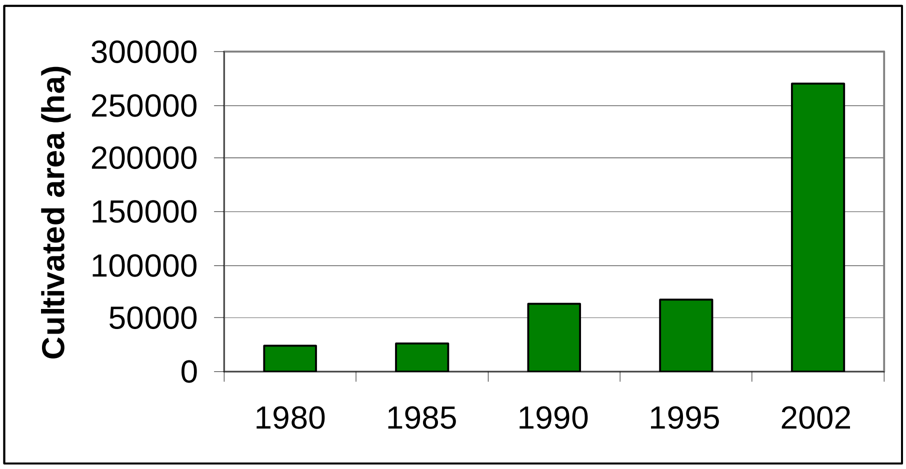


Figure 3.5 Agricultural land use development in UAE (Source: www.uae.gov.ae/uaeagricent; MAF, 1995; MAF, 1990, MAF, 1985).

Afforestation projects and the establishment of plantations of drought resistant trees for controlling desertification, sheltering the cultivated areas and protecting roads from wind blown sands have become an important policy in the UAE. As a result, in 1993 an area of about 580 km^2 was under the Afforestation projects. A recent estimation of forest land cover is reported to be 3000 km^2 (El-Keblawy and Ksiksi 2005).

Since the establishment of the UAE federation in 1971, urban land use has also rapidly expanded, due to the increasing population and economic development which is focused in the capitals and main cities of the emirates (Figure 3.6). Yagoub (2004) investigated the urban development of the inland oasis city of Al-Ain using available maps, aerial photographs and satellite imagery between 1990 and 2000. The biggest change was found to be in the agricultural areas that had increased by 77.7%, while the total area covered by buildings had also seen an increase of 36%. He related these latter changes to the increase in population, income, and establishment of new services buildings (schools, hospitals, etc.). The main decrease in the land cover of Al Ain was in the desert area which is due to intrusion of agriculture and buildings on the desert (Table 3.1).

Figure 3.6 Satellite image of northern Emirates of Dubai, Sharjah and Ajman showing areas under cultivation (red), urbanization (grey), bare soil (brown) and sea water (black) (source: http://faculty.uaeu.ac.ae/myagoub/main_satellite_gallery.htm).

Table 3.1 Change in land cover at Al Ain city between 1990 and 2000 (after Yagoub, 2004).

Land cover	**1990 (ha)**	**2000 (ha)**	**% change**
Agriculture	18 400	32 700	77.7
Buildings	14 870	20 222	36.0
Desert	66 105	43 405	-34.3
Mixed	4 500	7 548	67.7
Total	103 875	103 875	

The area of industrial land use in UAE is small but important. The main industrial areas are dominated by the oil and gas industry such as Al-riwes industrial complex. Dubai Aluminium Company in the Jabal Ali area is one of the principal non oil industrial projects in UAE. The Jabal Ali area is one of the largest man-made ports for industrial and free trade zone activities (UAEU.

1993). Other manufacturing centers for small industrial establishments can be found adjacent to some main cities of the UAE.

3.5 Water Resources

The available water resources of the UAE have been generalised into two categories by Rizk and Al-Sharhan (2000). The first category is the conventional resources which consist of groundwater, *Falajes* (which are man-made streams that intercept groundwater at the footslopes of mountains and transport it to the surface at lower altitudes for irrigation purposes (Rizk, 1993), springs and surface runoff of Wad`i catchments. The second category is the non-conventional resources which mainly consist of desalinated water and treated waste water.

3. 5. 1 Groundwater aquifers

In the absence of permanent surface water resources, the UAE depends on groundwater for all its agricultural and rural water supplies. There are four main groundwater aquifers (Figure 3.7) which include limestone aquifers in the north, fractured Ophiolite rock aquifers in the east, the gravel plains aquifers bordering the mountain range from both the east and west sides and the sand dune aquifers in the south and west of the country (Rizk and Al-Sharhan, 2000). In addition, a fifth aquifer is the coastal plain (*Sabkhas*) aquifer in the west of the country around the Arabian Gulf coastal line (UAEU, 1993).

- Limestone aquifer

The northern limestone aquifer is composed of fractured limestone and dolomite. These carbonate rock aquifers exist in the northern mountains (Rus Al Jibal) and in the outcrops near the Al-Ain region. Investigations have indicated the presence of substantial amount of water in the Karst topography (Khalifa, 1997). The reported fresh water capacity of this northern mountain unit was 14 billion m^3 (UAEU, 1993). The aquifer is fed by direct rainfall and surface overflow, and discharges in several karstic springs. The presence of hot water springs at Khatt spring, where the water issues directly from the limestone with an above-normal groundwater temperature of about 39 ^{o}C against the normal range of 28-32 ^{o}C, suggests that a considerable amount of water percolates quite deeply through the limestone structures in this aquifer (Rizk and El-Etr, 1994). The aquifer has a transmissivity ranging between 100 to 2500 m^2/day (UAEU, 1993).

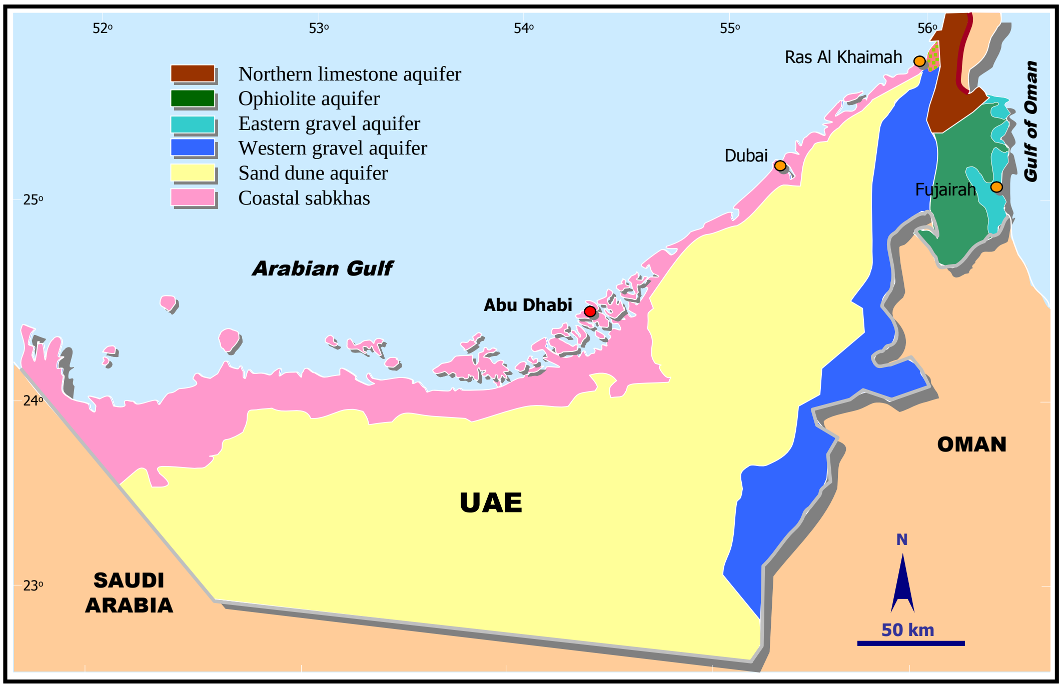


Figure 3.7 Main groundwater aquifers in UAE.

- Ophiolite Aquifer

This aquifer is composed mainly from Ophiolite, granite, gabbros and a mixture of volcanic and metamorphic rocks that are distinguished by their compactness and impermeability. A main fault system runs in a northwest-southeast direction. Fissures and fractures that accompany these faults allow for the formation of groundwater reservoirs. Groundwater is scarce and occurs only in joints and fractures. Some submarine springs are fed from this aquifer e. g. the Dadna spring (typical discharge of 42 l/s) and Al-Bidhah spring (120 l/s) (UAEU, 1993).

- Gravel plains (Quaternary) aquifers

The gravel plains aquifers are of Quaternary age and hence are known as the Quaternary Aquifers. They are the largest reservoir of fresh groundwater in the country, bounding the mountain range from east and west. These aquifers are the main source of the groundwater being abstracted at present. The east gravel plains aquifer is composed of conglomerates with high compactness and low permeability. Wells drilled in this region have a moderate productivity of 2-10 m^3/hr.The western gravel plains aquifer is composed of gravel, fine alluviums and conglomerates. The productivity of the western gravel plains aquifer is high in the plains adjacent to the carbonate mountains and moderate in the parts adjacent to metamorphic and ultra-basic rocks (UAEU, 1993).

- Sand Dune Aquifer

Sand dunes comprise 74% of the total area of UAE. These sandy desert plains in the western region of the country are underlain by Quaternary alluviums (UAEU, 1993). The deep aquifers such as Dammam and Umm-e Radhuma in the Southern desert were found to be highly saline, in spite of the existence of some fresh water (Rizk et al, 1997) which helps the continuation of some oases. IWACO (1986) reported transmissivities of 5-15 and 10-40 m^2/day for the Dammam and Umm-e Radhuma aquifers respectively.

- Coastal plain Aquifer

The western low coastal aquifer has a good productivity but severe salinity due to sea water intrusion (UAEU, 1993). Sanford and Wood (2001) studied the processes that control the hydrology of the coastal sabkha of Abu Dhabi Emirate. They developed a water budget model with estimated water fluxes on the basis of water levels and hydraulic conductivities measured in wells and evaporation rates measured with a humidity chamber. The analysis of the water budget indicates that the predominant source of water to the sabkha is recharge from rainfall, whereas lateral inflow is negligible. Estimates within a rectilinear sabkha, defined as 1 m wide by 10 km long by volume 10 m deep, indicate that about 1 m^3/year of water enters and exits by lateral groundwater flow; 40–50 m^3/year enters by upward leakage from the underlying Tertiary formations; and 640 m^3/ year enters by recharge from rainfall.

3. 5. 2 Surface runoff

The mean annual runoff from the Wadi catchments during the rainy season is about 125 million m^3 (Abdulrazzak, 1997). The water runs in the Wadis after large rainfall events for a period ranging from a few hours to weeks and even longer, depending upon the nature and the duration of the rainstorms. This water either drains to the sea or into the desert plains. The runoff coefficients vary between 3% and 19% in Wadi catchments (Rizk and Al-Sharhan, 2000; MAF, 1993). To reduce the flash flood risk and enhance the natural groundwater recharge, dams have been constructed in all major Wadi catchments (Figure 3.8). Table 3.2 shows the annual water volume stored in some dams since their construction.

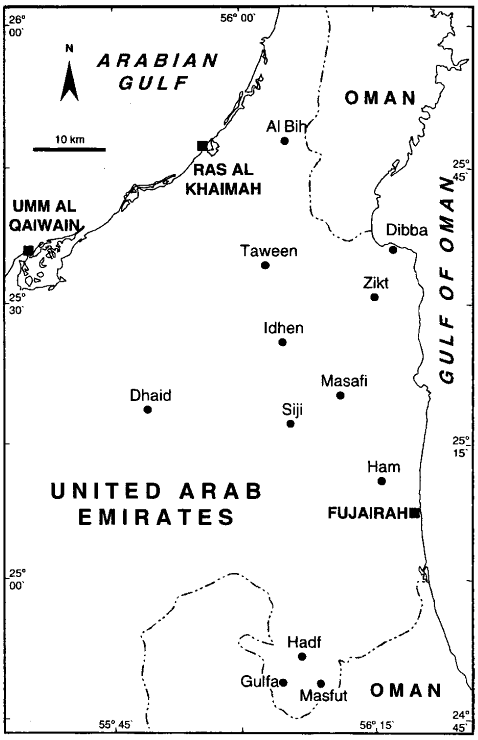


Figure 3.8 Location map of major recharge dams in Northern UAE (as indicated by Al-Asam, 2003).

Table 3.2 Flood water volume stored in dam reservoirs from 1990 to 2001 in million m^3 (after Al-Asam, 2003).

Catchment	Bih	Ham	Idhn	Gulfa	Hadf	Wurayyah
1990	1.150	4.870	0.500	0.165	-	-
1991	1.030	0.490	0	0.062	-	-
1992	3.300	0.120	0.67	0.192	0.542	-
1993	2.000	1.520	0.509	0.200	0.700	-
1994	-	0	0.40	0.102	0.250	-
1995	4.760	1.050	2.060	0.537	1.375	-
1996	2.350	0	1.080	1.150	2.675	-
1997	1.890	3.105	0.270	0.920	1.125	0.550
1998	8.150	0.650	0.370	0.300	0.400	0.150
1999	0.650	1.500	-	-	-	0.500
2000	-	-	-	-	0.50	0.500
2001	0.500	-	0.500	-	-	0.250
Total	***25.78***	***13.305***	***6.359***	***3.628***	***7.567***	***1.95***

3. 5. 3 Falajes and springs

The traditional *Falaj* system (Figure 3.9) is a network of open channels, cut and cover aqueducts and tunnels, usually driven into a hillside or sloping ground where the groundwater is found at a sufficiently high head to allow gravity drainage of the water to the flat low lying areas under cultivation. Although the dependence on *Falajes* for agricultural water supplies has reduced greatly with the introduction of deep boreholes, there still exist about 48 *Falajes* all over the country. The *Falajes* discharge varies from one Falaj to another and from year to year (Rizk and Al-Sharhan, 2000). The discharge of a Falaj depends on the location of the main wells, nature of the source aquifer, seepage from the tunnel and the mean annual rainfall. According to Rizk (1993) the total annual average discharge of the Falajes is about 20 million m^3.

Springs can be seen as indicators of discharge areas in arid regions. In UAE, records of spring discharges for the period 1984-1991 indicate that Bu Sukhanah spring has highest discharge of 2.50×10^6 m^3/yr, whereas Siji spring has the lowest discharge of 0.06×10^6 m^3/yr (Rizk and AL-Sharhan, 2000). The correlation of spring discharge to rainfall indicates that the discharge rates of some springs are directly related to rainfall; in contrast some other springs show no direct relation to local rainfall (Rizk and El-Etr, 1994). It is also reported that the construction of a recharge dam in Wadi Siji catchment maintained a constant discharge of Siji spring for the period of 1987 to 1991 due to continuous groundwater recharge for the spring (Rizk and Al-Sharhan, 2000 and Rizk and El-Etr, 1994).

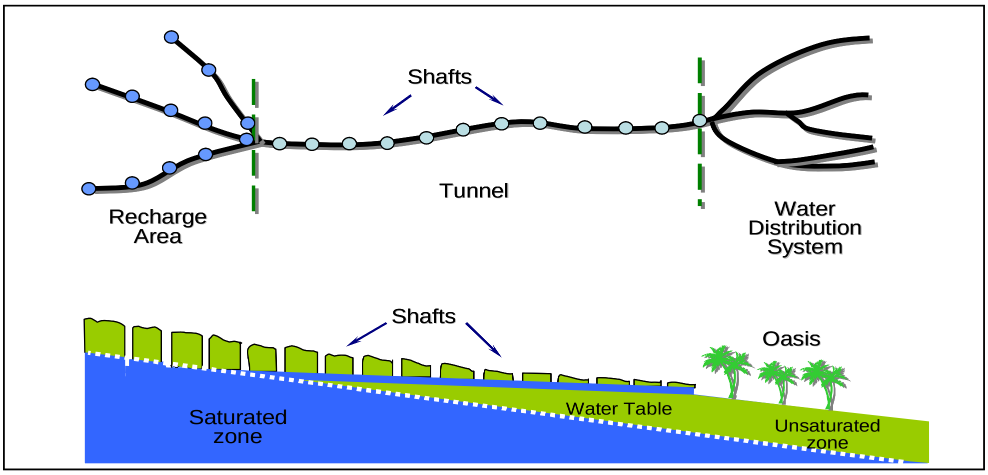


Figure 3.9 Schematic representation of *Falaj* irrigation system.

3. 5. 4 Desalinated Water

Desalinated water is the main source for domestic and industrial supplies in the UAE. The UAE started water desalination in 1973 in Abu Dhabi with an annual production rate of 7 million m^3 which reached 395 million m^3 in 1997 due to rapid development of this water resource (Rizk and Al-Sharhan, 2000). The Abu Dhabi and Dubai Emirates have the largest share of production (Figure 3.10), with the daily production of desalinated water for Abu Dhabi reported at 590,000 m^3 in 1989 (Rizk and Al-Sharhan, 2000). The main desalination plants are located on the coast, while a number of small plants have been built inland where brackish groundwater is desalinated, although the major inland city of Al-Ain receives desalinated water via a 150 km pipeline from a coastal plant in the Abu Dhabi Emirate (UAEU, 1993). At present, the use of desalinated water for irrigation is limited due to the high cost of production and distribution.

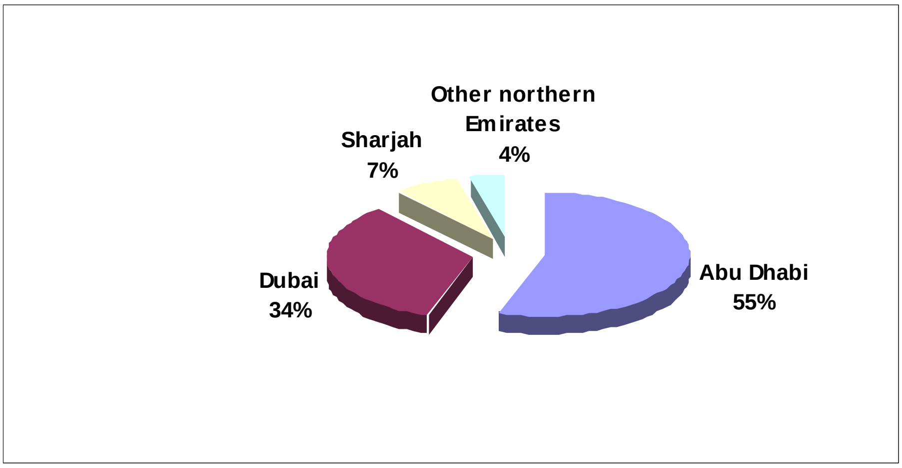


Figure 3.10 Percentage of desalinated water production by Emirates for 2000 (Al Hosani et al., 2000).

3. 5. 5. Treated Waste Water

Treated waste water is an important source of irrigation water for the landscaping projects of the major cities of the country. The major plants are in Abu Dhabi, Dubai and Sharjah. The first sewage treatment plant was established in the Abu Dhabi emirate in 1973 with a daily capacity of 4000 m^3. In 1994 the total production of the treated waste water in UAE was about 80 million m^3. In year 2000 the discharge of treated waste water reached 175 million m^3 (Rizk and Al-Sharhan, 2000).

3.6 Groundwater resource status in UAE

The groundwater consumption in the country has increased dramatically during the last two decades, partly as a result of population growth. For example, the population of the Abu Dhabi Emirate has increased to 2,262,309 (in 1997) compared to some 200,000 inhabitants in the early 1960's (Sommariva and Syambabu, 2001). The other main cause is the expansion of the irrigated agricultural lands, where agriculture consumes about 85% of total groundwater abstraction (Al-Asam, 2003). The annual groundwater recharge in the UAE is estimated at 120 million m^3/year, while the groundwater abstraction is estimated at 880 million m^3/year (Rizk and Al-Sharhan, 2000).

The over pumping of the groundwater in the cultivated areas has lead to deterioration in both quality and quantity of the groundwater. In some areas the groundwater levels have critically dropped, resulting in drying up of wells (Figure 3.11). *Falajes* and springs have experienced reduction in their yields over almost all the country, with some drying up. The groundwater levels in the main agricultural areas are lowered at an average rate of 2 m/a (Al-Asam, 2000 and IWACO, 1986). Sea water intrusion has become a major problem in some coastal areas and many wells have been abandoned due to high salinity (Figure 3.12) (Rizk and Alsharhan, 2000) and (Rizk and Alsharhan, 1999).

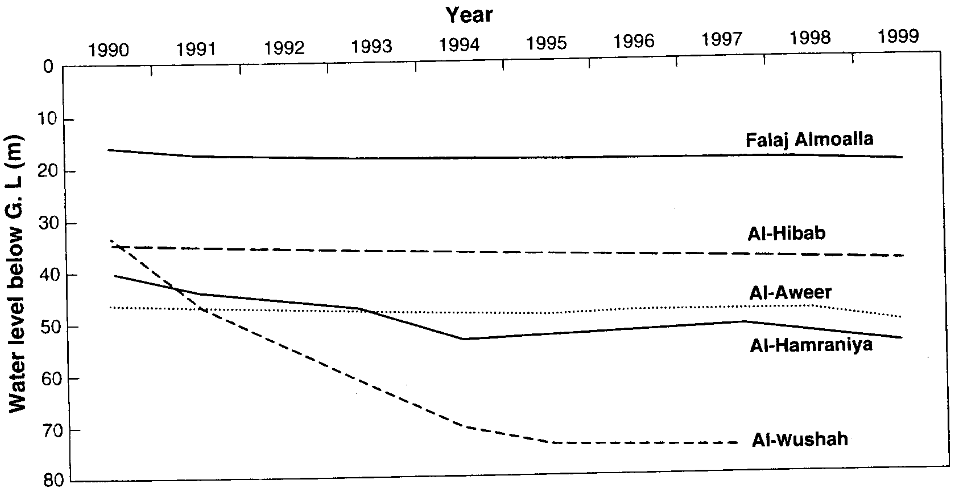


Figure 3.11 Examples of change in groundwater levels in observation wells in UAE (Al-Asam, 2003).

Figure 3.12 Abandoned date palm farm due to drying up of groundwater wells.

In order to develop and manage the vulnerable groundwater situation in the country the government has implemented several measures and actions (Al-Asam 2003; Al-Asam, 2000 and Rizk and Alsharhan, 2000) which can be summarised as following:

-Development and expansion of non-conventional water resources mainly desalinated water and treated wastewater, as the main groundwater conservation measure.

-Construction of 132 dams and recharge facilities in all major Wadi catchments (MAF, 2005). The monitoring results of the rise and fall of groundwater levels shows noticeable improvements in the water table records, indicating substantial recharge especially in the downstream vicinity of the dams.

-Establishment of a groundwater monitoring network to aid in groundwater studies, assessment and development. The network of groundwater level monitoring wells started in some locations in 1966 and are operated manually or by instrumentation such as chart recorders and (more recently) data loggers. At present about 125 wells are monitored by Ministry of Agriculture and Fisheries (MAF) and a computerized database has been established.

-Subsidising water saving techniques and equipment in the agricultural sector as an important action to preserve the total agriculture water use. Techniques such as the adoption of modern irrigation systems (drip, bubbler and sprinkler) instead of the conventional open channel irrigation system can save up to 60% of irrigated water losses according to MAF reports. Other technologies such as fully automated irrigation application, protected agriculture and greenhouse cultivation and soil amendments all are encouraged and subsidised by MAF as practical methods for irrigation water conservation.

-Improving the public awareness of water conservation by developing continuous public education programmes including TV, radio and printed materials. The World Water Day and GCC countries Water Week have been used to organize vast awareness campaigns with the participitation of official authorities, the general public and commercial establishments in the activities.

- Approved the comprehensive federal law (No. 24/1999) as a legal tool for management, development and protection of groundwater resources in the country.

- Promote field research on different disciplines related to water resources management in the country. This research includes utilisation of brackish and saline water for irrigation of salt-tolerant crops, introduction of new drought tolerant and less water intensive crops and assessment of available water resources as a necessary prerequisite for effective groundwater management.

The overall management and usage of groundwater resources in UAE shall take place within the broader context of integrated water resources management by integrating other available resources of desalinated water and treated waste water in the demand and supply of water cycle in UAE (Al-Asam, 2003). Sufficient quantities of fresh groundwater must be available in future, by following the law of the hydrological cycle and reducing the huge imbalance between the recharge and abstraction of groundwater.

To contribute to the previous goals, this current research is aiming to apply a comprehensive hydrological model to simulate the hydrological processes at the catchment scale. This includes the assessment of the available water resources in terms of recharge and irrigation water abstraction within a catchment. The selected model shall be able to simulate different hydrological processes within a data-scarce situation and shall be able to simulate recharge dam functionality as it is a major part of Wadi catchments under the climatic conditions of the UAE and many other Gulf countries. The successful application of such a catchment scale hydrological model shall provide the basis for an applicable tool for assessment, management, scenario simulation and decision making for water resources in the country and the wider Gulf region.

3.7 Selection of case study catchment

In order to examine the applicability of the watershed scale model to simulate the hydrological processes under an arid Wadi catchment environment, a representative case study catchment is required. The watershed scale model will be set up for the catchment using the available datasets and be, calibrated and validated prior to the application of management scenarios. To select an appropriate catchment as a case study for this research, certain criteria were identified. These criteria are:

-The selected catchment should clearly be an arid region Wadi catchment that represents the hydrological behaviour of such environments as discussed in chapter 2 previously.

-The catchment should contain significant agricultural activities and development.

-The selected catchment should contain a recharge dam, since these recharge enhancement facilities are becoming an important part of catchment management practises for many arid regions, in the UAE. The successful modelling of the dam as an integrated part of the catchment should lead to the better understanding and management of catchment systems.

- Availability of some essential datasets for the catchment to be set up within the selected model (e.g. rainfall, land use) and for the calibration and validation (e.g. discharge) of the output simulation results.

Based on the above criteria, Wadi catchments throughout the UAE were reviewed in order to select the appropriate Wadi catchment for this research. Table 3.3 shows the short listed catchments which were identified as potential case studies. Finally, the Wadi Ham catchment was selected for the study, mainly due to the availability of data (e.g. rainfall, weather, discharge, landuse and topography) and because irrigated agriculture has been practised within the catchment and downstream of the dam site for a long period of time, leading to groundwater depletion mainly in the downstream coastal part of the Bajada. In addition, although not a criteria, understanding and improving the management of Wadi Ham is of local importance because of the risk of flooding of Fujairah airport which is located near to the Wadi Ham recharge dam.

Table 3.3 Short listed Wadi catchments for the case study.

Catchment	Location	Area (Km^2)	Dam construction date
Bih	Ras Al Khaima	468	1982
Ham	Fujairah	192	1982
Gulfa	Ras Al Khaima	115	1985
Hadf	Masfoot	62	1991
Zikt	Fujairah	68	1991
Tawiaeen	Ras Al Khaima	190	1991
Wurayyah	Fujairah	113	1997

Available datasets that directly relate to Wadi Ham catchment have been collected from several sources in UAE. These datasets consist of the following:

- A digitised contour map (5 m interval) covering the catchment, provided by the municipality of Fujairah (UAE) and Map Geosystem (UAE).
- Aerial photography of the area (1999) provided by the municipality of Fujairah (UAE).
- A topographical map (1:250,000 scale) of northern UAE provided by the Ministry of Agriculture and Fishery (MAF).
- Daily climatological data for three rainfall stations and one climate station from the study catchment for the period from 1980 to 1999 from MAF.

- Available daily runoff data for the Bithna runoff gauge station from the period of 1980 to 1999 from MAF.
- Volume of water stored in Wadi Ham dam from the period of 1980 to 1999 from MAF.
- Agricultural statistics for the Eastern Agricultural Region of UAE for the period of 1980 to 1999 from MAF.
- Major reports of Wadi Ham dam and groundwater recharge facilities: Vol. 1. Design (1981), and Wadi Ham dam for groundwater recharge and loss prevention (1980) by Electrowatt Engineering Services Ltd. from MAF.
- Several other technical reports prepared for MAF, reviewing the Wadi Ham dam operation and effects, and site geophysical and hydrological studies were obtained.

3.8 Description of Wadi Ham catchment

Wadi Ham catchment is located in the north-eastern part of the UAE. The catchment lies between the city of Fujairah on the Oman Gulf to the east and the town of Masafi located on the divide of the mountain chain separating the Arabian Gulf drainage from the Oman Gulf drainage (Figure 3.13). The area of the Wadi Ham catchment itself is 90 km^2; however the tributaries of Wadi Farfar and Wadi Yabsah bring the total catchment area upstream of Wadi Ham dam (the downstream limit of the studied catchment) to about 192 km^2.

The upper part of the catchment is characterised by narrow valleys, with distinct channels in the alluvial fill, and steep flanks along the surrounding peaks. The lower part of the Wadi Ham catchment widens and forms a large fan until it reaches the sea. The elevation of the catchment ranges from 75 masl near the dam site to about 1000 masl, the height of mountain peaks upstream. The land use in the catchment consists of the natural vegetation of typical arid region plants, the cultivated farm lands and housing areas (Figure 3.14).

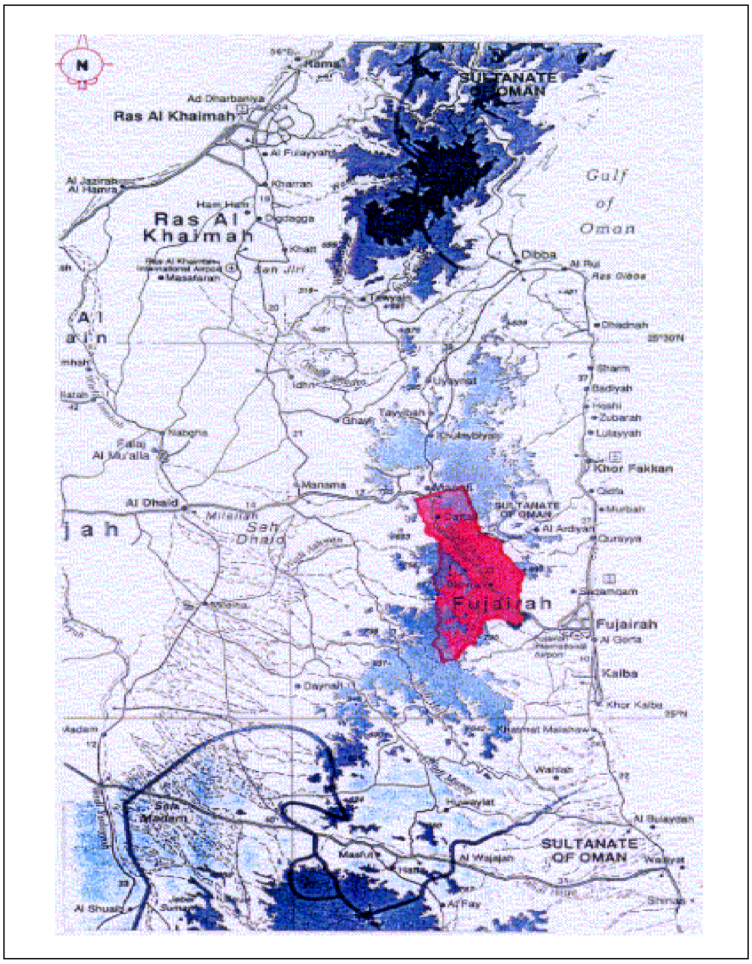


Figure 3.13 The location of Wadi Ham catchment (depicted in red) in northeastern UAE.

The entire catchment is underlain by rocks of the Semail complex which are considered to be an Ophiolite suite of basic igneous rocks. However, extensive exposures of metasedimentary rocks such as metashales, metasiltstone and metasandstones occur in the area. The Semail complex was placed as a thrust sheet from the east. Stresses set up during the thrusting resulted in several tear faults, one of which runs along the Wadi Ham in a Northwest direction. The Wadi Ham fault is considered to be a zone containing several faults, some of which are exposed as brittle, fractured rock on the northeastern slopes of the wadi. Other faults are presumably covered by the Wadi Ham alluvial deposits. The exposed faults appear to have a low permeability (Entec, 1996). The channel gravel occurs as loose sands and gravel along the braided active channels. The channels are between 50 to 100 m wide and contain probably not more than 30 m of unconsolidated alluvium, the upper part of which is resorted during each major flood (MAF 1988; MAF 1996).

Figure 3.14 Typical land uses in the catchment.

A large number of wells have been developed in the Wadi Ham catchment and downstream mainly for irrigation (Figure 3.15) and domestic purposes. Irrigation is used in the cultivation areas along the Wadi streams and the larger farming areas near the coast. Generally water demands for both domestic and agricultural uses are increasing while the quality and quantity of existing useable supplies are decreasing.

Figure 3.15 Irrigation of alfalfa and date palm with open irrigation channels.

The Wadi Ham surface water flows have been measured at a MAF flow gauging station located below Bithna Weir. For most of the year there are no flows in the channel, but the occasional intense rainfall can lead to short duration flash floods (Figure 3.16). The Bithna flow gauge measured flows for a catchment area of 90 km^2 from 1979 to February 1990 when the gauging station was destroyed in a massive flood event.

A dam has been constructed across Wadi Ham at the exit of the Wadi from the mountains into the coastal plain, which aims to provide flood protection and an increase of recharge into the sand and gravel aquifer of the Wadi (Figure 3.17). The dam is an earth and rockfill structure constructed in 1981/1982 across the upper part of Wadi Ham fan. The total volume of the dam itself is 7 million m^3 (Figures 3.18 and 3.19).

Figure 3.16 Two flood events of 11/7/2004 and 23/1/2005 in Wadi Ham catchment (source: http://www.wam.org.ae).

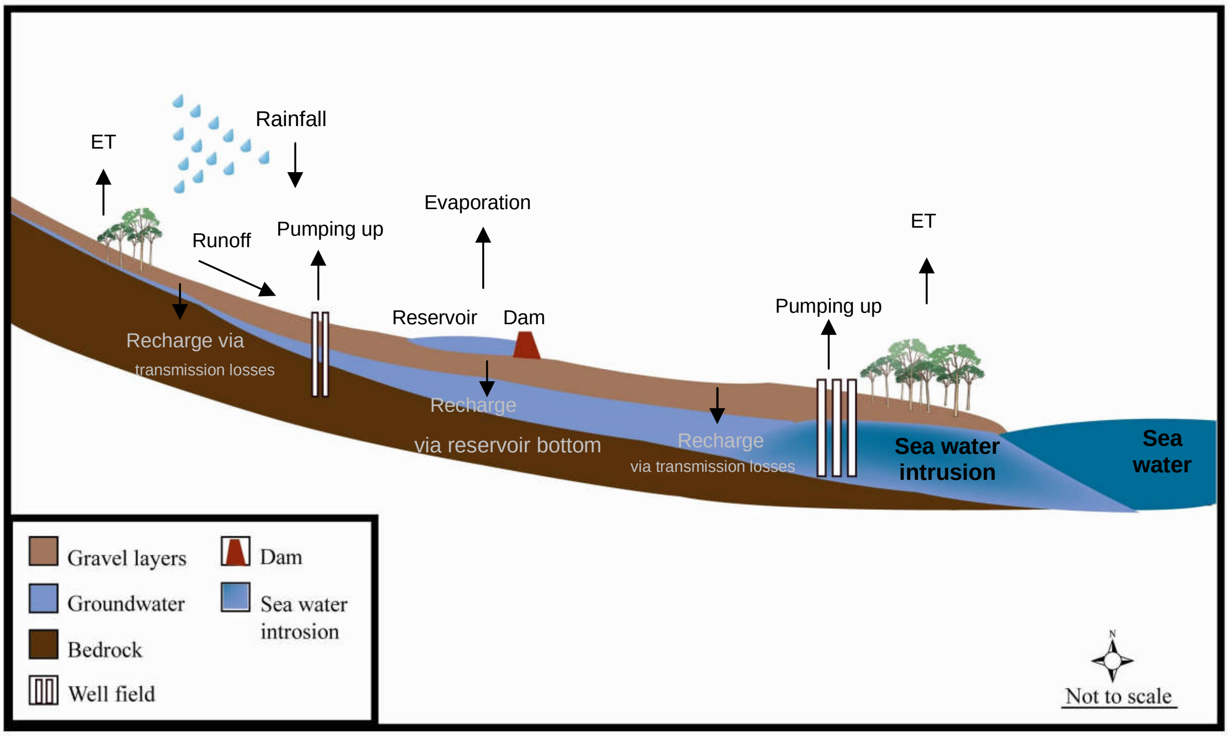


Figure 3.17 The hydrological system in Wadi Ham catchment.

Figure 3.18 General view of Wadi Ham dam reservoir.

Figure 3.19 Wadi Ham dam reservoir filled with flood water (Source: www.uae.gov.ae/maf).

3.9 Summary

This chapter has described the complex interactions between the arid environment and its hydrological cycle and the actions of man in UAE and the Wadi Ham catchment (Figure. 3.16). The state of water resources in UAE generally and in the study catchment can be synthesised based on the Driver-Pressure-State-Impact-Response (or DPSIR) framework, which was first proposed by the OECD in the early 1990s (OECD, 1993) and has been widely used in environmental management for the last 10 years (e.g., Turner et al., 1998; La Jeunesse et al., 2003; Holman et al., 2005). It has proved useful as a conceptual model for promoting dialogue between the different disciplines who must work together to solve complex environmental problems, as it assumes cause-effect relationships between interacting components of social, economic, and environmental systems (Figure 3.19). As an investigation of the current problems, this research proposes hydrological simulation as a contribution to the identification of the States of, and Impacts on, the hydrological cycle and landscape at the catchment scale. The simulations shall aid in the estimation of recharge and irrigation water abstraction volumes and sediment movement. Such a calibrated and validated model can subsequently be used to examine different scenarios and alternative management plans which might represent possible Responses to the identified Impacts.

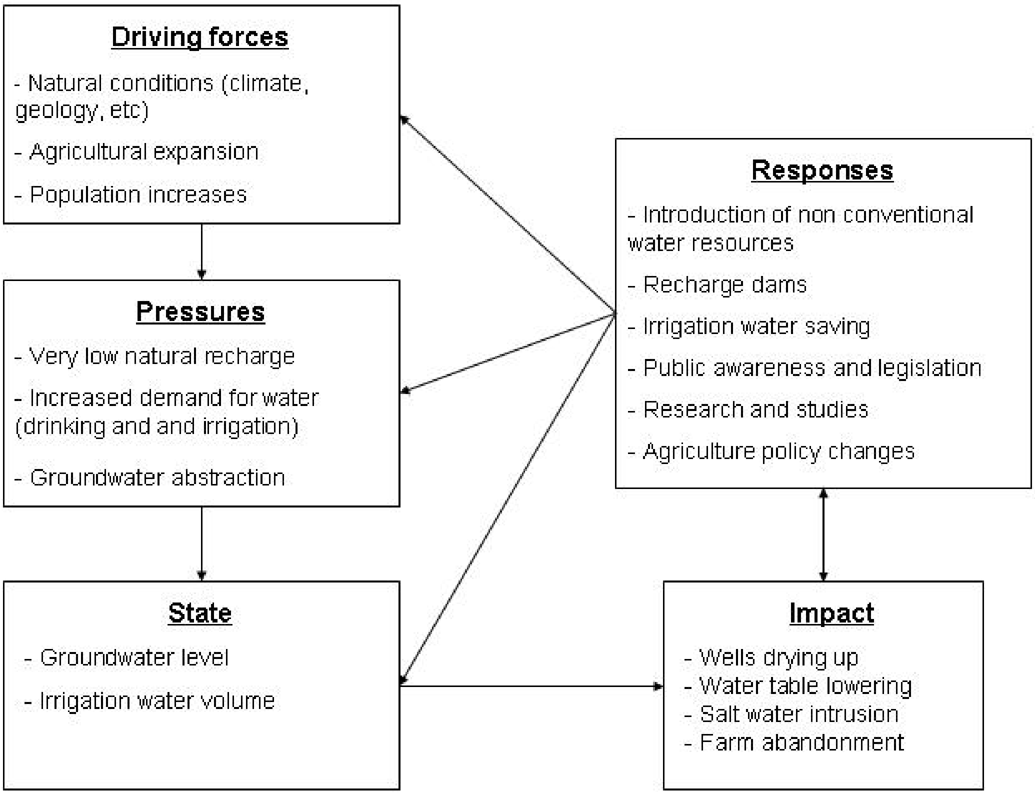


Figure 3.19 A synthesis of the water resources problem in the UAE.

4

Integrated Wadi catchment management and modelling

4.1 Introduction

The water resources situation for many arid and semi-arid regions is commonly described as a scarce water condition (e.g. Fadlelmawla and Al-Otaibi, 2005; Rappold, 2005 and Al-Weshah, 2003). Pereira et al. (2002) defined water scarcity as a situation where water availability in a country or in a region is below 1000 m^3 per person per year. However, they continue that many regions in the World experience much more severe scarcity, living with less than 500 m^3 per person per year, which could be considered severe water scarcity.

Water scarcity is a dominant problem in the region (Figure 4.1), which may reach severe levels if mismanaged. The causes of water scarcity are largely natural but can be significantly augmented by human behaviour and agency which can be summarised as:

- Population growth and the increase in local food production which is obtained mainly by an expansion in irrigated farming.

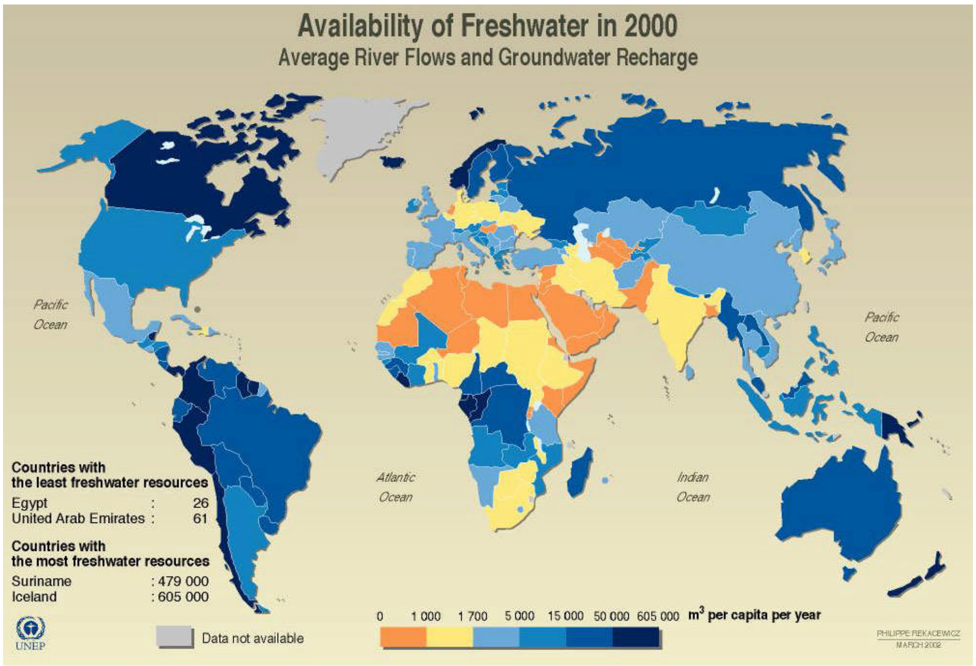
- Land use modification such as draining of large wetlands, conversion of watershed areas (e.g. expansion in the cultivated areas) or by localised desertification as a result of unsuitable farming practices.

- Contamination of existing water supplies of surface water and groundwater by e.g. agro-chemical run-off from fields, industrial effluent.

- Failures in demand management of water-intensive sectors, such as irrigated farming and heavy industry.

- Climatic change and variability that can lead to certain regions dependent on water (e.g. major farming areas or large population centres) experiencing more water scarcity due to decreased rainfall.

- Financial and institutional obstacles which lead to a country's water potential not being realised because of financial shortages and institutional failures.



Source: *World Resources 2000-2001, People and Ecosystems: The Fraying Web of Life*, World Resources Institute (WRI), Washington DC, 2000.

Figure 4.1 Per capita freshwater availability (from World Resources Institute, 2000).

Effective water resources management for an area should allow an adequate and sustainable supply of water whilst maintaining its quality at acceptable standards and finally allowing economic development over the short and long term (Heathcote, 1998). The sustainable supply of water is the ability to meet the needs of the here and now without compromising the ability of future generations to meet their own needs. To attain the previous goal of water sustainability, an integrated water resources management approach is needed. According to Thomas and Durhamb (2003) this should include (1) development of alternative water resources, (2) protection of water resources to stabilise and improve their quality and quantity and (3) demand management implemented at the level of each basin.

The following sections review the water resource constraints in Wadi catchments, and the management approaches which have been suggested. In light of the potential contributions which hydrological models can make to Wadi catchment management, a range of models are reviewed in order to identify an appropriate catchment scale model to simulate the case study catchment.

4.2 Constraints on water resources of Wadi hydrological systems

The water resources of Wadi systems face many constraints, some due to their hydrological nature and others caused by unsustainable human practises, which have been reviewed by Benbiba (2002). The following sections summarise with illustrated examples these constraints in different Wadi catchments:

4.2.1 Problems related to water resource availability in Wadi systems

4.2.1.1 Temporal nature of surface water

In addition to the obvious water scarcity in arid environments, Wadi hydrological systems are characterised by important temporal disparities, which lead to either drought periods that can last for several years or heavy rainfall events which cause massive flash floods (Figure 4.2), such as described by Torab (2002) for flash flood hazard mapping of Hafit Mountain Wadis in eastern UAE; Shehata and Amin (1997) for damages caused by flash floods in the Wadis of western Saudi Arabia and by Shaw (1989) for a “massive” flood in Wadi Adai (380 km^2) in northern Oman. The development of water resources and flash flood prevention in such regions requires the construction of costly hydraulic structures (Table 4.1) such as rockfill dams, gabion weirs and earthfill dykes.

Table 4.1 Approved dam construction projects in Saudi Arabia and their costs in Saudi Reyal (AL_WATAN, 2003).

Dam	Height (m)	Length (m)	Storage capacity (million m^3)	Cost (million RS)
Wadi Baish	106	340	194	198.5
Wadi Al-lith	79.5	420	88.75	124.3
Wadi Rabeg	80	-	220.35	169
Wadi Hali	95	-	250	223.6

(Source:AL-WATAN newspaper,15/3/2003-issue: 928)

Figure 4.2 Flash flood in Wadi catchment after heavy rainfall event.

4.2.1.2 High erosion and sedimentation rates

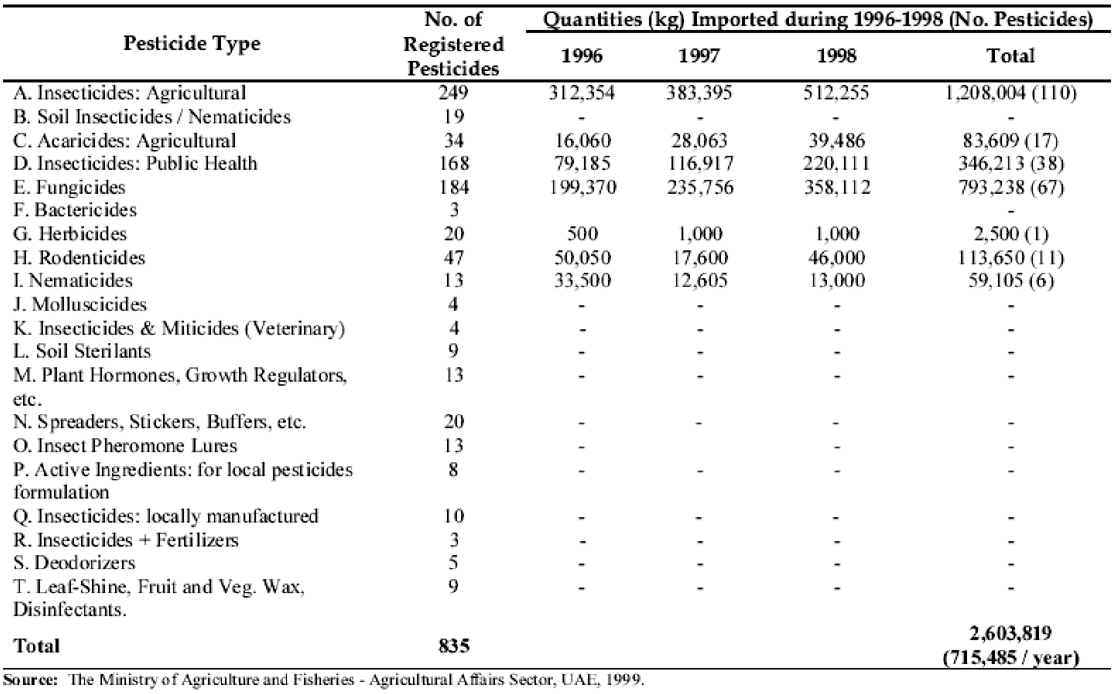
The main factors which govern catchment soil erosion and the subsequent siltation of dam reservoirs in arid regions are the climate (mainly rain and wind), topography, soil, land use and human activities. In Morocco, the national sedimentation of reservoirs was estimated at 70 million m^3/year, which is about the loss of one medium-sized dam per year (Benbiba, 2002). Another example is from Wadi Al-Kabir recharge dam in Oman. The dam is 8.9 m in height and 2.6 m in length with a storage capacity of about 0.5 million m^3. Within the five years since the dam began operation, a 1.4 m thick layer of fine material and sediments has accumulated in the dam reservoir, at an annual accumulation rate of 20,000 m^3/year (UNEP, 1998). Obviously, such processes decrease the infiltration rate and storage capacity of the recharge dam which negatively affects its operating efficiency.

4.2.1.3 Degradation of water quality

Water resource availability can be further impacted by degradation of water quality, which can arise in Wadi systems from many causes. Examples include intensive use of agriculture chemicals and pesticides, domestic and industrial waste water and solid discharges, eutrophication of reservoirs due to contaminant transportation (i. e. chemical fertiliser) and water logging and salinisation of soils in irrigated areas. For example, in the Al-Karak area (southern Jordan), Hussain, (2000) reported elevated levels of heavy metals in sediments affected by wastewater produced by a wastewater treatment plant in the area. In further investigations conducted by El-Hasan and Jiries (2001) in Wadi Al-Karak, the geographical distribution of samples, collected from the major and minor valleys of the catchment, which showed higher Cu, Zn, Pb, Cd and Cr concentrations were mainly around heavily inhabited areas indicating an anthropogenic source of such contamination. Another example from Jordan is reported by Al-Kharabsheh (1999) for the Wadi Kufranja (112 km^2) basin, in which the water quality from springs, which were used for drinking water, were adversely affected (chemically and biologically), especially during summer season, by the urban extension in the upper part of the basin.

In UAE a study has suggested that the source of the high concentrations of chloride in the Eastern Gravel Plain aquifer of UAE, which is a Bajada form of several Wadi systems that drain towards the Gulf of Oman, could be related to agricultural fertilizers and pesticides being used in that region (Murad and Krishnamurthy, 2004). Similarly, Kaakeh et al. (2004) have discussed the current status of pesticide use in UAE (Table 4.2) and emphasised its high potential risk as a source of surface and groundwater resource contamination, concluding with the need for a “solid plan of pesticide management” to control the use and handling of pesticide at every stage in the region.

Table 4.2 Number of registered pesticides and quantities imported to UAE during the years 1996-1998 (after Kaakeh et al., 2004).



Pesticide Type	No. of Registered Pesticides	Quantities (kg) Imported during 1996-1998 (No. Pesticides)			
		1996	1997	1998	Total
A. Insecticides: Agricultural	249	312,354	383,395	512,255	1,208,004 (110)
B. Soil Insecticides / Nematicides	19	-	-	-	-
C. Acaricides: Agricultural	34	16,060	28,063	39,486	83,609 (17)
D. Insecticides: Public Health	168	79,185	116,917	220,111	346,213 (38)
E. Fungicides	184	199,370	235,756	358,112	793,238 (67)
F. Bactericides	3				-
G. Herbicides	20	500	1,000	1,000	2,500 (1)
H. Rodenticides	47	50,050	17,600	46,000	113,650 (11)
I. Nematicides	13	33,500	12,605	13,000	59,105 (6)
J. Molluscicides	4	-	-	-	-
K. Insecticides & Miticides (Veterinary)	4	-	-	-	-
L. Soil Sterilants	9	-	-	-	-
M. Plant Hormones, Growth Regulators, etc.	13	-	-	-	-
N. Spreaders, Stickers, Buffers, etc.	20	-	-	-	-
O. Insect Pheromone Lures	13	-		-	-
P. Active Ingredients: for local pesticides formulation	8	-	-	-	-
Q. Insecticides: locally manufactured	10	-	-	-	-
R. Insecticides + Fertilizers	3	-	-	-	-
S. Deodorizers	5	-	-	-	-
T. Leaf-Shine, Fruit and Veg. Wax, Disinfectants.	9	-	-	-	-
Total	**835**				**2,603,819 (715,485 / year)**

Source: The Ministry of Agriculture and Fisheries - Agricultural Affairs Sector, UAE, 1999.

4.2.1.4 Transboundary catchments

In some shared transboundary catchments a number of pressures, which depend on the utilisation of water and the hydraulic infrastructure in each country, can affect the water resources. National political, economical and social differences in the countries of the shared catchment can constitute a barrier to the implementation of joint or multilateral development of such shared catchments (Benbiba, 2002). Such a situation has been reported by ESCOWA (2002), although they highlight the case of the Hamad basin which is shared between Jordan, Saudi Arabia, Iraq and Syria as a successful regional cooperation experience (Figure 4.3). The basin was studied by the Arab Center for Studies of Arid zones and Dray lands (ACSAD) aiming at acquiring the basic data and information necessary for the comprehensive socio-economic development of the basin and evaluating natural resources of the basin, including surface and groundwater resources.

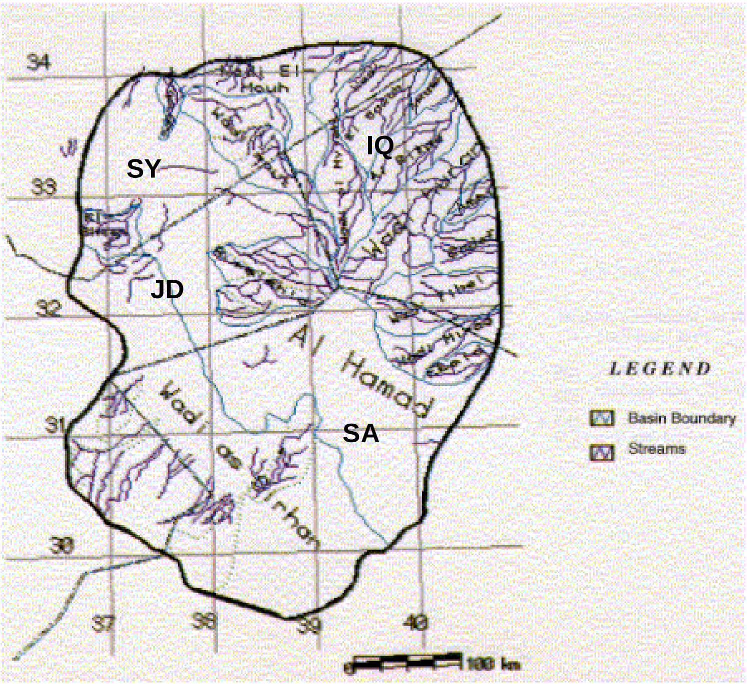


Figure 4.3 The shared transboundary Wadi catchments of Hamad basin (SA: Saudi Arabia, JD: Jordan, IQ: Iraq and SY: Syria) (after Rafael et al., 1995).

4.2.2 Problems related to water resources usage in Wadi catchments

4.2.2.1 Increasing water demand

Water demand is continuously increasing in many of the Wadi systems within Arab countries, due to increased socioeconomic development, and a desire to ensure food security. According to Benbiba (2002), it is expected that by 2025, most Arab countries will go beyond the critical water scarcity threshold of 500 m^3/inhabitant/year due to population increase, as the resource is constant. The previous assumption can be reasonable based on insignificant climate change that affects the precipitation pattern in the rainy season in the region as predicted by climate change models (IPCC, 2001). Alternatively, the decrease in renewable water resources in the region is likely to increase the scarcity level which lead to accelerate the mining of non renewable principle groundwater aquifers in the region. For the GCC countries in particular Al-Zubari (1998) expected that the overall annual increase in total water demand by the year 2020 will be 0.8% per annum, taking into account the implementation of all conservation, rationalization and surface water harvesting plans (Figure 4.4).

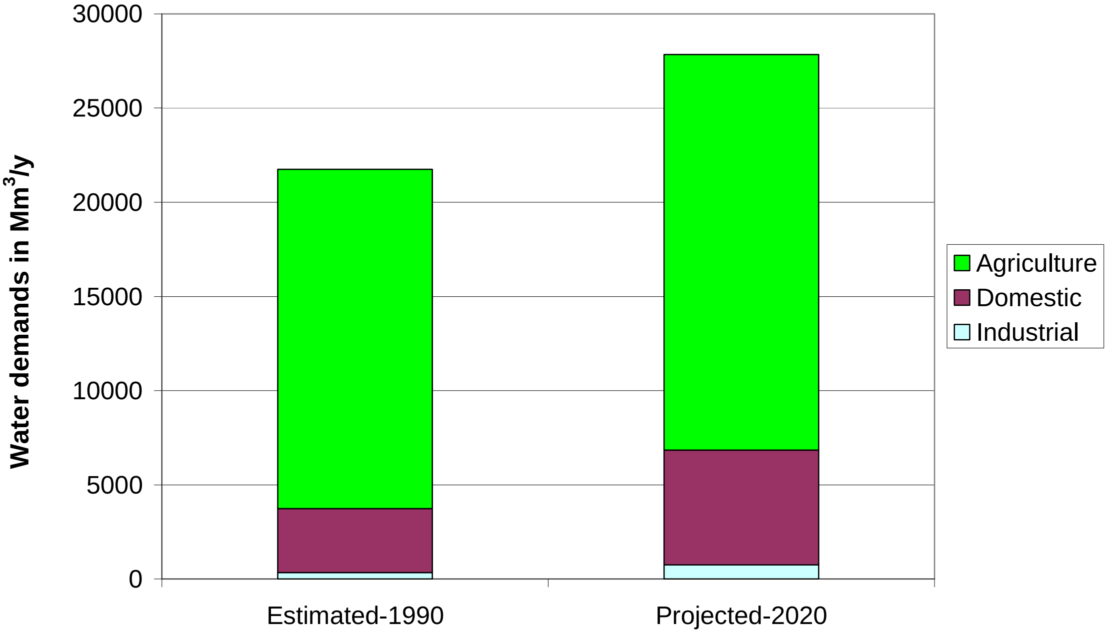


Figure 4.4 Water demands projection for GCC countries by 2020 in Mm^3/y (Developed from Al-Zubari, 1998).

From Figure 4.4 it can be seen that agriculture is the most challenging sector, showing the highest water demand together with a 1.7% annual rate of increase in the region. Figure 4.5 shows the continuous rapid expansion of agriculture development (from 1978 to 2000) in the coastal strip along the Al-Batinah coast in Oman which is downstream of the Batinah Wadi system catchments. Agriculture appears to be continuously expanding with the development of new farms in the region and in particular in the area of irrigated agriculture because of the new inputs of irrigation water mainly from newly constructed boreholes (Figure 4.6). Such situations add to the difficulties in management of the demands on the available water resources of Wadi system catchment in the region (Harris, 2003).

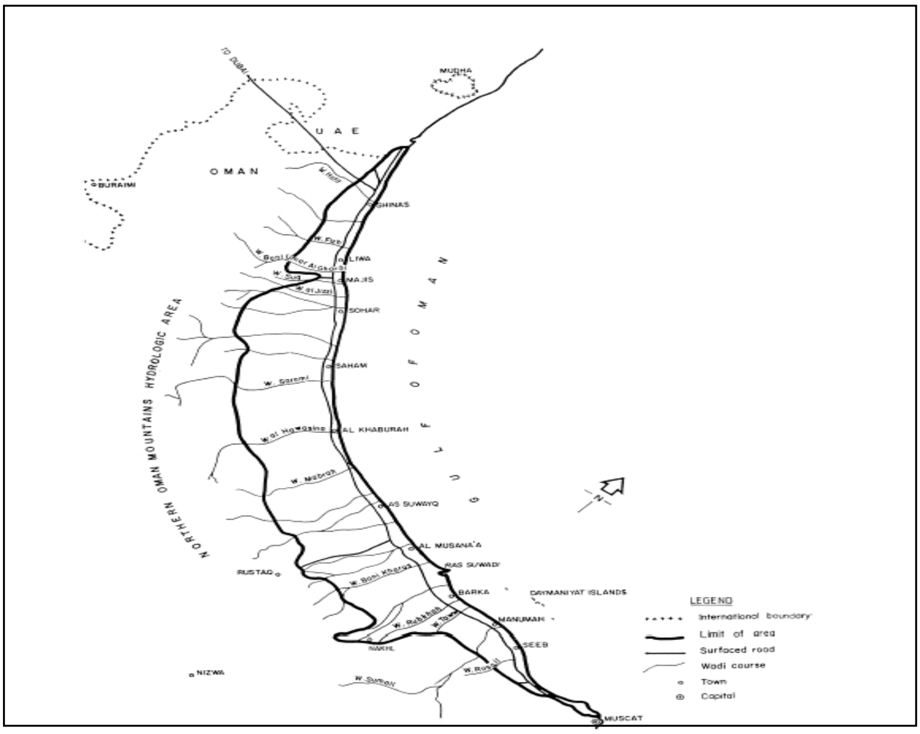


Figure 4.5 Al-Batina coastal Wadi system showing the location of the major Wadis in the catchment (Al-Ismaily and Probert 1998).

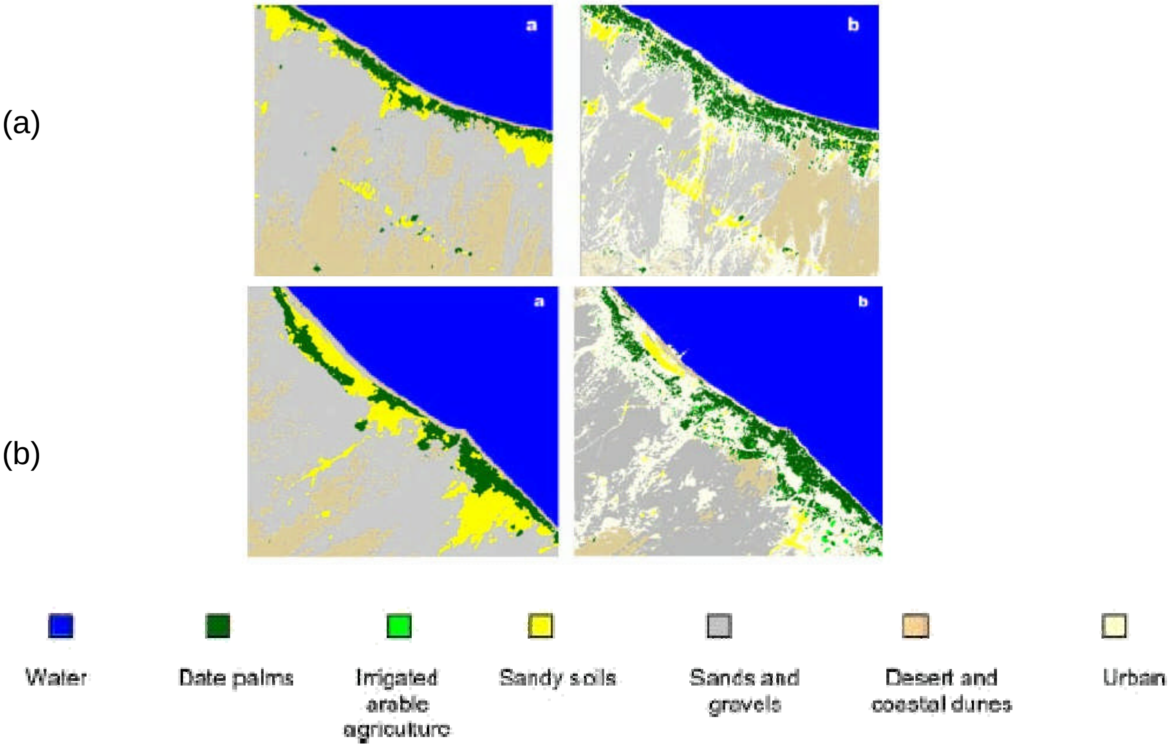


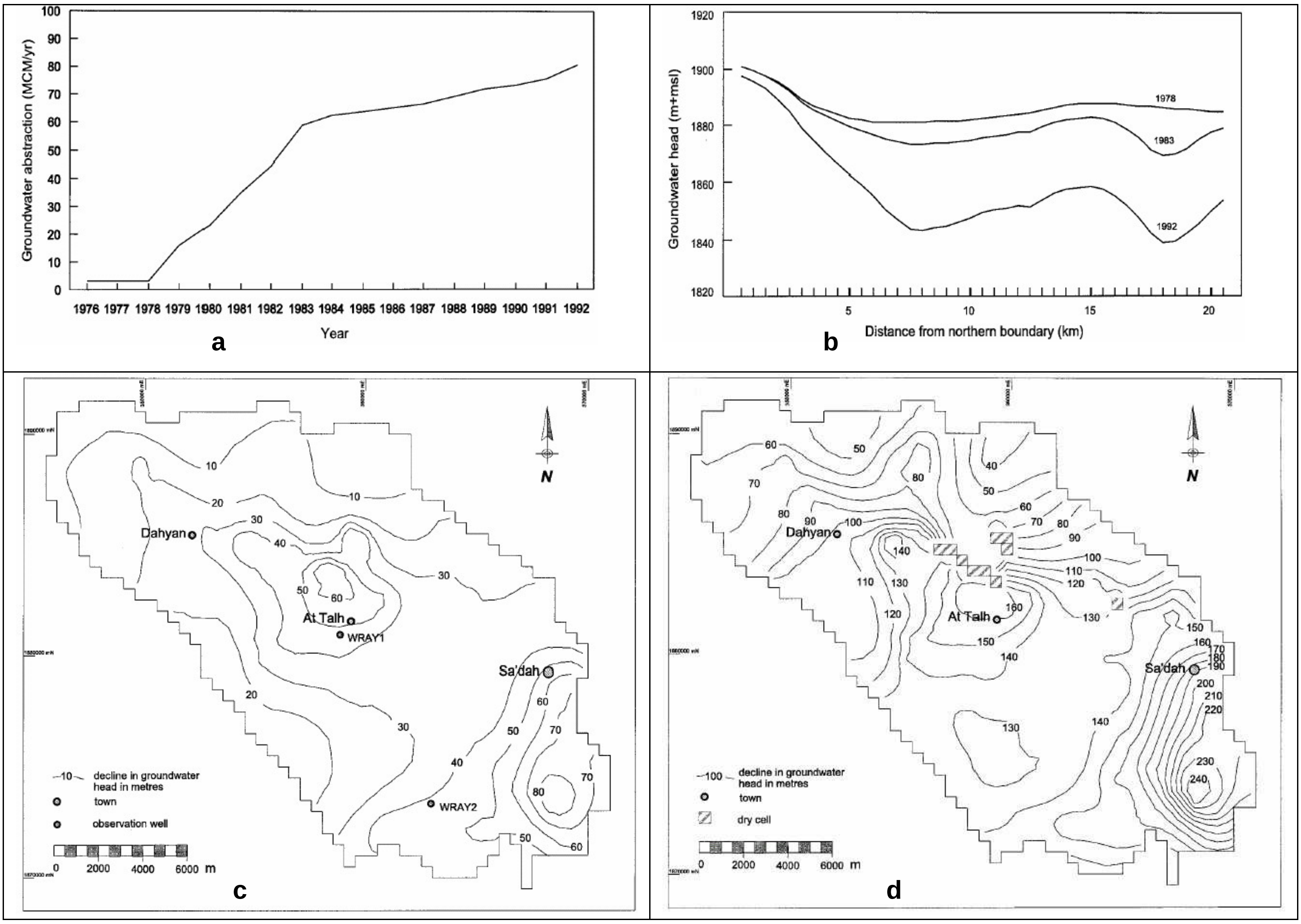
Figure 4.6 Landsat image showing the development of agriculture from 1978 (left) to 2000 (right) in two locations in the coastal Al-Batinah Wadi system catchment in Oman, (a) Khaburah area and (b) Sohar area (Harris, 2003).

4.2.2.2 Over-exploitation of groundwater aquifers

Groundwater resources in many Wadi hydrological systems are exposed to risks / vulnerable to pressures that may cause a degradation of their quantity and quality. The key reasons behind such degradation in groundwater resources can be due to the lack of a rational management strategy for groundwater, the lack of legislative instruments to organise the utilisation of groundwater resources as reported by Al-Sakkaf et al. (1999), a multiplicity of users, inadequate assessment of the resource and finally pollution from human activities and sea water intrusion (Benbiba, 2002).

The literature provides many cases of groundwater over-exploitation in Wadi catchments. Such cases have been identified in UAE (Bhattacharya, 2004 and Rizk and Alsharhan, 2000), Oman (Al-Ismaily and Probert, 1998), Tunisia (Paniconi, 2001) and Egypt (El-Bihery and Lachmar, 1994). A comprehensive case study is given by Al-Sakkaf et al. (1999) for the problem from Yemen Republic. They have studied the patterns of water demand from groundwater resources in the Sa’dah Plain which is part of the catchment of Wadi Marwan, a tributary of Wadi Najran that drains into the Rub’ Al-Khali Desert (Yemen). This was driven by the direction of socioeconomic development which emphasised the development of irrigated agriculture to replace rainfed agriculture as a major economic activity in the area. The annual gross groundwater abstraction rate for irrigation purposes increased from about 1 million m^3 in 1970 to about 80 million m^3 in 1992 (Figure 4.7a), as more than 2500 wells drain the aquifer at an annual rate of abstraction that far exceeds the natural recharge rate in such arid areas. This has resulted in over-exploitation of the groundwater resources, leading to groundwater depletion (Figure 4.7 b and c). As an attempted solution to the situation Al-Sakkaf et al. (1999) have suggested a water-demand management strategy based on increasing irrigation efficiency, changing cropping patterns and adopting an abstraction quota to reduce net abstraction by about 11% per annum starting in the year 2000 in order to balance the annual natural recharge by the year 2020 (Figure 4.7d).

Looking at groundwater quality effected by over-exploitation, Sharaf et al., (2001) found that the over-exploitation of the groundwater aquifer in the downstream part of Wadi Fatimah, in western Saudi Arabia, has led to salinisation problems because of both upconing of deep saline groundwater that occurs in isolated pockets within the catchment and saline water intrusion in the lower part of the Wadi area towards the Red Sea coast (Figure 4.8).



Figeure 4.7 Groundwater situation in Sa'dah Plain. From left to right (a) Growth in annual abstraction, (b) Fall of piezometric levels along cross section in the study area, (c) Decline in groundwater levels from 1978 to 1992 according to calibrated groundwater model and (d) Decline in groundwater levels from 1978 to 2020 under present conditions according to the calibrated groundwater model. (After Al-Sakkaf et al., 1999).

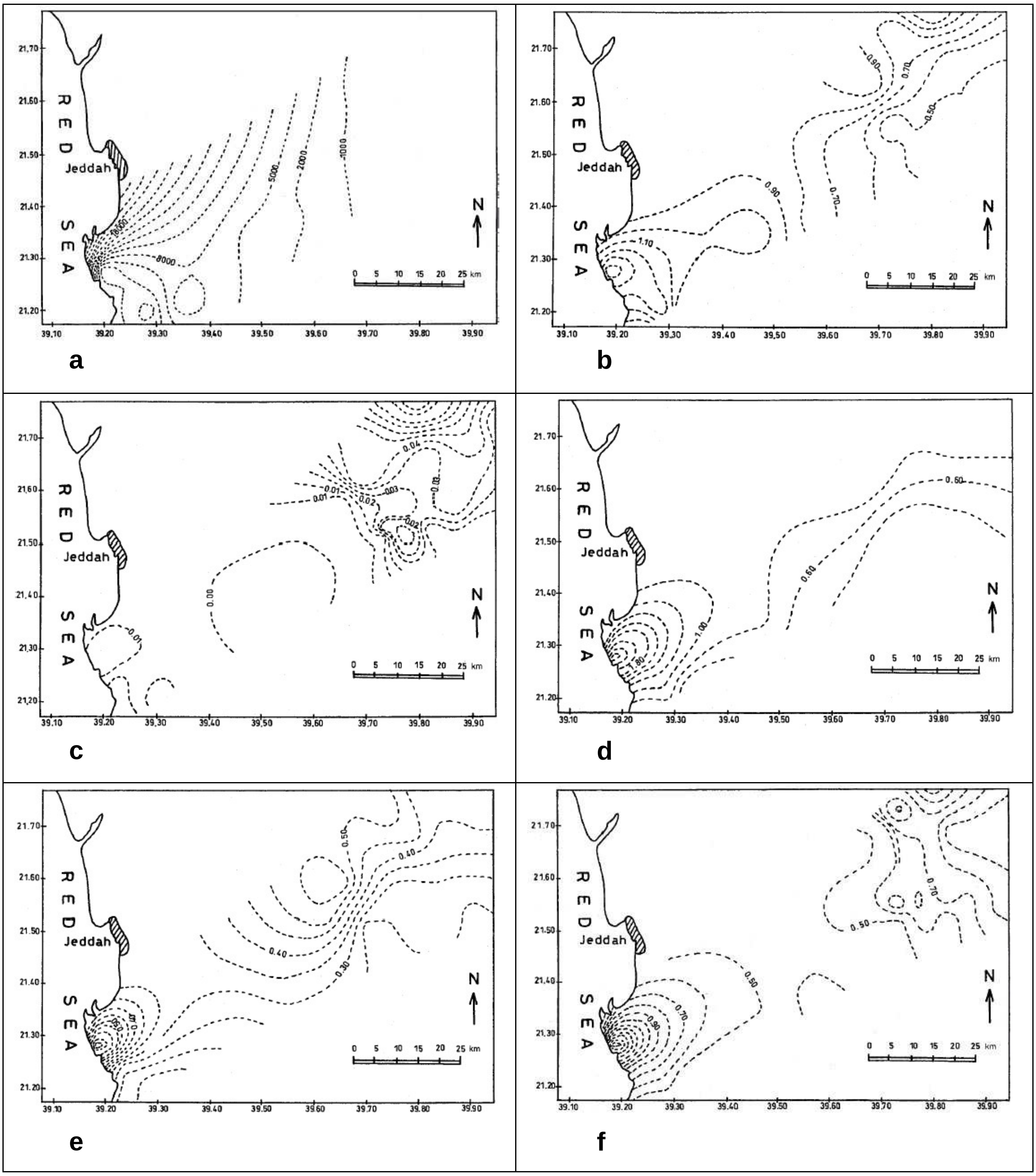


Figure 4.8 Areal distribution of chemical properties (mg/l) of groundwater in Wadi Fatimah: (a) TDS, (b) Na/Cl ionic ratio, (c) HCO_3/Cl ionic ratio, (d) SO_4/Cl ionic ratio, (e) Mg/Cl ionic ratio and (f) Ca/Cl ionic ratio (after Sharaf et al., 2001).

4.2.2.3 Inefficient irrigation and water distribution networks

Water losses in irrigation practises and the hydraulic structures of irrigation distribution and domestic water networks are important constraints to the overall water balance evaluation in the arid region. The major factors that lead to such water losses are the inefficient application methods used in irrigation such as surface irrigation, and the lack of structured maintenance and rehabilitation practises for the irrigation networks.

Irrigation water comprises the largest water consumption share in arid countries (Figure 4.9). Abu Rizaiza and Al-Osaimy (1996) found that irrigation water has increased from less than 2000 million m^3/year in 1976 to more than 10,000 million m^3/year in 1987 comprising more than 80 percent of the total water requirement of Saudi Arabia. According to FAO (1997) all of the agriculture of Saudi Arabia in 1992, estimated at about 1.6 million ha, was equipped for full/partial control irrigation. Surface irrigation was practiced on the old agricultural lands that represent about 34% of the irrigated area, with sprinkler irrigation practiced on about 64% of the irrigated areas. The central pivot sprinkler system covers practically all the lands cropped with cereals. The irrigation application efficiency, which is the average ratio of the amount of water applied and stored in the root zone to the gross amount of water applied of this method, is estimated at between 70 and 85%. Vegetables and fruit trees are in general irrigated by drip and bubbler methods respectively with application efficiency for those two methods between 80 and 90%, where most of the inefficient water is lost via evaporation.

Figure 4.9 Freshwater withdrawals by agriculture in 2000 as a percentage of total water withdrawals (from World Water Resources Institute, 2000).

4.3 Wadi catchment management

To meet the challenges of sustainability and Wadi catchment management requires an approach that assesses resource usage options and environmental impacts integratively. Such an approach can be found within the concept of Integrated Catchment Management (ICM) that is defined as the co-ordinated and sustainable management of land, water, soil, vegetation, and other natural resources on a catchment basis (Booth, 2001).

The Wadi catchment water resource itself has to be developed with regard to all of the technical, organizational, legislative and institutional aspects of integrated catchment management. Benbiba (2002) identifies the main technical aspects that could lead to better water resources development in Wadi Catchments as:

- assessment of water resources;
- planning, and;
- management of water resources.

The assessment of water resources is a fundamental factor in the integrated development strategy for water resources. The results of the assessment are the basis for any decision making process, that may lead to large investments and serious consequences on the environment. Water resources assessment consists of determining the quantity, quality and availability of water for sustainable development and management. The planning is a set of policies, programmes and projects which contribute to the realisation of objectives which allows optimal use of the available water resources and achievement of socioeconomic development. The third aspect is the water resources management which can be defined as a set of actions to be realised in the medium and long term considering all recommendations and measures resulting from the planning process with the participation of all parties related to the water sector.

As an attempt at an integrated approach to Wadi catchment management, Saleh and Ghanem (2002) presented briefly the case study of Wadi Hanifah catchment (4400 km^2) located in Saudi Arabia, which has experienced rapid urban growth since 1930. The fast growth of urbanisation within the catchment had a negative environmental impact on the natural hydrological processes in the catchment causing a unique problem in such an arid area. Groundwater levels beneath Riyadh city are rising, leading to the unusual presence of perennial surface flow within the catchment. The cause of the problem is recharge to groundwater by discharges from storm drainage systems and de-watering projects since 1985 that discharged into the saturated alluvial bed of the Wadi.

The integrated approach in Wadi catchment management in Wadi Hanifah catchment, according to Salih (2002), included a sustainable development plan focussing on environmental protection of the natural resources, ecosystems and cultural heritage of the catchment. The plan is divided into two distinct tasks. The first task was an immediate, rapid programme to remove or halt environmental deterioration in the Wadi, establish an effective monitoring system, remove rubbish and illegal land uses from the Wadi and managing the environmentally harmful industrial activities. The second task was the establishment of a comprehensive development plan based on studies of the water resources, land use, farming activities, land ownership, soil types, cultural and natural heritage sites and transportation and traffic systems in the Wadi catchment. They concluded the description of integrated management of Wadi Hanifah by stating that “Although management issues differ with different contexts, the underlying challenges remain the same – how to achieve sustainability in providing needed services to the expanding populations and economies that depend on Wadi systems”.

4.4 Watershed (catchment) Models

Watershed hydrology models are an assemblage of mathematical descriptions of components of the hydrological cycle (Singh and Woolhiser, 2002). Depending upon the model type, they can simulate numerous components of the water cycle including: evapotranspiration, rainfall, run-off, overland flow and routing of water in streams, and provide estimates of the sediments and nutrients transported by those processes.

Thus models are suited and used widely as a resource decision-making tool at a catchment scale as the catchment is a natural management area (Pullar and Springer, 2000). According to Heathcote (1998) the uses of simulation models can provide benefits which include:

- Insights into basin processes and cause-and-effect relationships between sources and receiving water impact
- A powerful and flexible tool for comparison of management alternatives and for extending the understanding of the system to periods for which data are unavailable.

The role of simulation models in the development of watershed management plans can be illustrated with examples of applications in some arid environments. Al-Abed (2005) reported on surface water management in the Zarqa river basin (330,000 ha), described as one of the major and most significant surface water systems in Jordan because of its population, location and economy. The study successfully simulated the surface water flow of the basin using SWBM and HEC-HMS models as a first step in testing different future scenarios related to climate change and land-use change. Another use of simulation models was reported by Ouessar and Chaieb (2004) who investigated the multiple impacts (runoff mobilization, ground water recharge, agro-socio-economic impacts) of the water harvesting works undertaken in the watershed of oued Oum Zessar (367 km^2) in southeastern Tunisia. They applied the event-based physical soil transport model (STM) developed by Biesemans (2000) to determine the overland flow processes and the resulting soil transport, net erosion and deposition of each specific water harvesting technique. Detailed evaluation of the performance of the APSIM model for water balance predictions of dry land agriculture in south eastern Australia was carried out by Verburg and Bond (2003). The APSIM model was found to reproduce closely the water balance measurements from farming data sets in south eastern Australia. The observed sensitivity of the water balance to management changes and to conditions during the summer fallow period was reproduced well by the model. They suggested that APSIM is a valid tool for evaluating the impact of changes to cropping systems and agronomic practices on the water balance of dry land regions.

Models may provide estimates for the whole watershed and/or provide information about the processes occurring in different parts of the watershed. Hydrological models can be classified (Singh and Woolhiser, 2002 and Davie, 2002) mainly according to their process description as lumped, semi-distributed or distributed and according to their technique of solution as empirical, conceptual or physically based. Lumped models have no spatial discrimination, since all the processes operate at one spatial scale and provide estimates for the whole watershed. Semi-distributed models recognise that in a catchment, areas can have similar hydrological behaviour and react in the same way, and may provide estimates for the whole watershed and/or provide information about the processes occurring in different parts of the watershed.

With regard to their technique of solution, watershed models can be classified as empirical models (i.e. *black-box* models), conceptual models or physically based models (Davie, 2002). The black-box model is the simplest form of numerical model that simulates the hydrological process (such as surface runoff) as a direct relationship between it and another measured variable or variables. An example for such a model is a regression relationship derived between annual rainfall and annual runoff for a particular catchment e.g.N-LES model (Simmelsgaard, 2000). Such models are simple but are restricted to the particular case and conditions for which they are calibrated. The conceptual model is an attempt to reproduce the different hydrological processes within a catchment in a numerical form. The term conceptual is used because the equations governing the hydrological process are deemed to be conceptually similar to the physical processes operating in the catchment. Such models usually need to be calibrated for a given catchment, since the outputs of the model are controlled by a series of parameters that needs to be adjusted until the best fit is obtained between the predicted and measured values of the outputs. The physically based models e.g. SHE model (Abbott et al., 1986) simulate all the processes operating within catchment as a series of physical equations at points distributed throughout the catchment. Such models in theory require no, or less, calibration than conceptual models. The main disadvantage of physically based models is the huge amount of data required to set up the model (Davie, 2002).

4.5 The role of Geographic Information Systems in arid catchment modelling

A growing number of semi-distributed and distributed hydrological models at both catchment and field scale e.g. MMS; AGNPS 98 and F2D models (ASCE, 1999), have been integrated with Geographic Information Systems (GIS). The GIS is used as a tool for the management, querying, visualisation and analysis of spatially referenced information (Westervelt, 2001). The GIS can be coupled with the hydrological model to provide a tool to run a simulation and to interpret the results in a spatial context. The integration between GIS and watershed models can offer improvements to hydrological models by streamlining data input from GIS map layers, especially in the case of distributed models with large data requirements, and for visualising model outputs.

Three levels of integration between the hydrological model and the GIS can be observed: loose coupling, tight coupling and fully integrated. Loose coupling means the systems are separate and operated by the user exchanging information through file exchange. Tight coupling means that one system provides a user interface for viewing and controlling the application, which may be built from several component programs. Fully integrated means the model is embedded as a component in the host GIS application (Nyerges, 1991).

The spatial characteristics of land use, vegetative cover, soil, topography, precipitation etc. for catchment modelling requires a tool that can effectively manage such spatial data. GIS can offer effective support for hydrological modelling, capable of archiving, analysing and handling the large amounts of data required to describe the hydrological processes of watershed. For example in the Walnut Gulch Watershed in USA, GIS capability was used to manage the spatial physical, structural, and functional characteristics of the arid and semiarid ecosystems of the watershed (Fox, 2005).

Hydrological models depend upon inherent physical properties, such as the way water flows across a landscape, which is driven by the topography. The GIS has tools to assist in selecting a well defined watershed for analysis, for removing topographical depressions or sinks within this watershed and for enforcing drainage patterns so that the model operates accurately. Advances in digital mapping have provided essential tools to closely represent the three dimensional nature of the landscape. The Digital Elevation Models (DEM) can automatically extract topographic variables such as basin geometry and stream networks. In the same Walnut Gulch Watershed, Miller (2003) found strong statistical relationships between channel variables measured in the field (i. e. width, depth and cross-sectional area) and those that were defined using GIS and DEM techniques. Although it is preferable to collect field data as an input for hydraulic routing models, the high cost and time involved make DEM an attractive data source to parameterise channel properties. In general, high resolution DEM (<100 m) are becoming available through a number of public and commercial providers (e.g. US Geological Survey), and the automated extraction of hydrology-related topographic parameters from the DEM is a functional alternative to traditional and expensive surveys and manual evaluation of topographic maps.

As an application of hydrological simulation models interfaced with GIS within an arid to semi-arid catchment, the Zarqa river basin (330,000 ha) in Jordan was modelled by Al-Abed (2005) using the Spatial Water Budget Models (SWBM) and HEC-HMS / HEC-GeoHMS extension model for river basin modelling. The use of a GIS hydrological modelling approach was justified because of its capability of presenting the relationship between the spatial and hydrological features of the watershed in an efficient way. According to the conclusion, GIS proved to be very useful in helping with the calibration of the models, because of its ability to compile many different data sources to aid in calculating hydrologic parameters such as the Curve Number.

4.6 Model selection criteria

Considering the wide range of modelling approaches available and the enormous number of watershed models, the selection of an appropriate model for this study needs to be made according to relevant criteria. Heathcote (1998) suggests that model choice should take into account the dimensionality in which the model simulates the system (one, two or three dimensions), time period (i.e. single rainfall event or continuous), state of simulation (steady state condition or unsteady state), the variables to be modelled and data availability.

According to the review of hydrological processes and the previous modelling approaches taken in arid regions described in the preceding chapter and the aim and objectives of this research project, the selected model for this research project should satisfy the following criteria:

1- The model should operate at the watershed scale and simulate processes in the rural and urban areas within the catchment.
2- The model should be a comprehensive model that simulates ET, rainfall-runoff, transmission losses, catchment erosion, channel and reservoir sedimentation, reservoir performance and groundwater, as well as crop growth and irrigation practices.
3- Physically or conceptually based and semi-distributed as an alternative to empirical and lumped models.
4- Be able to be parameterised and validated with the limited datasets typically available in arid region Wadi catchments.
5- Have a daily time-step in order to capture the short timescale runoff events.
6- Have been used in a wide range of climatic regions, especially arid region or semi-arid regions.
7- Calculate ET using either the Penman-Monteith-FAO 56 or Hargreaves methods, or be able to import previously calculated ET data.
8- Be able to predict the effects of different land management practices (such as land use change), excessive groundwater abstraction and different reservoir operations on water resources within the catchment.
9- The model should be continuous, rather than event-based in order to be used in long term simulation.
10- The model should have a GIS interface to be used in catchment data management and model parameterisation and calibration.

In addition, it would be beneficial for current and future usage if:

11- The model operates on a personal computer (PC);
12- The source code is easily or freely available for future development;
13- Existence of an active user group can provide effective technical support during the modelling exercise.

4.7 Review of available models

There are many hydrological processes simulation models available worldwide which could be reviewed. However, the model criteria previously described have been used to prioritise the model selection

Based upon an initial screening review of the literature, a shortlist of potential models was produced which were described as integrated catchment models. These models were then reviewed in greater detail against the criteria. Table 4.3 summarise the properties of these models.

The SWIM Soil and Water Integrated Model (Krysanova and Becker 1999) simulates the hydrological cycle, erosion, vegetation growth and nutrient transport in watersheds and has been used to analyse climate change and land use change impacts on hydrology and water quality at the regional scale. However, SWIM runs under the UNIX environment, and does not contain a reservoir component. In addition, PET is estimated using the Priestley-Taylor method which is not a preferred method of ET calculation in arid regions.

ANSWERS-2000 *(*Bouraoui and Dillaha, 1996) is a distributed, physically based, continuous simulation, watershed scale model. The model simulates interception; surface retention/detention; infiltration, percolation, sediment detachment and transport of mixed particle size classes in rills, interrill areas, and channels, crop growth, plant uptake of nutrients. The model has an ArcInfo based user interface that facilitates data file creation and manipulation. The model is in the public domain. According to a review by (Dillaha et al., 2005) the model was tested on two watersheds in Watkinsville, Georgia, and performed well in predicting runoff, sediment, nitrate, dissolved ammonium, sediment-bound TKN, and dissolved phosphorus losses from both watersheds. The model was also tested on the 1153 ha Owl Run watershed in Virginia where it performed well for the largest storms, and cumulative predictions of runoff volume, sediment yield, nitrate, ammonium, sediment-bound TKN, and orthophosphorus were within 40% of the measured values. There are a number of weaknesses to the model such as:

- the empirical sediment detachment sub-model which is out of date and needs to be replaced with a more physically based sub-model (Dillaha et al, 1998);
- The model lacks a reservoir component;
- Documentation and user support is very limited;
- The model is currently only suitable for use by expert modellers with a good knowledge of upland hydrology and agriculture.

WINHSPF (Bicknell et al., 1997) is a conceptual, continuous simulation watershed model. It simulates interception, soil moisture, surface runoff, interflow, base flow, snowpack depth and water content, snowmelt, evapotranspiration, ground-water recharge, dissolved oxygen, biochemical oxygen demand (BOD), temperature, pesticides, faecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, and zooplankton. The overall model is physically based, so that the data needs can be extensive. Basic WINHSPF operation requires several meteorological variables, since it is driven by a meteorological data time series including precipitation, temperature, dew point, solar radiation, wind speed, and evaporation (Saleh and Du, 2002). The model has a Windows interface and has no GIS interface.

Process **Model**	Watershed urban and rural hydrology simulation	Processes Representation (conceptual/physical)	GIS integration	Time Step (continuous)	ET Runoff Sediments Transmission losses	Reservoir simulation	Accessibility
SWIM		√	-	√	**X (Transmission loss)**	**X**	**X**
ANSWERS-2000	√	√	√	√	**X (Transmission loss)**	**X**	√
WINHSPF	√	√	**X**	√	√	√	√
AGNPS	√	√	√	**X**	√	√	√
ACRU	√	√	**X**	√	**X (Transmission loss)**	√	√
MIKE SHE	√	√	√	√	√	√	√
SWAT	√	√	√	√	√	√	√

Table 4.3 List of short listed models and their properties for modelling watershed hydrological processes.

The ACRU (Schulze, 1994) agrohydrological modelling system simulates the components and processes of the hydrological cycle affecting the soil water budget, including canopy interception of rainfall by vegetation, net rainfall reaching the ground surface, reference potential evaporation, total evaporation (i.e. actual evapotranspiration), stormflow and baseflow, reservoir yield analysis (overflow, reservoir status, abstractions, transfers) and sediment yield analysis (daily, monthly, annual; reservoir sedimentation). The model has been mainly used in southern Africa (e.g. Ewitt et al., 2004, Butterworth et. al., 1999). ACRU has no component to simulate transmission losses from the stream channel. The model operates in DOS and has no GIS interface.

MIKE SHE *(*Abbott et al., 1986) is an integrated modelling tool that can simulate the entire land phase of the hydrologic cycle and can be linked to ESRI's ArcView$^{®}$ for GIS applications. The weaknesses of MIKE SHE for this research are that the fully distributed features of the model make it difficult to use in a data poor region. Also the cost of the full model and unavailability of the source code are disadvantages.

SWAT -Soil and Water Assessment Tool (Neitsch et al., 2001) is a continuous time series model that operates on a daily time step at the river basin scale. The model is mostly physically based, semi-distributed, and quite widely used across the world e.g. USA (Bosch et. al., 2004 and Spruill et. al., 2000)); Germany (Huisman et al., 2004), UK (Kannan, 2003) and it has been used for hydrological simulation in some semi-arid catchments e.g. (Muttiah and Wurbs 2002; and Hernandez, 2000). SWAT simulates all of the relevant hydrological processes for the study area including transmission losses. It has an available GIS interface for ESRI ArcView$^{®}$ and has an active user network.

From the previous model reviews it is apparent that there are integrated catchment models available (MIKE SHE and SWAT) which could be used in this research work. However, considering all of the criteria it is considered that the most suitable model is SWAT which matches all of the criteria since it is:

- conceptually- based and semi-distributed (Criteria 3);
- has been successfully used to study some semi-arid and ephemeral catchments (Criteria 6);
- has components (Figure 4.10) to simulate all of the relevant hydrological processes in the proposed study, including rainfall-runoff, sedimentation, transmission losses, reservoir performance etc. (Criteria 2)
- benefits from a GIS interface (Criteria 12), freely available source code for future development (Criteria 11);
- has an active user group and community (Criteria 13).

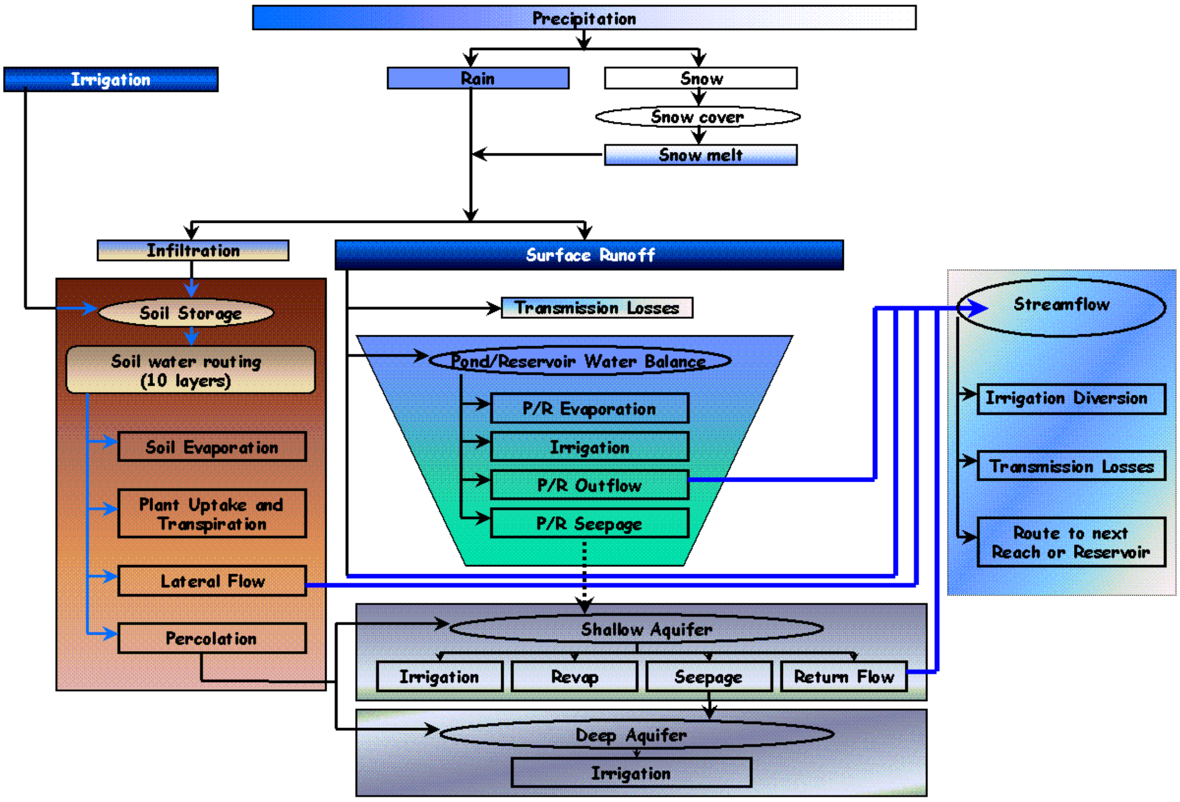


Figure 4.10 The potential pathways of water movement as simulated by SWAT in the Hydrological Response Unit (HRU) (from Neitsch et al., 2001).

4.8 Selected model (SWAT) description

The Soil and Water Assessment Tool (SWAT) is a conceptual, physically based, semi distributed and continuous time watershed scale simulation model, developed for the United States Department of Agriculture (USDA), Agriculture Research Service (ARS). SWAT was developed in order to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds (Neitsch et al., 2001).

SWAT is a collection of about 220 computer programs written in the FORTRAN 90 language (Arnold and Föhrer 2005). It is a continuation of over 30 years of model development and modifications. SWAT incorporates a number of earlier USDA-ARS models including CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems, Knisel, 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems, Leonard et al., 1987) and EPIC (Erosion Productivity Impact Calculator, Williams et al., 1984). SWAT can be described as a direct outgrowth of the SWRRB model (Simulator for Water Resources in Rural Basins, Williams et al., 1985; Arnold et al., 1990).

SWAT can be run from the DOS prompt or by using a Windows interface. A GIS interface is also available for SWAT using both GRASS (Graphical Resources Analysis Support System) and ArcView® interface (AVSWAT).

4.8.1. SWAT ArcView® interface

SWAT ArcView® interface (AVSWAT-2000) is a graphical user interface, written in Avenue language (DiLuzio et al. 1998). The AVSWAT consists of three key components:

(1) a pre-processor to generate the sub-basin topographic parameters and model input parameters;
(2) a facility for editing input data and to execute the SWAT simulation;
(3) a post-processor to view the graphical and tabular simulation results.

AVSWAT-2000 contains databases for soils, crops, pesticides, fertilisers, tillage operations and urban simulations. All the existing databases are specifically related to the United States, but the user can easily add information to the databases according to requirements.

The AVSWAT-2000 requires

1- Personal computer using a Pentium I processor or higher, which runs at 166 MHz or faster

2- 64 Mb RAM minimum

3- Microsoft Windows 95, 98, NT 4.0 or Win2000 operating system with most recent kernel patch

3- VGA graphics adapter and monitor.

4- 50 Mb free memory on the hard drive for minimal installation and up to 300 Mb for a full installation.

5- ArcView 3.1 or 3.2 (GIS software)

6- Spatial Analyst 1.1 or later (GIS software)

7- Dialog Developer 3.1 or later (GIS software)

In addition to the 50 Mb memory of hard disk space for installing the interface, a minimum 2 Gb hard drive is needed for storing Arc View, the SWAT/Arc View interface, and project generated maps and tables (Neitsch *et al*., 2002).

In setting up the model run/input files with AVSWAT, a series of operations are required:

1) generate catchment and sub-basin boundaries using the DEM;
2) define HRU's;
3) locate the weather files, etc.

AVSWAT operates by taking a Digital Elevation Model (DEM) as an input and delineating the catchment boundary and stream networks based on a threshold number of cells draining to a particular point. Sub-basins are derived automatically based on the stream networks. The user can remove or include additional sub-basins by adding outlets at appropriate locations or junctions of the stream, depending on requirements.

AVSWAT will overlay the given soil and land use maps and reclassify them into a series of Hydrological Response Units (HRU) defined on a per sub-basin basis. The HRU's are lumped land areas within the sub-basin that are comprised of unique land use, soil type and land management combinations. Weather station locations are specified and input files generated by AVSWAT, which the user may update with appropriate information prior to running the model. These input files are watershed configuration (.fig); soil input (.sol); sub-basin input (.sub); main channel (.rte); HRU input (.hru); groundwater (.gw); management input (.mgt); reservoir (.res) and other input files related to pond and water quality simulation. The simulation results output files will be generated in both text and GIS format. The main output files are HRU output file (.sbs) that contains information for each of the hydrological response units; the sub-basin output file (. bsb) which contains information for the sub-basins in the watershed; the main channel output file (.rch) that contains information for each routing reach in the watershed and the reservoir output file (.res) that contains information for the watershed reservoir. Figure 4.11 shows the schematic framework of the AVSWAT model.

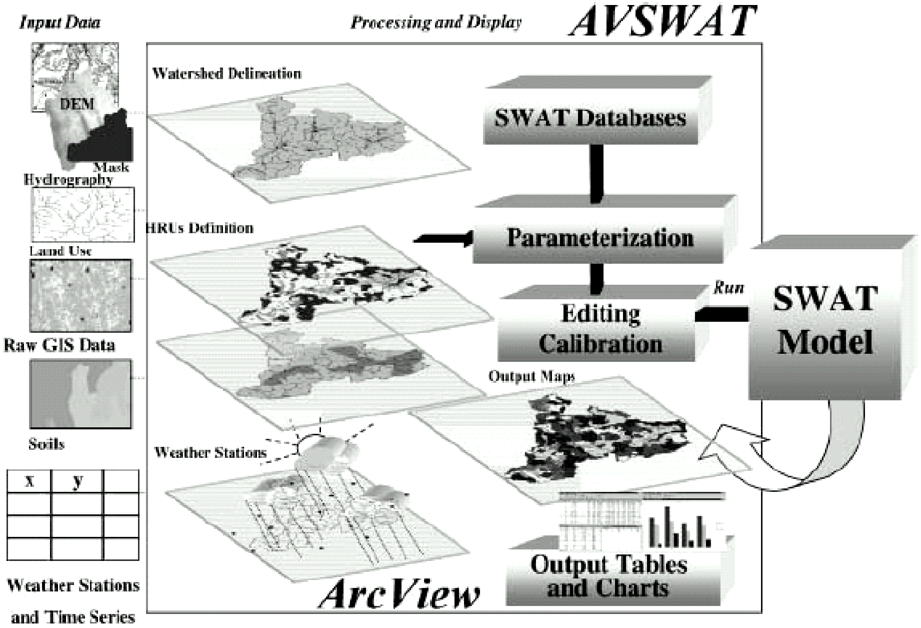


Figure 4.11 The schematic framework of AVSWAT system (after Diluzio and Arnold, 2004).

4.8.2. SWAT model hydrological background

SWAT simulates the hydrological cycle of a watershed in two phases, the land phase and the routing phase. The land phase of the hydrologic cycle controls the movement of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin. The routing phase of the hydrologic cycle simulates the movement of water, sediments, etc. through the channel network of the watershed to the outlet.

The following sections describe both phases (i.e. the land and routing phases) and their components as simulated by SWAT. However, the description is focused on the relevant components and processes to this current work, so that the parts related to chemical modelling are not described. A full description of all processes in SWAT is given in Neitsch et al., (2001).

4.8.2.1 Land phase hydrology

In SWAT, the land phase hydrological cycle (Figure 4.12) is simulated based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad (4.1)$$

Where, SW_t is the final soil water content on day *i* (mm)
SW_0 is the initial soil water content on day *i* (mm)
R_{day} is the precipitation on day *i* (mm)
Q_{surf} is the surface runoff on day *i* (mm)
E_a is the evapotranspiration on day *i* (mm)
W_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm)
Q_{gw} is the amount of return flow on day *i* (mm)

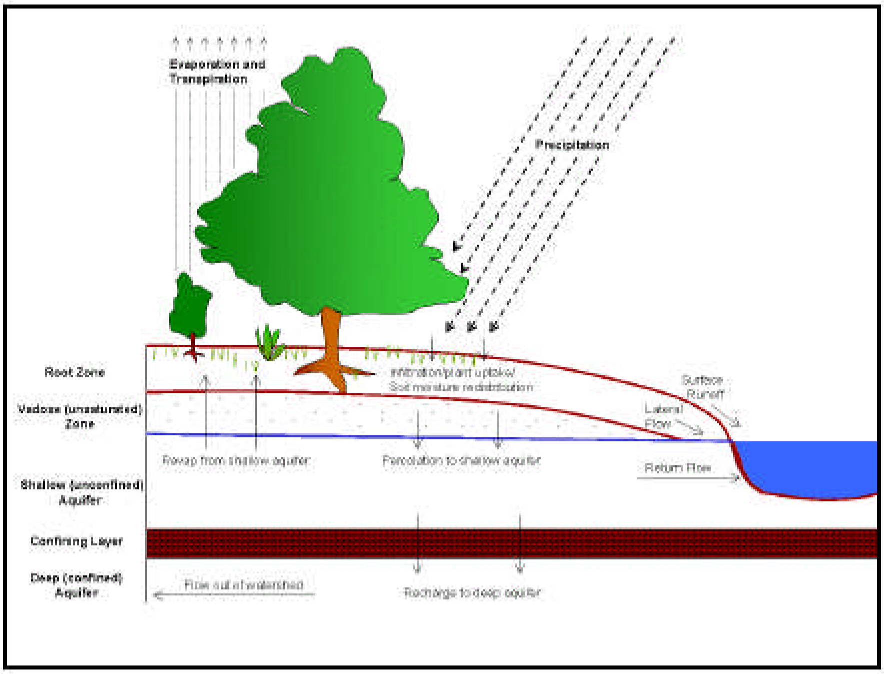


Figure 4.12 Representation of land phase hydrological cycle in SWAT (Neitsch et al., 2001).

As precipitation falls, it may be intercepted and held in the vegetation canopy or it may reach the soil surface. Water on the soil surface will infiltrate into the soil profile or flow overland as runoff. Runoff will move relatively quickly towards a stream channel and contribute to short-term stream response. The infiltrated water may be held in the soil and later be evapotranspired or it may slowly make its way to the surface-water system via underground paths (e.g. lateral sub-surface flow).

SWAT computes the surface runoff for each HRU separately. When the value of the rainfall exceeds zero, surface runoff and infiltration are calculated (e.g. using the SCS method). If surface runoff generation is possible (value of Surface runoff > 0), then the peak rate, transmission losses, sediment yield, nutrient and pesticide yields are calculated for the HRU. If the surface runoff generation is not possible, then soil water routing will be carried out after the calculation of evapotranspiration, crop growth and groundwater flow. After the soil water routing, stream flow will be generated for the HRU. Output variables for a sub-basin are calculated from area weighted HRU values. Finally, stream flow and sediment are routed through the sub-basin channel reach.

4.8.2.2 Watershed weather

Weather data provides the moisture and energy inputs that control the entire water balance of the watershed. In general, the model allows daily values of precipitation, maximum and minimum air temperature, solar radiation, wind speed and relative humidity, to be input from records of observed data or generated during the simulation. For each sub-basin, AVSWAT assigns the nearest weather station or rain gauge to the sub-basin centroid (Di Luzio et al. 2001).

4.8.2.3 Canopy storage

Canopy storage is the water intercepted by vegetative surfaces where it is held and made available for evaporation. When SWAT uses the SCS curve number method to compute surface runoff, canopy storage is taken into account in the surface runoff calculations, as the curve number method lumps canopy interception into the ‘initial abstraction’ variable. This variable also includes surface storage and infiltration prior to runoff and is estimated as 20% of the retention parameter value for a given day (see section 4.8.2.5).

SWAT allows the user to input the maximum amount of water that can be stored in the canopy at the maximum leaf area index for a given land cover. This value and the leaf area index will be used by the model to compute the maximum storage at any time in the growth cycle. When evaporation is computed, water is first removed from canopy storage before any water is allowed to reach the ground.

4.8.2.4 Evapotranspiration

Evapotranspiration includes evaporation from rivers and lakes, bare soil, and vegetative surfaces; and transpiration from the leaves of plants. SWAT offers three options for estimating potential (Neitsch et al., 2001) evapotranspiration:

Penman-Monteith (Allen et al., 1989), Priestley-Taylor (Allen, 1998) and Hargreaves (Hargreaves & Allen, 2003). When an evaporation demand for soil water exists, SWAT first partitions the evaporative demand between the different layers. The amount of evaporative demand for a soil layer is determined. The actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant transpiration is simulated as a linear function of potential evapotranspiration and leaf area index.

4.8.2.5 Surface Runoff

SWAT simulates surface runoff volumes and peak runoff rates for each HRU using daily or sub-daily rainfall amounts using a modification of the SCS-curve number method or the Green & Ampt infiltration method (Neitsch et. al., 2001), respectively. In the curve number method, the curve number varies non-linearly with the moisture content of the soil profile, reaching its lowest value when the soil profile approaches wilting point, and increases to near 100 as the soil approaches saturation. The SCS curve number equation is

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)} \tag{4.2}$$

Where Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), I_a is the initial abstraction (mm) which includes surface storage, interception and infiltration prior to runoff, and S is the retention parameter (mm).

The retention parameter varies spatially within the watershed due to changes in soils, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{4.3}$$

Where CN is the curve number for the day. The initial abstraction, I_a, is commonly approximated as $0.2S$ and equation 3.1 becomes

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)}$$

(4.4)

Runoff will only occur when $R_{day} > I_a$. A graphical solution of equation (3.4) for different curve number values is shown in Figure 4.13.

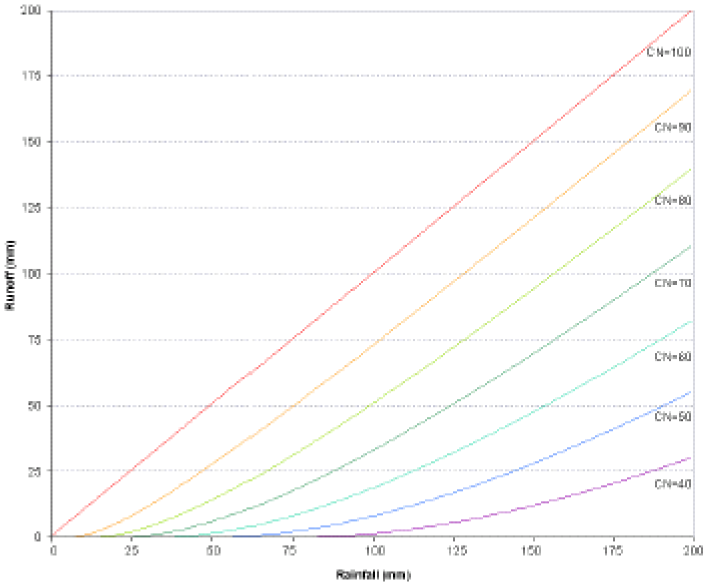


Figure 4.13 Relationship of runoff to rainfall in SCS curve number method.

The SCS defines three antecedent moisture conditions: 1- dry (wilting point), 2- average moisture, and 3- wet (field capacity). The moisture condition 1 curve number is the lowest value the daily curve number can assume in dry conditions. The curve numbers for moisture conditions 2 and 3 are calculated with the equations:

$$CN_1 = CN_2 - \frac{20 \cdot \left(100 - CN_2\right)}{\left(100 - CN_2 + \exp\left[2.533 - 0.0636 \cdot \left(100 - CN_2\right)\right]\right)}$$

(4.5)

$$CN_3 = CN_2 \cdot \exp\left[0.00673 \cdot \left(100 - CN_2\right)\right]$$

(4.6)

Where CN_1 is the moisture condition 1 curve number, CN_2 is the moisture condition 2 curve number, and CN_3 is the moisture condition 3 curve number.

Peak runoff rate which is the maximum runoff flow rate that occurs with a given rainfall event is simulated with a modification of the rational method (Neitsch et al., 2001). In the modified rational method, the peak runoff rate is a function of the proportion of daily precipitation that falls during the sub-basin time of concentration (t_c), the daily surface runoff volume, and the sub-basin time of concentration. The proportion of rainfall occurring during the sub-basin (t_c) is estimated as a function of total daily rainfall using a stochastic technique. The sub-basin time of concentration is estimated using Manning's Formula considering both overland and channel flow (Neitsch et al., 2001). The modified rational formula used to estimate peak flow rate is obtained by the following equation:

$$q_{peak} = \frac{\alpha_{tc} \cdot Q_{surf} \cdot Area}{3.6 \cdot t_{conc}} \tag{4.7}$$

Where q_{peak} is the peak runoff rate (m^3/s), α_{tc} is the fraction of daily rainfall that occurs during the time of concentration, Q_{surf} is the surface runoff (mm), $Area$ is the sub-basin area (km^2), t_{conc} is the time of concentration for the sub-basin (hr) and 3.6 is a unit conversion factor.

4.8.2.6 Transmission losses

SWAT uses Lane's (1982) method to estimate transmission losses. Water losses from the channel are a function of channel width and length and flow duration. Transmission losses are estimated with the equation:

$$tloss = K_{ch} \cdot TT \cdot P_{ch} \cdot L_{ch} \tag{4.8}$$

Where $tloss$ are the channel transmission losses (m^3), K_{ch} is the effective hydraulic conductivity of the channel alluvium (mm/hr), TT is the flow travel time (hr), P_{ch} is the wetted perimeter (m), and L_{ch} is the channel length (km).

4.8.2.7 Infiltration

Infiltration refers to the entry of water into a soil profile from the soil surface. If the curve number method is used to calculate surface runoff, as opposed to the Green & Ampt infiltration method, then it is not possible to directly model infiltration because the curve number method operates on a daily time-step. Thus, infiltration is calculated as the difference between the amount of rainfall and the amount of surface runoff.

4.8.2.8 Redistribution

Redistribution, which refers to the continued movement of water through a soil profile after input of water via precipitation or irrigation has ceased at the soil surface, is caused by differences in water content within the profile. The redistribution component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow, or percolation, occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. The flow rate is governed by the saturated conductivity of the soil layer.

4.8.2.9 Lateral flow

Lateral subsurface flow, or interflow, is the stream flow contribution which originates below the soil surface but above the zone where rocks are saturated with water. Lateral subsurface flow in the soil profile (0-2m) is calculated simultaneously with redistribution. A kinematic storage model is used to predict lateral flow in each soil layer. The model accounts for variation in hydraulic conductivity, slope and soil water content within the HRU.

4.8.2.10 Modelling and management of plant growth and land cover

The model utilizes a single plant growth model (Neitsch et al., 2001) to simulate all types of land covers. SWAT is able to differentiate between annual and perennial plants. Annual plants grow from the planting date to the harvest date or until the accumulated heat units equal the potential heat units for the plant. Perennial plants maintain their root systems throughout the year, becoming dormant in the winter months. They resume growth when the average daily air temperature exceeds their minimum, or base, temperature requirement. The plant growth model is used to assess removal of water and nutrients from the root zone, and biomass/yield production.

SWAT allows the user to define management practices taking place in every HRU. The user may define the beginning (planting) and the ending (harvesting) of the growing season; specify timings and amounts of fertilizer, pesticide and irrigation applications. Additionally, operations such as grazing, automated fertilizer and water applications, and management options for water use are available.

4.8.2. 11 Erosion

SWAT estimates erosion and sediment yield for each HRU with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1995). MUSLE uses the daily amount of runoff to simulate erosion and sediment yield. The hydrology model supplies estimates of daily runoff volume and peak runoff rate which, with the sub-basin area, are used to calculate the runoff erosive energy. The MUSLE is:

$$sed = 11.8 \cdot \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \qquad (4.9)$$

Where *sed* is the sediment yield on a given day (metric tons), Q_{surf} is the surface runoff volume (mm/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the USLE soil erodibility factor (m^3-metric ton cm), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{SUSLE} is the USLE topographic factor and C_{FRG} is the coarse fragment factor.

The crop management factor is recalculated for every day that runoff occurs, since plant cover varies during the growth cycle of the plant. It is a function of above ground biomass, residue on the soil surface, and the minimum value for the cover and management factor for the land cover. Other factors of the erosion equation are evaluated as described by Wischmeier and Smith (1978) as reported in Neitsch et al. (2001).

4.8.2.12 Routing phase hydrology

Once SWAT determines the loadings of water, sediment, nutrients and pesticides to the main channel, the loadings are routed through the stream network of the watershed using a command structure similar to that of HYMO (Williams and Hann, 1972) as reported in Neitsch et al. (2001).

4.8.2.13 Flow routing

As water flows downstream, a portion may be lost due to evaporation and transmission through the bed of the channel. Another potential loss is removal of water from the channel for agricultural or human use. Flow may be supplemented by the fall of rain directly on the channel and/or addition of water from point source discharges. Open channel flow is defined as channel flow with a free surface, such as flow in a river. SWAT uses Manning's equation to define the rate and velocity of flow. Water is routed through the channel network using the variable storage routing method developed by Williams (1969) or the Muskingum river routing method (Cunge, 1969). Both the variable storage and Muskingum routing methods are variations of the kinematic wave model.

4.8.2.14 Sediment routing

The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation operating in the reach. Bagnold (1977) defined stream power as the product of water density, flow rate and water surface slope. Williams (1980) used Bagnold's definition of stream power to develop a method for determining degradation as a function of channel slope and velocity. In SWAT, the equations have been simplified and the maximum amount of sediment that can be transported from a reach segment in a sub-basin is a function of the peak channel velocity. Available stream power is used to reentrain loose and deposited material until all of the material is removed. Excess stream power causes bed degradation. Bed degradation is adjusted for stream bed erodibility and cover.

4.8.2.15 Reservoir modelling

In the SWAT theoretical documentation (Neitsch et al., 2001), a reservoir (Figure 4.14) is defined as an impoundment located on the main channel network of a watershed as opposed to pond, wetland and depression which are located within a sub-basin.

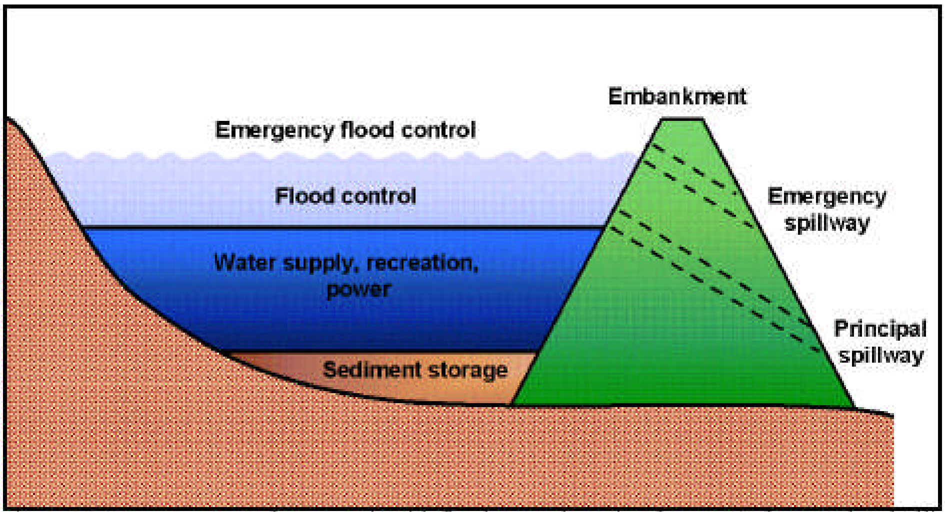


Figure 4.14 reservoir representations in SWAT

The water balance for a reservoir is:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \tag{4.10}$$

where V is the volume of water in the impoundment at the end of the day (m^3), V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3), V_{flowin} is the volume of water entering the water body during the day (m^3), $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3), V_{pcp} is the volume of precipitation falling on the water body during the day (m^3), V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3), and V_{seep} is the volume of water lost from the water body by seepage (m^3).

SWAT offers three alternatives for estimating outflow from the reservoir. The first option allows the user to enter measured outflow. The second option, designed for small, uncontrolled reservoirs, requires the users to specify a water release rate, a principle storage volume and an emergency spillway volume (Fig. 4.14). When the reservoir volume exceeds the principle storage, the extra water is released at the specified rate. However, any volume exceeding the emergency spillway volume is released within one day. The third option, designed for larger, managed reservoirs, has the user specify monthly target volumes for the reservoir.

For reservoirs, sediment inflow may originate from transport through the upstream reaches or from surface runoff within the sub-basin. The sediment settling in the reservoir is estimated using a simple continuity equation based on volume and concentration of inflow, outflow, and water retained in the reservoir. Settling of sediment in the reservoir is governed by an equilibrium sediment concentration and the median sediment particle size. The amount of sediment in the reservoir outflow is the product of the volume of water flowing out of the reservoir and the suspended sediment concentration in the reservoir at the time of release. The volume of water lost by seepage through the bottom of the reservoir on a given day is calculated:

$$V_{seep} = 240 \cdot K_{sat} \cdot SA \qquad (4.11)$$

Where V_{seep} is the volume of water lost from the water body by seepage (m^3), K_{sat} is the effective saturated hydraulic conductivity of the reservoir bottom (mm/hr), and SA is the surface area of the water body (ha).

5

Data availability, model input parameter derivation and model set up

5.1 Introduction

The SWAT ArcView® extension is a graphical user interface for the SWAT model (Arnold et al., 1998). To create the SWAT input datasets, the interface needs to access ArcView® map themes and database files which provide certain types of information about the modelled watershed. The necessary maps and database files therefore need to be prepared prior to running the interface. The main data types needed for AVSWAT to model the Wadi Ham catchment (or indeed any other catchment) can be summarised as time series data, spatial data and attribute datasets (Figure 5.1). Other data are required for management operations such as crop cultivation calendars, irrigation schedule, fertilisation etc. Finally, for the model performance evaluation, data such as stream flow are required to calibrate and validate the model.

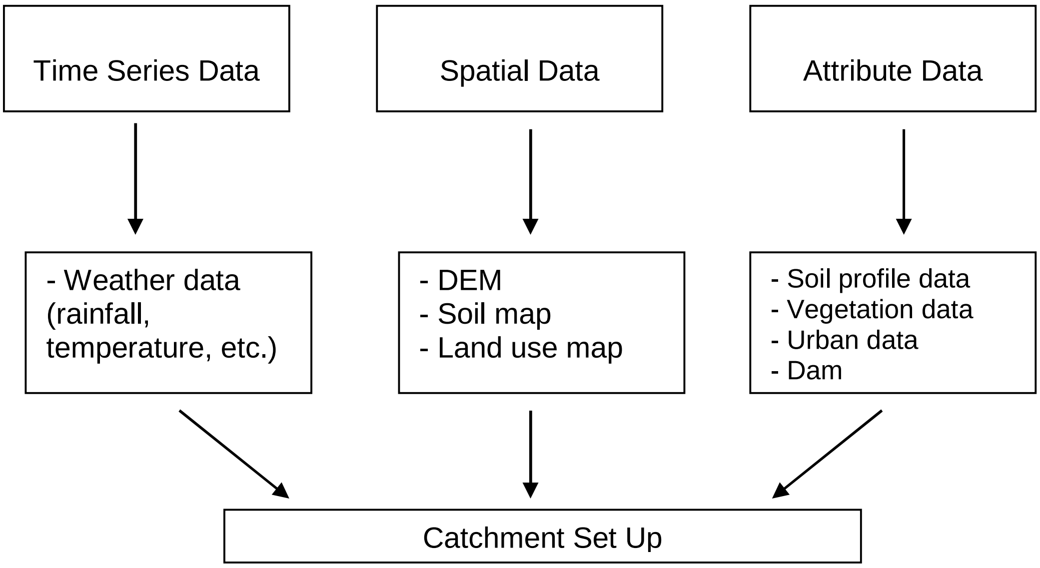


Figure 5.1 Data types required for Wadi catchment set up and modelling within AVSWAT model.

In general the Wadi Ham catchment is an arid region catchment where data availability is limited due to environmental, financial and other factors. In this chapter the data availability is reviewed and the model input parameter derivation and development of theme maps are discussed. Finally, the model set-up for the Wadi Ham catchment simulations is demonstrated.

5.2 Time series data

5.2.1 Weather data

Various forms of weather data are available from a number of stations around the catchment (Figure 5.2). For the study area the most comprehensive (although limited) available daily data are from the climate station at Masafi, located on the north boundary of the catchment. The available daily data from Masafi consists of maximum and minimum temperature and rainfall and also some monthly pan evaporation. The Masafi climatic station is one of the longest established climate stations in the eastern region of UAE operated by the Ministry of Agriculture and Fisheries.

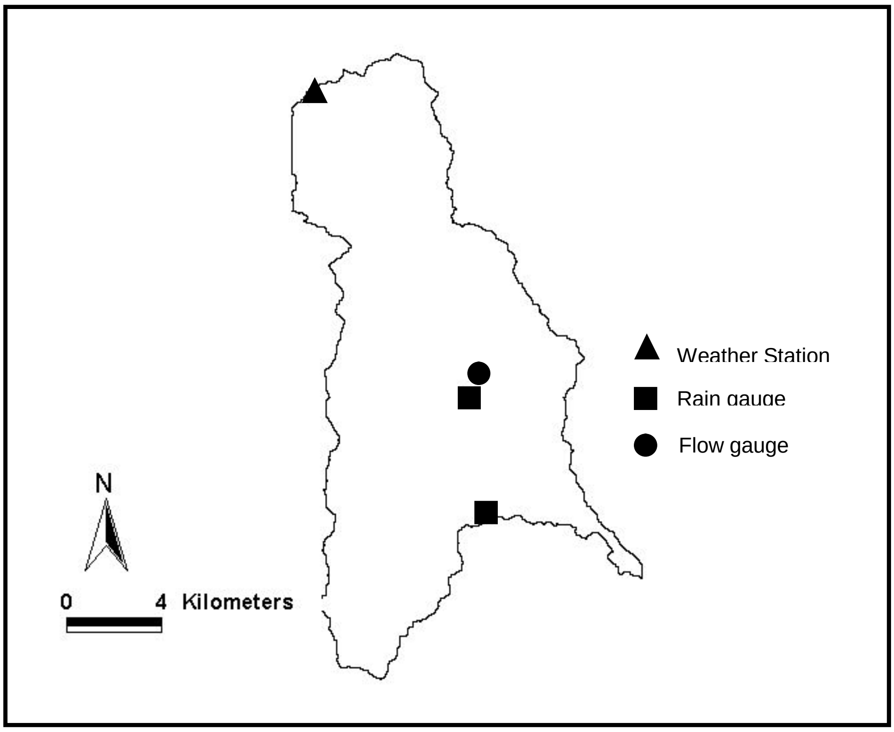


Figure 5.2 Location map of hydrometeorological stations in Wadi Ham catchment.

5.2.1.1 Rainfall data

Daily rainfall data in and around the catchment area are measured at a number of MAF rainfall recording and climate stations. Continuous daily rainfall data records from 1980 are available from three stations (Table 5.1). The stations at Bithna and Farah are located within the catchment, while the Masafi station, as mentioned above, is located at the northern boundary of the catchment.

Although all three stations have similar average annual rainfall totals, the rainfall over the catchment is highly variable both in space (between stations) and time (from year to year) (Table 5.2). The majority of the rainfall usually falls within the period of February to April, with February being the wettest month, and May to July the driest period (Figure 5.3). From the previous figure it can be seen that Masafi station rainfall is relatively higher in drier months and lower in wetter months compared to the other locations. This can be an indication of convective storm rainfall in the summer in mountain areas which may affect the accuracy of spatial rainfall representation over the catchment because of the lack of spatial interpolation of rainfall data by SWAT.

Table 5.1 Rainfall recording stations from 1980 in Wadi Ham catchment.

Station	**Location***		**Elevation (masl)****
	Northing	**Easting**	
Masafi	2798172.05	415960.81	459.86
Bithna	2785250.27	422547.78	188.20
Farah	2780114.57	423293.79	158.82

* Co-ordinate system: WGS UTM 40

** masl: Metre above sea level

Table 5.2 Total annual rainfall and 10 year average for the three stations in the catchment.

Hydrorological Year (Oct – Sept)	Total annual rainfall (mm)		
	Masafi	**Bithna**	**Farah**
1980-1981	95	104.2	108.4
1981-1982	348.2	309.4	312.8
1982-1983	249.5	350	394.2
1983-1984	110.4	76	43.4
1984-1985	33.6	22.8	22.4
1985-1986	77.6	63.8	72.8
1986-1987	158.8	166	181.4
1987-1988	242.4	252.2	290.6
1988-1989	65	62.6	45
1989-1990	291	228.8	220.4
1990-1991	79.8	42.6	72.6
Annual average	*159.2*	*152.6*	*160.4*

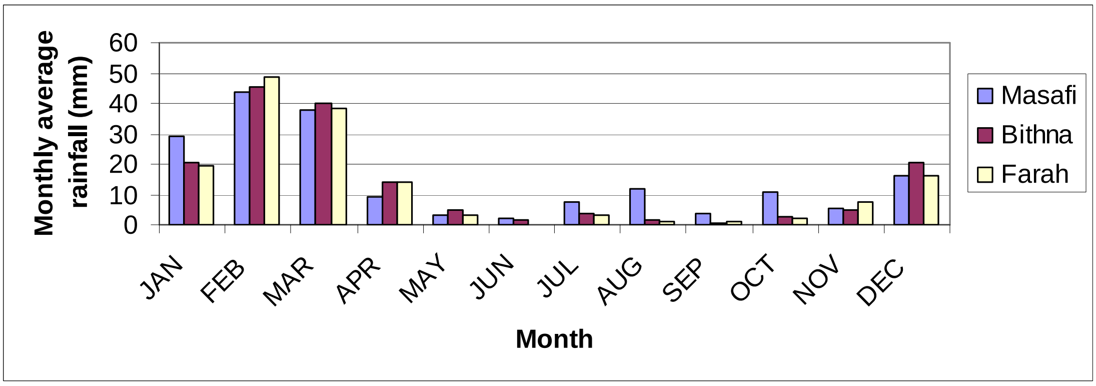


Figure 5.3 Monthly average rainfall (mm) for Masafi, Bithna and Farah stations.

5.2.1.2 Temperature data

Daily maximum and minimum temperature data for the period of simulation have been obtained from the Masafi climate station. From Figure 5.4 it can be seen that the lowest daily temperatures occur from December to February and highest temperatures from June to August.

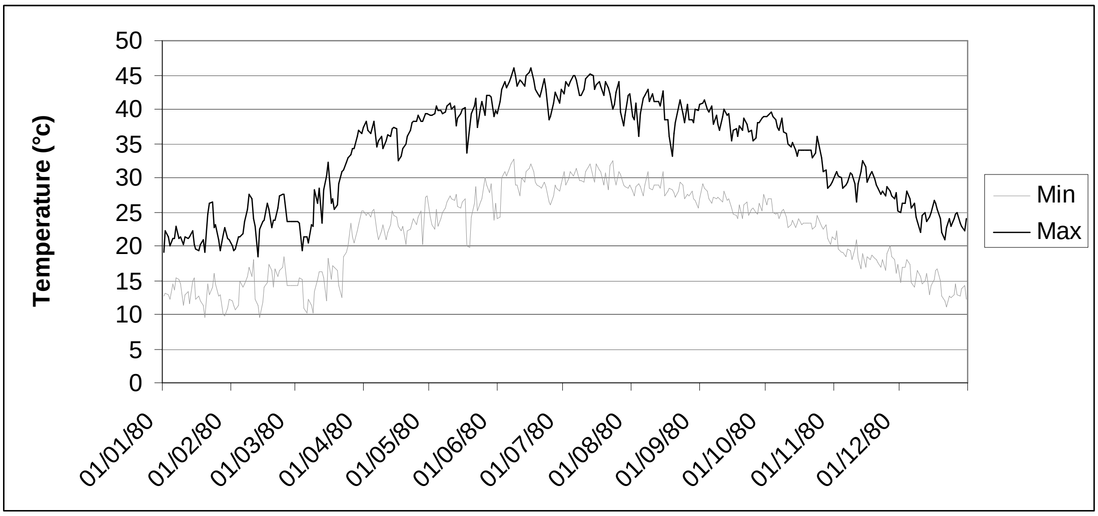


Figure 5.4 Daily maximum and minimum temperature values in Masafi station for 1980.

5.2.1.3 Evaporation data

Evaporation rates were measured at the Masafi station using a Class “A” Pan between early 1974 and the end of 1984 (Figure 5.5), although the data are incomplete with many gaps in the series. The highest monthly evaporation rates are from May to July when rates can occasionally exceed 20 mm/d. The lowest monthly evaporation rates are from December to February.

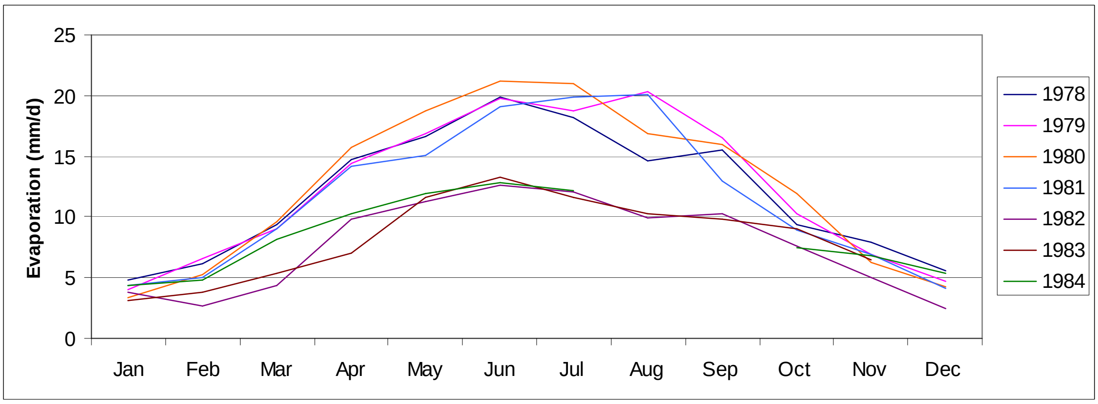


Figure 5.5 Monthly average evaporation (mm/d) at Masafi station measured using Class "A" Pan.

5.2.2 Surface flow data

Surface flow in the catchment has been measured only at the MAF-operated Bithna flow gauging station. The Bithna weir, located at grid reference 2782760 N, 424060 E, measured runoff for an area of 90.4 km^2 of the entire catchment area (192 km^2). Surface flow measurements were collected from 1979 until the end of February 1990 (Figure 5.6) when the station was destroyed in a massive flood event.

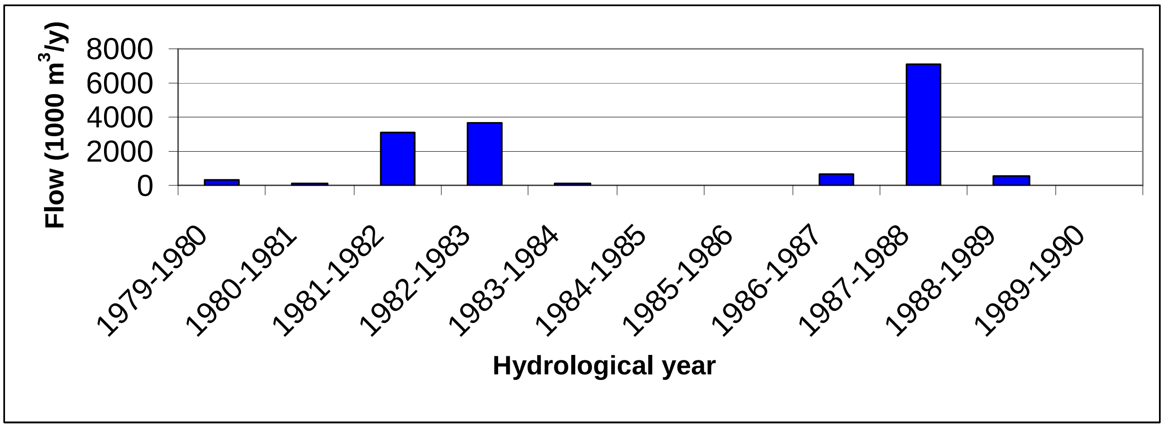


Figure 5.6 Total annual discharges of Wadi Ham catchment at Bithna flow gauge station.

The annual surface flow is highly variable, with no flow occurring in some years, as in 1985 and 1986. The majority of a year's runoff in the Wadi Ham catchment occurs within a relatively short period of time as flash floods, which reflects the intermittent nature of the rainfall events over the catchment (Figure 5.7).

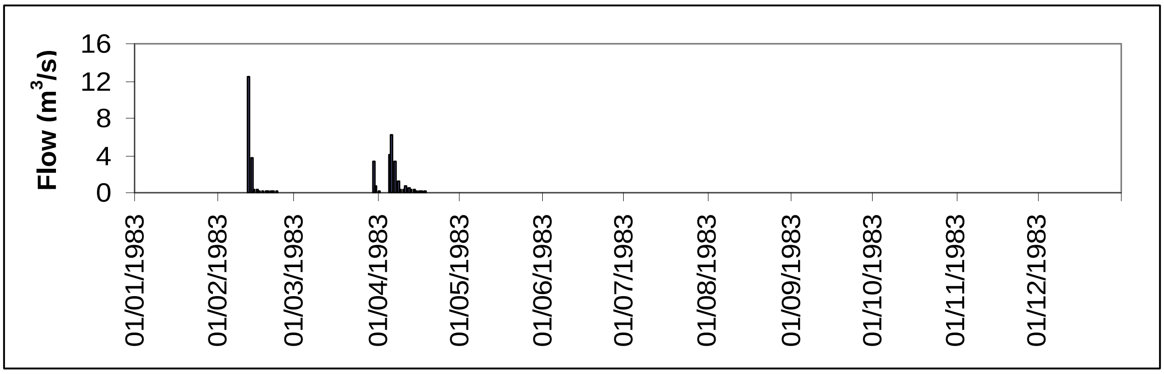


Figure 5.7 Daily surface flow (m^3/s) at Bithna flow gauge station for 1983.

5.2.3 Sediments data

For the study catchment there are no measured sediment data available. According to MAF hydrological report (1993) the annual sediment yield for Wadi Ham catchment is estimated at 29640 m^3/year using an empirical method.

The report also estimated the average annual sediment load for Wadi Ham dam reservoir as 61690 tonnes, based upon the mean annual discharge of the catchment and Flemings design curves method (MAF, 1993) as follows:

$$S = 58 * V^{0.7156}$$

Where S is average annual sediment load in 10^3 tonnes and V is average annual flow in 10^6 m^3.

5.3 Spatial data

5.3.1 Digital Elevation Model (DEM) of study area

The AVSWAT interface uses a DEM to delineate the stream networks and the catchment boundary by applying elementary raster functions provided by ArcView® along with its Spatial Analyst® extension and the derived Hydrology Extension for delineation of streams from a raster digital elevation model

(Diluzio and Arnold, 2004). Elevation data in the form of digital contour maps (5 m interval) from the Municipality of Fujairah (Emirate of Fujairah, UAE) and MAPS geosystems (MAPS Co., UAE) have been used to create a DEM for the study area. A DEM was prepared by joining the individual maps within a GIS to form a single contour map and then interpolating elevation data using the standard geoprocessing programs in ArcMap® software. A 50 m x 50 m resolution was selected for the derived grid as an appropriate resolution for the 1:25,000 scale of the digital contour maps and has been used as an input resolution in a number of SWAT studies (Cotter, 2003; Hernandez et al., 2000 and Krysanova and Becker, 1999).

5.3.2 Soil map of Wadi Ham catchment

There is no detailed soil map available for Wadi Ham catchment or the UAE in general. A landscape-based soil map for the Wadi Ham catchment therefore had to be developed based on a conceptual understanding of soil development and distribution in the catchment.

5.3.2.1 Review of soil information in study area

The Global Soil Regions map which is based on a reclassification of the FAO-UNESCO Soil Map shows the distribution of 4 soil orders i.e. Aridisols, Entisols, Inceptisols and Spodosols in the region of UAE (Figure 5.8).

The soils of the northern UAE were developed on sand and gravel outwash derived from the Oman Mountains (Stevens, 1969). The coarser outwash is found adjacent to the Oman Mountains whilst the finer outwash material is distributed along the western edge of the plains. These fine materials were covered by Aeolian sands encroaching from the southwest desert foreland (Figure 5.9).

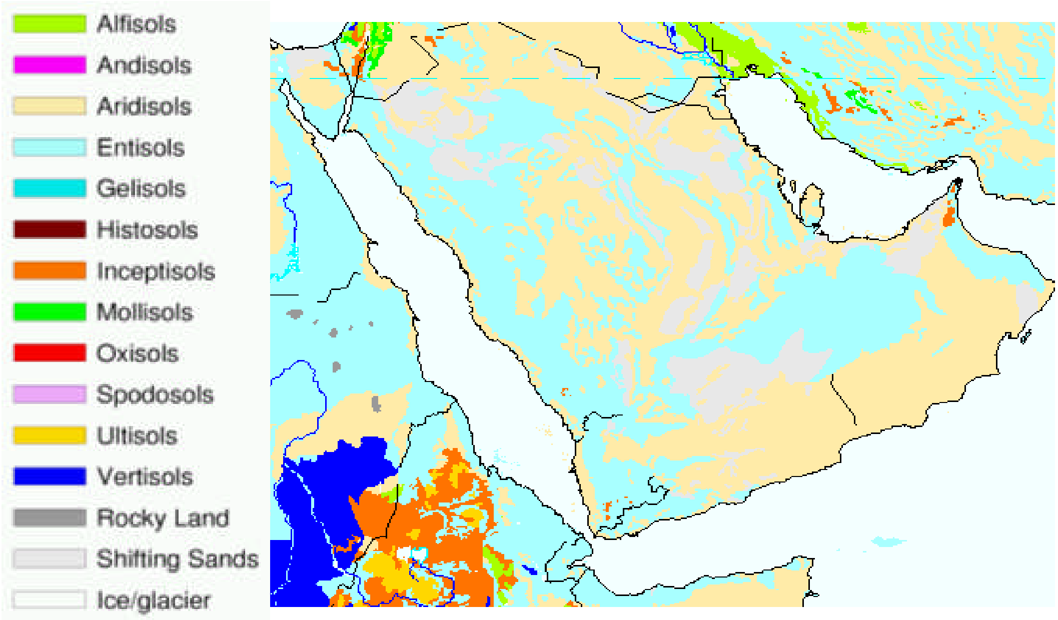


Figure 5.8 Global Soil Regions map (Middle East region) (Source: http://soils.usda.gov/use/worldsoils/mapindex/order.html).

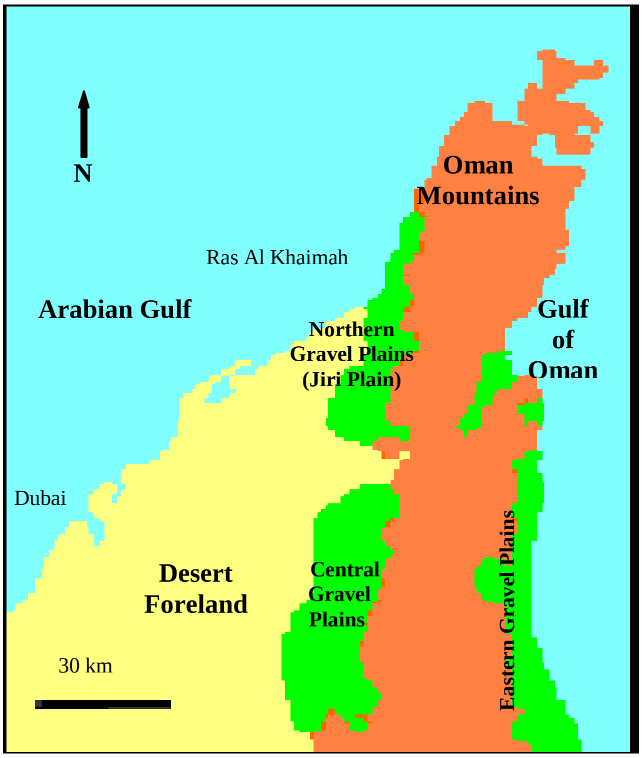


Figure 5.9 Physiographic regions of Northern UAE (Stevens, 1969).

It is apparent, therefore, that topography is expected to have a distinct role in determining the nature of the soil and the degree of soil development in such environments. In common with much of Northern UAE, the Wadi Ham catchment can topographically be distinguished into mountains, Wadi bottoms and gravel plains. This topographical variation affects the soil type distribution as can be seen in the 1:5,000,000 scale FAO-UNESCO (1974) soil map of South Asia, where the major soils in the Eastern part of the UAE are Lithosols, Yermosols and Fluvisols where:

- *Lithosols* are dominantly found on mountains and rock outcrops (FAO, 1974). Lithosols are soils that are limited in depth by continuous coherent hard rock within 10 cm of the surface. Generally, Lithosols have little potential for agriculture development because of their shallowness, high stone and rock contents and steep slopes.

- *Yermosols* are dominantly found on the plains and Pleistocene alluvial terraces. Yermosols are soils that occur under an aridic moisture regime, which have a very weak ochric A horizon and one or more of the following diagnostic horizons: a cambic B horizon, an argillic B horizon, a calcic horizon, a gypsic horizon. They lack high salinity. The Yermosols are described as shallow and/or stony, but in some spots can be deep yellowish loams (FAO, 1974).

- *Fluvisols* are soils that are developed within recent alluvial deposits and have no diagnostic horizons other than (unless buried by 50 cm or more new material) an ochric or an umbric A horizon, a histic H horizon, or a sulfruric horizon. As used in this definition, recent alluvial deposits are fluvial, marine, lacustrine, or colluvial sediments, which are characterised by one or more of the following properties:

(a) having an organic matter content that decreases irregularly with depth or that remains above 0.35 percent to a depth of 125 cm (although thin strata of sand which have less organic matter in the finer sediment below meet the requirements).

(b) receiving fresh material at regular intervals and/or showing fine stratification.

(c) having sulfidic material within 125 cm of the surface.

The same topographical influence in the formation of soil of the region can be seen as well in the soil classification made in the national atlas of the UAE (UAE University, 1993). It used the 7th approximation system of soil taxonomy and differentiated the soils in the Northern UAE region into:

- ***Torrifluvents***: Entisols that are formed in the alluvial sediments of intermittent streams. They are stratified as a result of many layers of sediment accumulation reflecting different flooding episodes. The Torrifluvents that occur in or near the stream channels have textures ranging from silt loam to very gravely sand although most are loamy. Generally they are non-saline to moderately saline, mostly deep soils.

- ***Torriorthents***: Entisols that are formed in residuum or in colluvium on actively eroding slopes in materials that are resistant to weathering processes. They can also be formed in alluvium on stream terraces in some areas. The Torriorthents have a texture of loamy sand, fine sandy loam, loam or clay loam with gravely counterparts. Generally they are non-saline to strongly saline, mostly shallow soils but occasionally they attain considerable depth.

- ***Torripsamments***: Entisols that are formed in poorly graded sands on dunes and other sandy deposits. They have also been recognised where thin sand covers bedrock. They may have a calcareous composition and small areas of loam. Generally they are non-saline to strongly saline.

- ***Calciorthids***: Aridisols in which secondary carbonates have accumulated to form a calcic horizon that has its upper boundary within one metre of the soil surface. They occur throughout the sedimentary succession where limestone and calcareous sandstone are common sources of calcium carbonate. The Calciorthids have a texture range from sandy to loamy. They can be found to be non-saline to strongly saline or shallow to deep and stony where they are formed of materials derived from lava rock.

The physical and chemical properties of the soil can be comprehended from the major soil types survey in the area conducted by Aubert (1962), Bowen-Jones et al (1967) and US Salinity Labroratory (1953). They distinguished the soil types in the Northern UAE as Sierozems, Nonsaline-alkali and Saline-alkali soils. The texture of these major soil types was described as dominantly sandy loams, although clay loam and silty clay loam textured soils occur as patches on the western edge of the plains. The carbonate content of the soils vary from less than 25% to more than 50% reflecting the origin of the outwash from the different Oman Mountain rock types. Table 5.3 shows the general properties of the soil types.

The general land uses for the previous soils were described by UNESCO, (1977) and Driessen and Dudal (1991) for *Lithosols* as little potential for improved production because of their shallowness, stoniness and some time inaccessibility. *Yermosols* are suitable for traditional grazing but with irrigation can be suitable for much crop cultivation. *Fluvisols* are usable for a wide range of cropping and grazing.

Table 5.3 General properties of the three major soil types in the northern UAE (adapted from Bowen-Jones and Stevens 1967 and Stevens 1969).

	Sierozems	**Non-saline-alkali soils**	**Saline-alkali soils**
Distribution	Jiry plain and central gravel plain.	Occur as long low ridges, usually gravel covered and devoid of vegetation	Limited areal distribution (areas that formerly were part of extensive Ras-Al-Khaimah lagoon).
Ph	7.8 – 9	< 9	< 8.5
EC (mmho/cm)	< 0.7	< 4	11
C.E.C (meq/100g)	Clay loams = 30 Sandy loams = 20-25	25 at surface to > 40 at 1 m depth	30
Organic matter %	< 3	< 0.5	
C:N ratio	8-12 in the top soil	< 11 in top of cultivated soils	
Available Phosphate (mg/g)	Very low (< 0.7)	Very low	
Exchangeable sodium percentage (E.S.P)	< 15	> 15	
Exchangeable potassium (meq/100g)	< 2		

5.3.2.2 Conceptual modelling and mapping of the spatial soil distribution in the Wadi Ham catchment

Predictive soil mapping is the development of numerical or statistical models of the relationships between environmental variables and soil properties, which are then applied to geographic databases to create a predictive map (Scull, 2003). Terrain analysis can quantify the relief components of models characterising soil formation, from which terrain attributes, derived from a DEM, can be used to capture the spatial variability of soil attributes and to develop a predictive soil map (McKensie, 2000; Moor, 1993 and Moor, 1991). This concept has been combined with the understanding of the distribution and properties of soils in the northern part of the UAE to develop a spatial landscape-based soil map for the Wadi Ham catchment.

As a starting point, a conceptual model has been developed from the literature review to relate the likely broad soil types in Wadi Ham catchment to the topography of the catchment. It is not the intention to develop a soil classification-based soil map. Based upon a visual analysis of the catchment, three landscapes or topographic exposure units (Figure 5.10) have been identified, which are expected (based upon the literature review) to have different soil properties, in particular depth of soil development, soil texture and soil organic matter content (Figure 5.11).

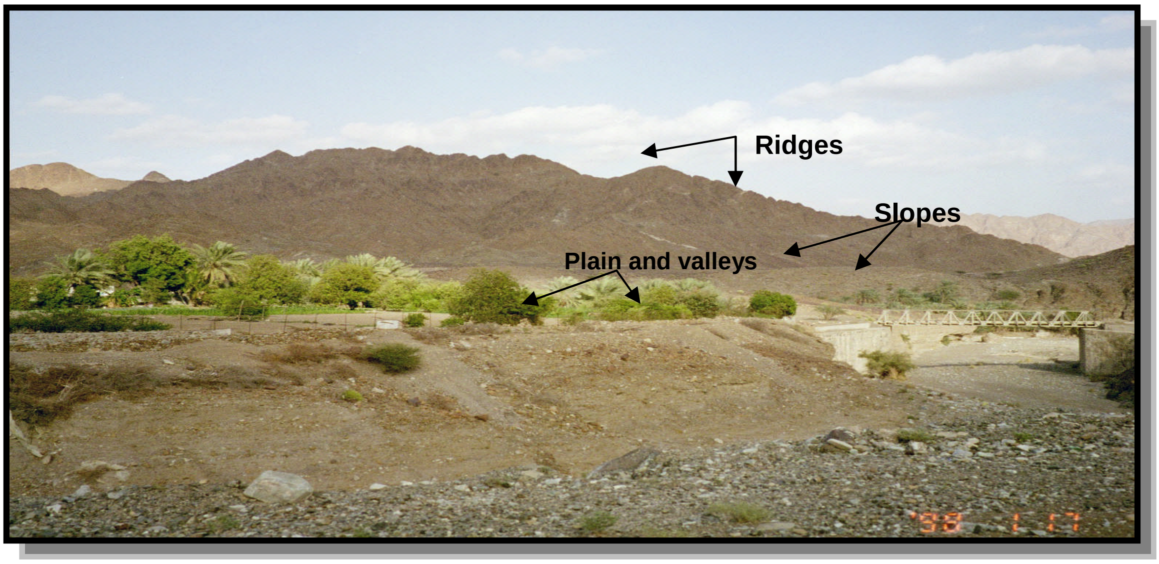


Figure 5.10 Wadi Ham catchment topographical exposure units.

The first soil type is found on the ridges and steep upper mountain slopes, which are associated with *Lithosols* found dominantly on mountains and rock outcrops. It is assumed to be composed of less than 10 cm of loamy sand textured soil. The second soil type covers the intermediate slope areas and is finer in texture and somewhat thicker in depth. Finally the soils of the plain areas and the valley bottoms which have the finest texture of loam and the greatest thickness are developed within the plains and alluvial terraces (associated with *Yermosols*) and the recent alluvial sediments of the intermittent streams, which can be associated with *Fluvisols* or *Torrifluvents* as classified by the UAE atlas.

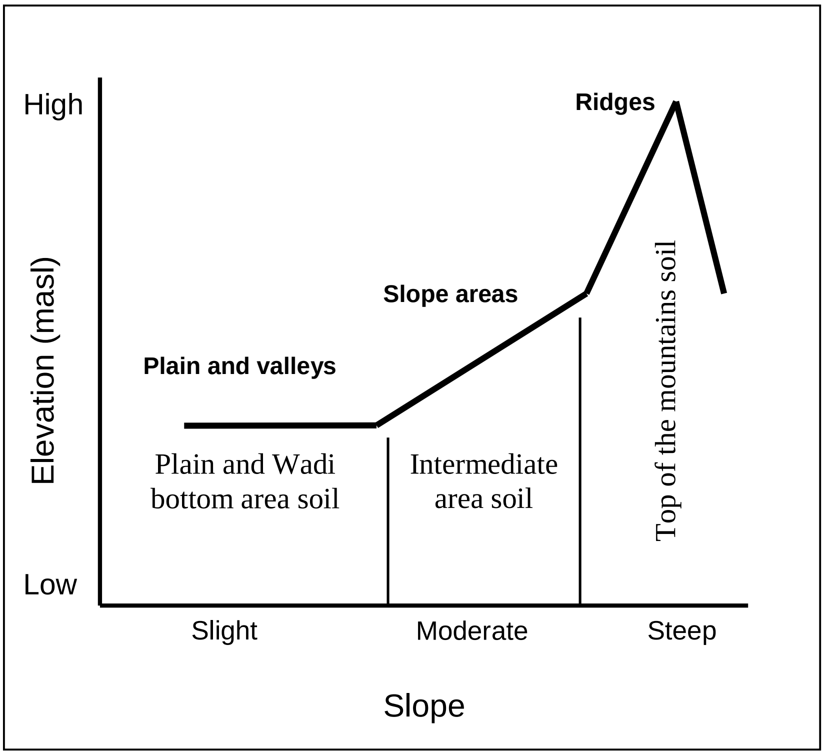


Figure 5.11 Conceptual model of the distribution of three broad soil types in the study area based on topographic features.

Terrain analysis software was used to associate the above conceptual model of soil distribution to Wadi Ham catchment topographical exposures within the DEM (Mayer, 2003, Personal communication). The *Toposcale.aml* and *Topoclass.aml* programs (Zimmermann, 2000) where used to convert the DEM of the study area into the topographic exposure units of ridges, slope areas and plain valley bottoms. Both Toposcale.aml and Topoclass.aml are ARC/INFO routines written in Arc Macro Language (AML). The *Toposcale.aml* works by applying circular moving-windows with increasing radii to the DEM, with the difference between the average elevation of the window and the centre cell of the window written to a temporary output grid file. The resulting temporary grid file is interpreted as the relative topographic exposure at different spatial scales (Zimmermann, 2000). The exposure is interpreted as a ridge or peak if the centre cell in the moving window has a higher elevation than the average elevation of the cells in the window. If the centre cell has lower elevation than the average elevation of the window, then it will be interpreted as "toe slope" or "valley bottom". A hierarchical integration into a single map is achieved by starting with the standardized exposure values of the largest window, then adding standardized values from smaller windows where the (absolute) values of the smaller (search-) scale grids exceed the values of the larger scale map.

The *Topoclass.aml* classifies the integrated grid of topographic position derived from *Toposcale.aml* into a grid containing class values, where the values of –1100 to –200 are reclassified as valley bottom, the values of -200 to –100 as toe slope, the values of –100 to 150 as slope, and the values above 150 are reclassified as ridge (Mayer, 2003, Personal communication).

The previous topographic characteristics were used as a basis for the predicted soil map of the study area (Figure 5.12). The exposures were divided into areas of ridges (top of the mountain soil type), sloped areas (intermediate area soil type) and valley bottom areas (plains and Wadi bottom soil type) as representative soil groups in the Wadi Ham catchment.

Finally, and in order to have better representation and control on the soil properties of the catchment in the AVSWAT environment, the cultivated areas in the catchment were digitised from available aerial photography of the study area and merged into the previous soil categories as a cultivated soil type. The cultivated areas were expected to be developed on deeper soil profiles and to have developed better soil fertility and higher organic carbon content (Bowen-Jones and Stevens 1967) than the uncultivated soils in the same topographical position. The locations of the digitised cultivated areas within the catchment are mainly on the plain and Wadi bottom soil type as predicted by the first original 3-fold classification of soil. The final predicted soil map of the Wadi Ham catchment therefore has four different spatial soil categories (Figure 5.13).

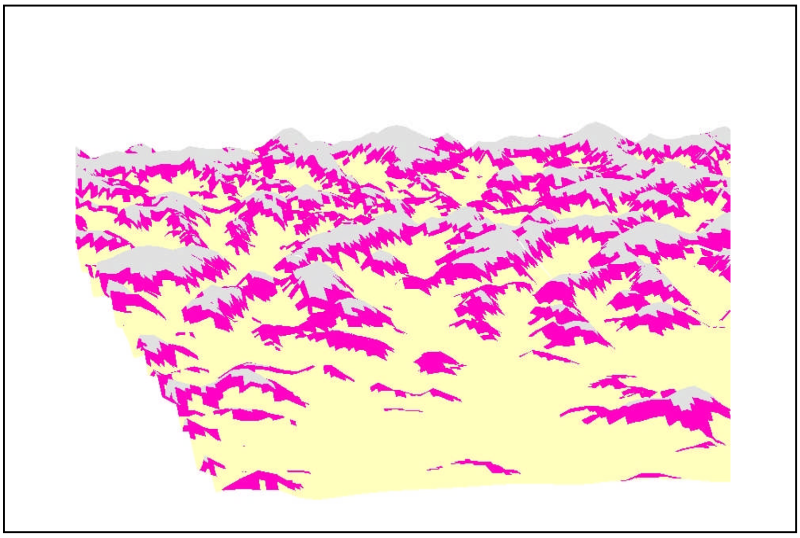


Figure 5.12 3D view for the three topographic exposures of ridge (grey), slope (red) and plains with valleys (yellow) within the Wadi Ham catchment.

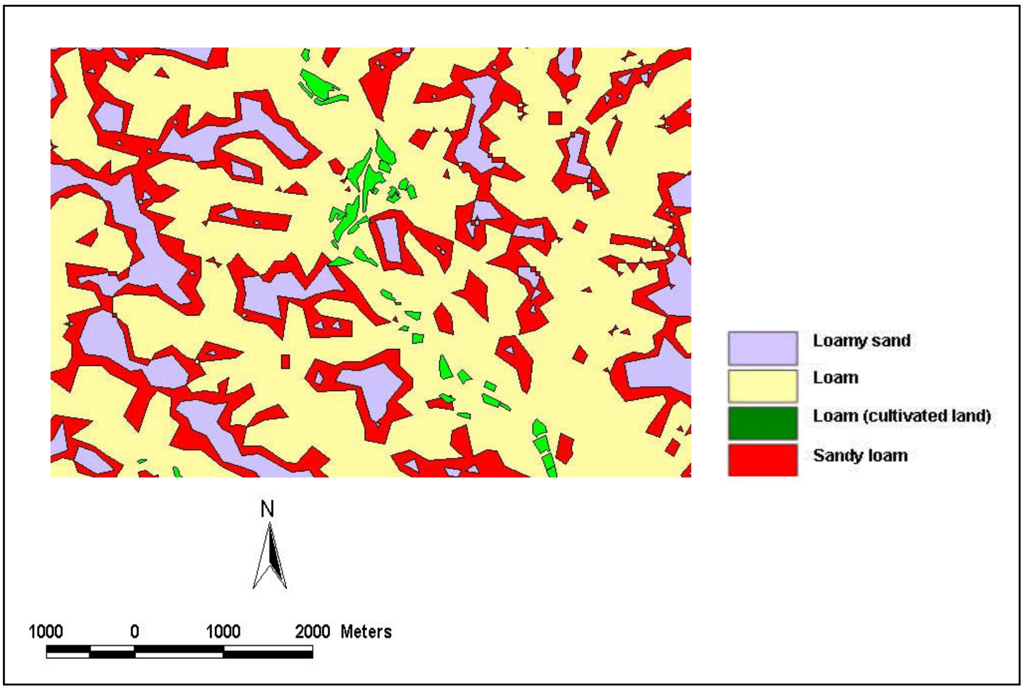


Figure 5.13 Distribution of soil texture based upon the predicted spatial soil categories within Wadi Ham catchment.

5.3.3 Land use map of the study area

Digital aerial photography from the Municipality of Fujairah (Emirate of Fujairah, UAE) and MAPS geosystems (MAPS Co., UAE) and the map of the north UAE provided by MAF were used to develop a land use map for the study catchment. Three major land use categories could be visually distinguished in the images: urban/developed areas, agricultural/cultivated areas and natural vegetation areas.

On-screen digitising was applied to the available digital aerial photography using ArcMap® software. The different land use categories were digitised separately as polygon features and finally merged together to create the final land use map. The resultant land use map contains the following categories: the natural vegetation land, urban areas, roads and cultivated areas. Within some cultivated areas it was possible to distinguish tree crops from other cropped areas. This information was used to correctly locate tree crops.

The resolution of the aerial photographs did not allow the identification of the areas of individual crop types within the cultivated areas which are required by SWAT. Therefore each of the polygons of the cultivated areas were subdivided to give the relative proportion for each major crop type in the mixed agriculture of a Wadi system (Figure 5.14) according to statistical data from the Eastern Agriculture Region. In 1985-1986 the distribution of agricultural land use in Eastern Agriculture Region was 71% fruit crops (such as date palm and citrus trees), 22% vegetable crops (such as tomato, cabbage and egg plant) and 7% field crops (such as alfalfa, barley and tobacco) (Figure 5.15). The final landuse map shows the natural vegetation land, urban areas, roads and cultivated areas, sub-divided to crop lands, tree lands and vegetable lands (Figure 5.16).

Figure 5.14 Traditional agriculture in Wadi systems consist of mixed cultivation pattern i.e. mixed trees within the same area and under-tree cultivation with vegetables or some fodder crops (Source:www.uaeinteract.com/photofile/index.asp).

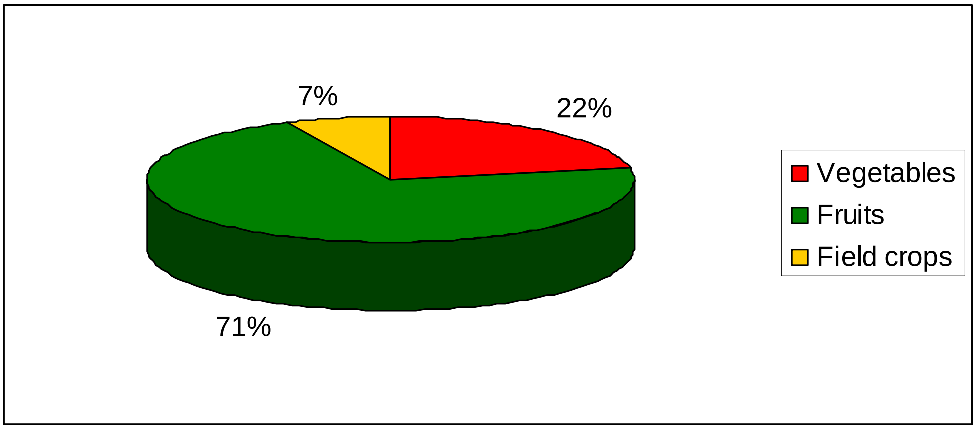


Figure 5.15 Percentage of cropping pattern area in the East Agricultural Region from 1980 to 1990 (MAF, 1991; 1986).

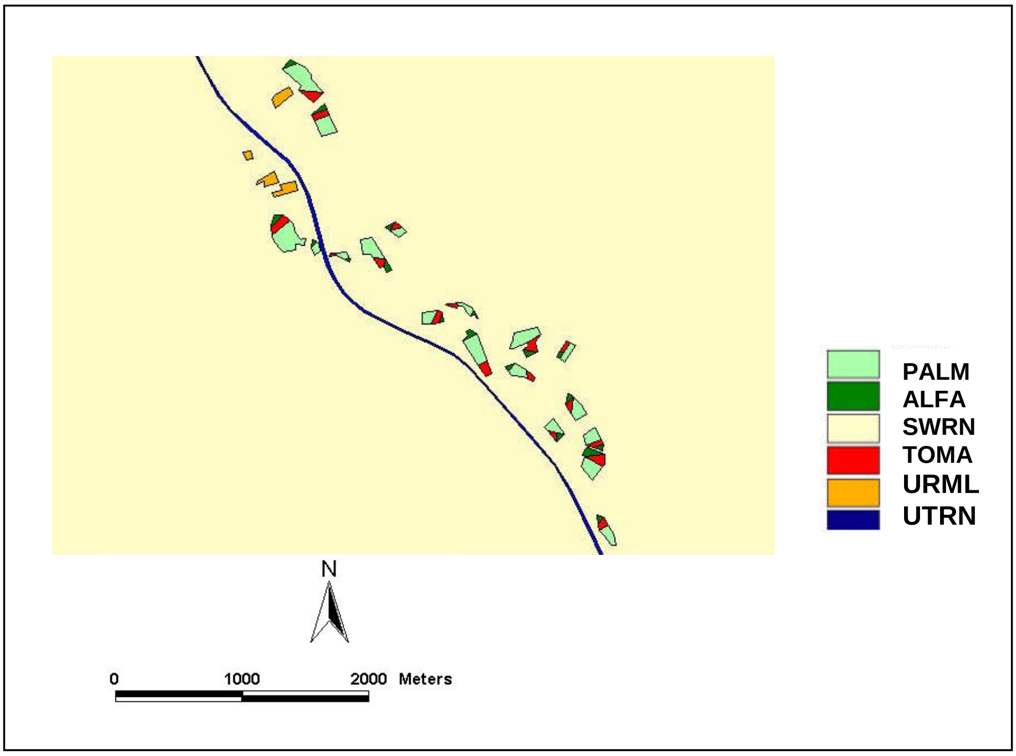


Figure 5.16 Derived land use map showing the categories for Wadi Ham catchment (SWRN is natural vegetation land, URML is urban areas, UTRN is road, ALFA is crop lands, PALM is tree lands and TOMA is vegetable lands).

5.4 Attribute Data

5.4.1 Soil profile data

Based on the earlier review of soil information, three main soil texture classes were proposed to be related to the different spatial soil categories. Loamy sand soils were related to ridge areas of the catchment, sandy loam soils to the slope areas and finally loamy soils to the plains and cultivated areas of the catchment.

The new soil types were added to the SWAT soil database and properties were assigned to each. The properties for the different soils (Table 5.4) were derived from published literature (Drenge, 1976; Soil map of the world, 1977; UAE national atlas, 1993; Sumner, 2000 and Brady and Well, 2002). The soil physical properties e.g. clay percentage, bulk density and available water capacity were given as standard average values for each soil texture class. The soil depth varies from shallow in the ridges soil unit to the deeper soils of the plain areas. The rooting depth is assumed to be the same as the depth of the soil. The soils of the ridges and slope areas are assumed to have a high runoff potential due to the high slopes and low soil water storage (due to the thin soil depth over hard rock) and have therefore been assigned to soil hydrologic groups D and C, respectively. The soils of the plain areas have been assumed to have a moderate runoff potential due to the lower slopes and proximity to the Wadi system, and have been assigned to soil hydrologic group B.

Table 5.4 Proposed soil properties for the different soil texture groups in the catchment.

Name	**Description**	**Loamy sand soil**	**Sandy loam soil**	**Loamy soil**
NLAYERS	Number of layers in the soil	1	1	1
HYDGRP	Soil hydrologic group (A, B, C, or D)	D	C	B
SOL_ZMX (mm)	Maximum rooting depth of soil profile	50	150	500
ANION_EXCL	Fraction of porosity (void space) from which anions are excluded	0.500	0.500	0.500
SOL_CRK	Potential or maximum crack volume of the soil profile	0	0	0
SOL_Z (mm)	Depth from soil surface to bottom of layer	50	150	500
SOL_BD (g/cm^3)	Moist bulk density	1.72	1.60	1.63
SOL_AWC (mm/mm)	Available water capacity of the soil layer	0.08	0.12	0.15
SOL_K (mm/hr)	Saturated hydraulic conductivity	61.10	25.90	13.20
SOL_CBN %	Organic carbon content	0.05	0.10	10
CLAY %	Clay content	5	10	20
SILT %	Silt content	15	25	40
SAND %	Sand content	80	65	40
ROCK %	Rock fragment content	5	35	60
SOL_ALB	Moist soil albedo	0.25	0.25	0.16
USLE_K (m^3 t cm)	USLE equation soil erodibility (K) factor	0.13	0.25	0.45
SOL_EC (ds/m)	Electrical conductivity	0	0	0

5.4.2 Vegetation data

5.4.2.1 Natural vegetation data

The natural vegetation types of the catchment are typical arid climatic zone annual plants, which complete their short life cycle during the period of water availability during the rainy season. The natural vegetation pattern in the arid Wadi system is determined mainly by the drainage system, depth to water table, rainfall and runoff frequency and the sediment characteristics (Dell and al Gifri, 1998).

Kürschner (1998) described three main vegetation types that occur on the Arabian Peninsula:

a. Wadi communities in arid, semi-arid and extra-tropical zones are dominated by Taxa of Saharo-Sindian origin which borders the large Wadi systems in the central part of the Arabian Peninsula.
b. Wadi communities in less arid zones are dominated by Taxa of Mediterranean and Irano-Turanian origin on the north-western and south-eastern corners of the Arabian Peninsula.
c. Wadi communities in the subtropical zone are dominated by Taxa of Sudanian and Xero-tropical African origin, in areas like western coastal plain of the Arabia and coastal lowlands of the Batinah coast of northern Oman.

In the Northern Oman Mountains region of the UAE, *Parietaria lusitanica* and *Onychium melanolepis* usually emerge and grow after the precipitation and runoff on the fine sand between the boulders. Other vegetation types that can be found in the Wadi alluvium are *Physorrhynchus chamaerapistrum, Ochradenus aucheri, Tamarix ssp.* and *Acasia tortilis.* On the gravelly wadi bed with higher water storing capacity, plants like *Phoenix dactylifera*, *Mangifera indica* and *Punica granattum* grow (Dell and al Gifri, 1998). Table 5.5 lists some of the indigenous plants species that can be seen in the Wadi Ham catchment.

Table 5.5 Indigenous plants species of Wadi Ham catchment (Karim, 1995 and Western, 1989)

Plant	Description	Location
Echinops sp	Perennial/2m tall/ flowering May-June	Common in large clumps on slopes throughout mountains.
Diplotaxis harra	Perennial / annual/40cm/ flowering Feb-June	Lower mountains and rocky wadis.
Asphodelus tenuifolius	Annual/45cm/flowering Jan.-Apr.	Dry slopes of the mountains and damp places
Anagallis arvensis	Annual/30cm/flowering Feb-Apr.	Cultivated fields and lower mountains on rocky slopes
Reseda aucheri	Annual/Biennial/60cm/flowering Jan-Jun.	Mountains and piedmont gravels
Tephrosia apollinea	Perennial/70cm/ flowering Dec-June	Foothills to 3000ft and mountain wadis and alluvial plains.
Salvia macilenta	Perennial/30cm/ flowering Jan-May	Fujairah mountains
Physorrhynchus chamaerapistrum	Perennial/2m/ flowering Fe-July	Mountains

From the above, it can be seen that many different species of plants inhabit the natural land of an arid Wadi catchment. The growth and life cycle of most of these plants is related to the rainfall season as they emerge and grow and reproduce. For SWAT plant growth modelling in the natural vegetation areas, the various natural vegetations of the Wadi system were simplified to one representative species. Due to the lack of detailed physiological information on these uneconomically-important indigenous species, it was not possible to derive input parameters for SWAT. Therefore this vegetation has been represented by the available parameterised arid range-southwestern US (SWRN) perennial plant included in the SWAT crop database. This plant should be the most appropriate available to represent the arid vegetation behaviour within the simulation.

5.4.2.2 Cropping and agricultural representation in SWAT

The agriculture land use in Wadi Ham is divided among small land holders with an average of only 1 ha per agriculture holding. The main cultivated crops are fruits (dominantly Date palms and citrus), vegetables and fodder field crops such as alfalfa and grass which are grown in permanent cultivation. The vegetable cultivation is highly variable i.e. Tomato, Eggplant, Potato, Onion and various leaf vegetables.

In the 1980s the majority of the cultivated areas were irrigated by groundwater resources using traditional irrigation systems. Two types of such irrigation system were prevalent in the area. The first type is the basin irrigation system which consists of flat beds, bordered by small dykes, which are filled with water. Water is usually conveyed to the basins by an earth furrow from a central channel. The area of each of these basins is up to 10 m^2. The basin irrigation system is usually used for vegetables, alfalfa and fruit trees. The second irrigation system is furrow irrigation. In this system furrows and ridges are constructed parallel to the water supply channel. Furrows are divided into convenient lengths of three to five metres by cross ridges. Water is diverted into these sections up to ¾ of the furrow height and then released to the next section. This irrigation system is used mainly for vegetable irrigation (Figure 5.17).

Figure 5.17 Traditional irrigation with open channel systems in Wadi catchments of UAE.

In order to simplify the highly variable agricultural land use in the Wadi Ham catchment for modelling by SWAT, three crops were selected to represent the three cultivated crop groups in the catchment. Alfalfa, tomato and date palm were selected to represent the crop lands, vegetable lands and tree lands, respectively, as they are the most cultivated crops in the region (MAF, 1990 and MAF, 1985). The SWAT land cover/plant growth database contains information about alfalfa and tomato which were used as initial input parameters for these crops (Table 5.6). Parameters for the date palm tree were not available in the SWAT database, and were therefore derived from the available literature of date palm and oil palm trees (Corley and Tinker, 2003; Kiniry, 2003 (personal communication) and Zayed, 1999) and added to the SWAT land cover database (Table 5.7).

5.4.3 Urban land use data

The urban land use in the Wadi Ham catchment consists of different houses and small village areas scattered within the catchment, together with the main road which runs through the middle of the area to connect the Fujairah Emirate to the central region of UAE. The urban areas database included in the SWAT model was used to provide input parameters.

5.4.4 Wadi Ham reservoir

The Wadi Ham dam was constructed in 1982 and is operated by the Ministry of Agriculture and Fishery. The information required by SWAT on the dam characteristics and its reservoir (such as reservoir surface area when it is filled to emergency spillway) were obtained from the design report prepared by Electrowatt Engineering Services Ltd. (1981).

Table 5.6 Initial plant input parameters from SWAT land cover/plant growth database which used for Wadi Ham catchment simulation (Neitsch, et al., 2001).

Variable name	Definition	Alfalfa	Tomato	Range
CPNM	A four character code to represent the land cover/plant name.	ALFA	TOMA	SWRN
IDC	Land cover/plant classification:	Legume	Warm season annual	Perennial
BIO_E	Radiation-use efficiency or biomass-energy ratio ((kg/ha)/(MJ/m^2)).	20	30	34
HVSTI	Harvest index for optimal growing conditions.	1	0.33	0.90
BLAI	Maximum potential leaf area index.	4	3	1.50
FRGRW1	Fraction of the plant growing season or fraction of total potential heat units corresponding to the 1st point on the optimal leaf area development curve.	0.15	0.15	0.05
LAIMX1	Fraction of the maximum leaf area index corresponding to the 1st point on the optimal leaf area development curve.	0.01	0.05	0.10
FRGRW2	Fraction of the plant growing season or fraction of total potential heat units corresponding to the 2nd point on the optimal leaf area development curve.	0.50	0.50	0.25
LAIMX2	Fraction of the maximum leaf area index corresponding to the 2nd point on the optimal leaf area development curve.	0.95	0.95	0.70
DLAI	Fraction of growing season when leaf area declines.	0.90	0.95	0.35
CHTMX	Maximum canopy height (m).	0.90	0.50	1
RDMX	Maximum root depth (m).	3	2	2
T_OPT	Optimal temperature for plant growth (ºC).	38	22	25
T_BASE	Minimum (base) temperature for plant growth (ºC).	8	10	12
USLE_C	Minimum value of USLE C factor for water erosion applicable to the land cover/plant.	0.010	0.030	0.003
GSI	Maximum stomatal conductance at high solar radiation and low vapour pressure deficit (m s^{-1}).	0.010	0.008	0.005
VPDFR	Vapour pressure deficit (kPa) corresponding to the second point on the stomatal conductance curve.	4	4	4
FRGMAX	Fraction of maximum stomatal conductance corresponding to the second point on the stomatal conductance curve.	0.750	0.750	0.750
WAVP	Rate of decline in radiation use efficiency per unit increase in vapour pressure deficit.	10	8	10

Table 5.7 Information added to SWAT land cover/plant growth database for the date palm tree (developed from Corley and Tinker, 2003; Kiniry, 2003 and Zayed, 1999).

Variable name	Definition	Value
CPNM	A four character code to represent the land cover/plant name.	DPLM
IDC	Land cover/plant classification:	trees
DESCRIPTION	Full land cover/plant name.	Date Palm
BIO_E	Radiation-use efficiency or biomass-energy ratio ((kg/ha)/(MJ/m^2)).	50
HVSTI	Harvest index for optimal growing conditions.	0.7
BLAI	Maximum potential leaf area index.	2.2
FRGRW1	Fraction of the plant growing season or fraction of total potential heat units corresponding to the 1st point on the optimal leaf area development curve.	1
LAIMX1	Fraction of the maximum leaf area index corresponding to the 1st point on the optimal leaf area development curve.	1
FRGRW2	Fraction of the plant growing season or fraction of total potential heat units corresponding to the 2nd point on the optimal leaf area development curve.	1
LAIMX2	Fraction of the maximum leaf area index corresponding to the 2nd point on the optimal leaf area development curve.	1
DLAI	Fraction of growing season when leaf area declines.	0.15-1
CHTMX	Maximum canopy height (m).	7.5
RDMX	Maximum root depth (m).	4
T_OPT	Optimal temperature for plant growth (ºC).	32
T_BASE	Minimum (base) temperature for plant growth (ºC).	7
USLE_C	Minimum value of USLE C factor for water erosion applicable to the land cover/plant.	0.025
GSI	Maximum stomatal conductance at high solar radiation and low vapour pressure deficit (m s^{-1}).	1.463
VPDFR	Vapour pressure deficit (kPa) corresponding to the second point on the stomatal conductance curve.	4
FRGMAX	Fraction of maximum stomatal conductance corresponding to the second point on the stomatal conductance curve.	0.75
WAVP	Rate of decline in radiation use efficiency per unit increase in vapour pressure deficit.	6-8

5.5 Setting up the SWAT model for Wadi Ham Catchment

5.5.1 Catchment delineation

The Watershed Delineation function in AVSWAT applies the GIS functionality of ArcView® and its extensions for segmenting the watershed into several hydrologically connected sub-watersheds for use in the watershed modelling within SWAT. The delineation process requires the DEM to be in ArcInfo grid format.

The previously prepared DEM was used as an input to AVSWAT interface to delineate the Wadi Ham catchment automatically (Figure 5.18). The resultant delineated catchment boundary and drainage network showed a close agreement with a previously available small scale catchment boundary and drainage network that had been prepared manually from maps (Entec, 1996). During the delineation processes, the Wadi Ham dam and reservoir were added to the catchment and additional sub-basin outlets including the Bithna runoff station were added.

5.5.2 Preparation and reclassification of soil and land use maps

SWAT requires land use and soil data to determine the area and the hydrologic parameters of each land-soil category simulated within each sub-basin. The previously prepared soil and land use maps were used as the spatial soil and land use maps for Wadi Ham catchment (Figure 5.19 and Figure 5.20).

The input land use map was reclassified using the reclassification tool in AVSWAT interface, to allow the land use map to be linked to the crop growth database. The catchment prepared soil information was incorporated into the existing SWAT soil database and names were assigned to them. Similarly the soil map was reclassified using the reclassification tool in AVSWAT interface to link with properties of the previously described soil categories of the soil map which had been added to the SWAT soil database.

5.5.3 Discretisation of the catchment into HRUs

The basis of the hydrological modelling in SWAT is the Hydrological Response Unit (HRU) which is a lumped land area within the sub-basin that is comprised of unique land cover, soil, and management combinations, which enables the model to reflect differences in evapotranspiration and other hydrologic conditions for different land covers/crops and soils.

There are two options in SWAT for determining the HRU distribution: either to assign a single HRU to each sub-watershed or to assign multiple HRU's to each sub-watershed. If a single HRU per sub-basin is selected, the HRU is determined by the dominant land use category and soil type within each watershed. If multiple HRU's are selected, the user must specify a threshold level to ensure each combination of land use and soil category within the sub-basin is defined as an HRU. For Wadi Ham catchment, the single HRU approach was used for the sensitivity analysis, while multiple HRU's were selected for the main simulation.

5.6 Preparation of input files and running the model

After subdividing the catchment into HRUs, the location of the weather station and rain gauges were specified in AVSWAT, which linked the rain gauges and temperature gauge to their database files (Figure 5.21). The AVSWAT interface prepared precipitation and weather data (temperature data in this case) for each sub-basin. At this stage the model is ready to run and simulation to proceed.

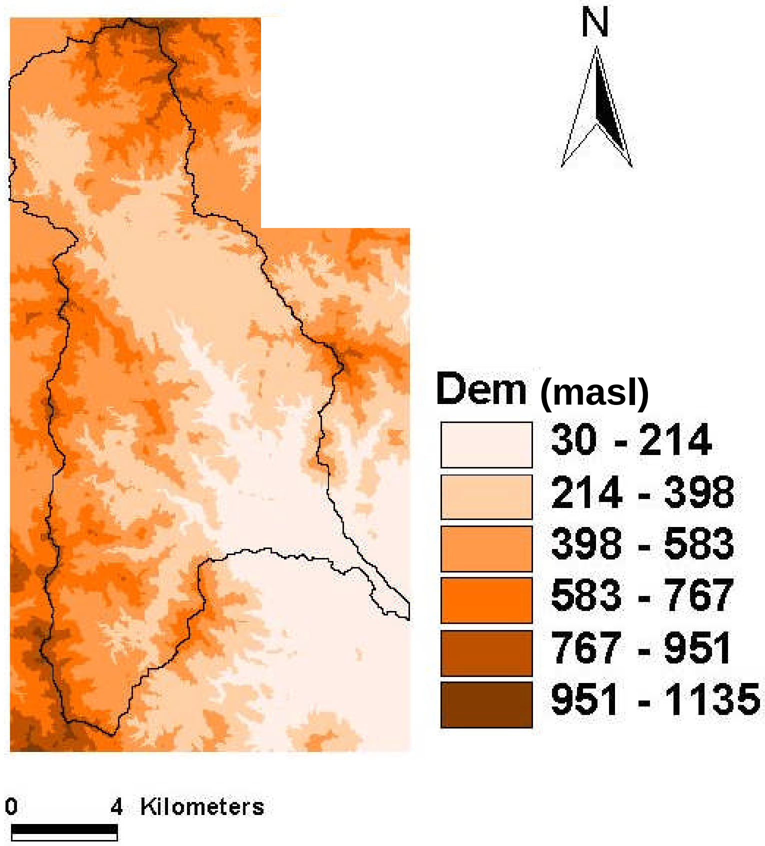


Figure 5.18 Wadi Ham catchment boundary automatically delineated from the prepared DEM by AVSWAT.

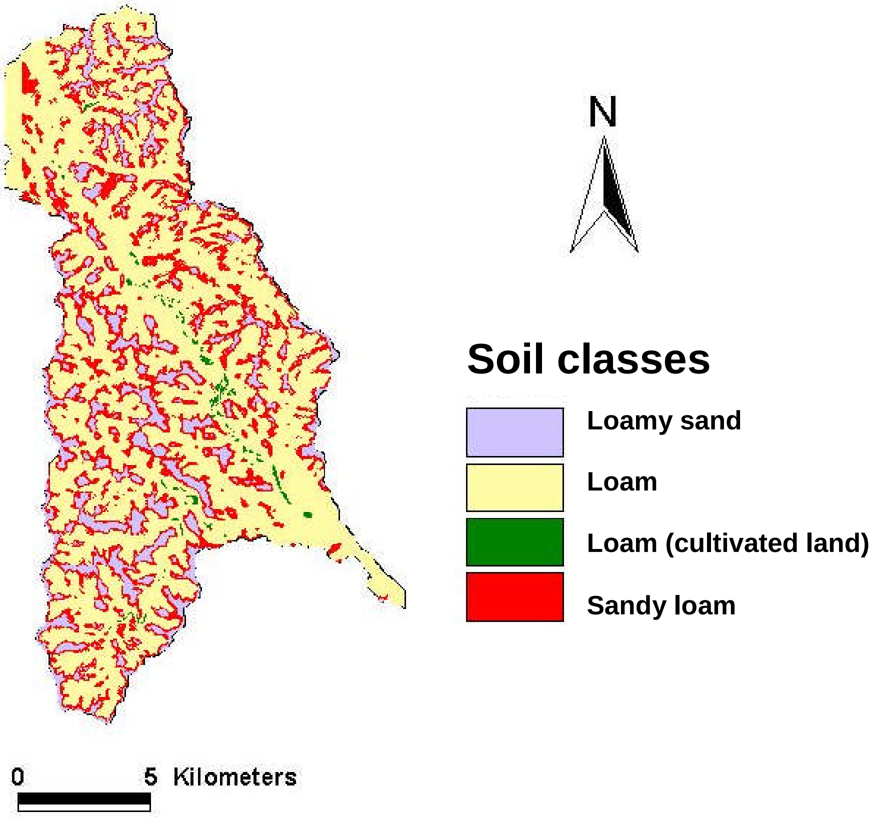


Figure 5.19 Derived soil classes for Wadi Ham catchment

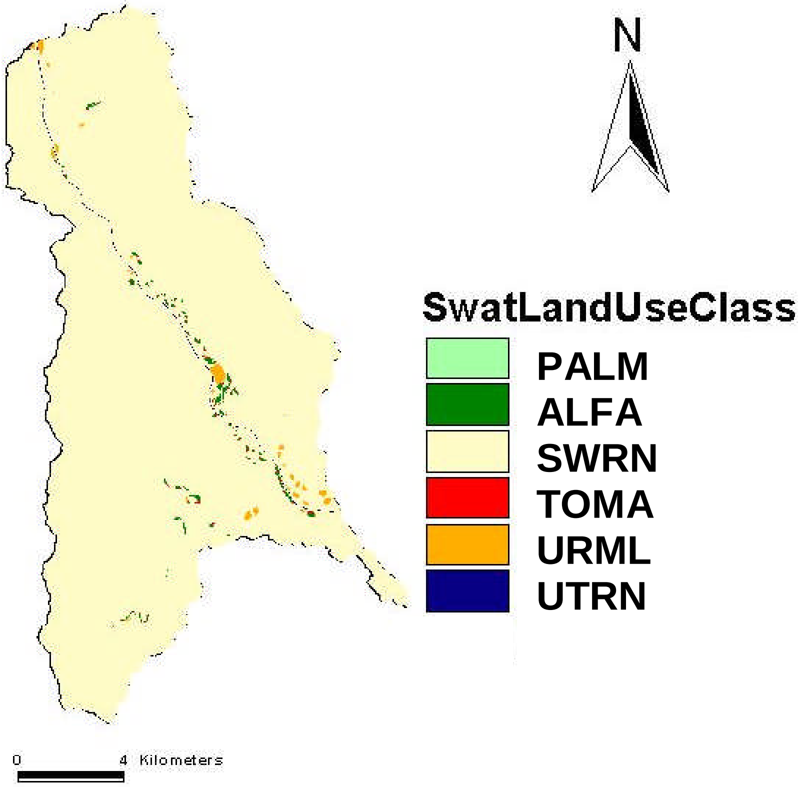


Figure 5.20 SWAT land use classes for Wadi Ham catchment.

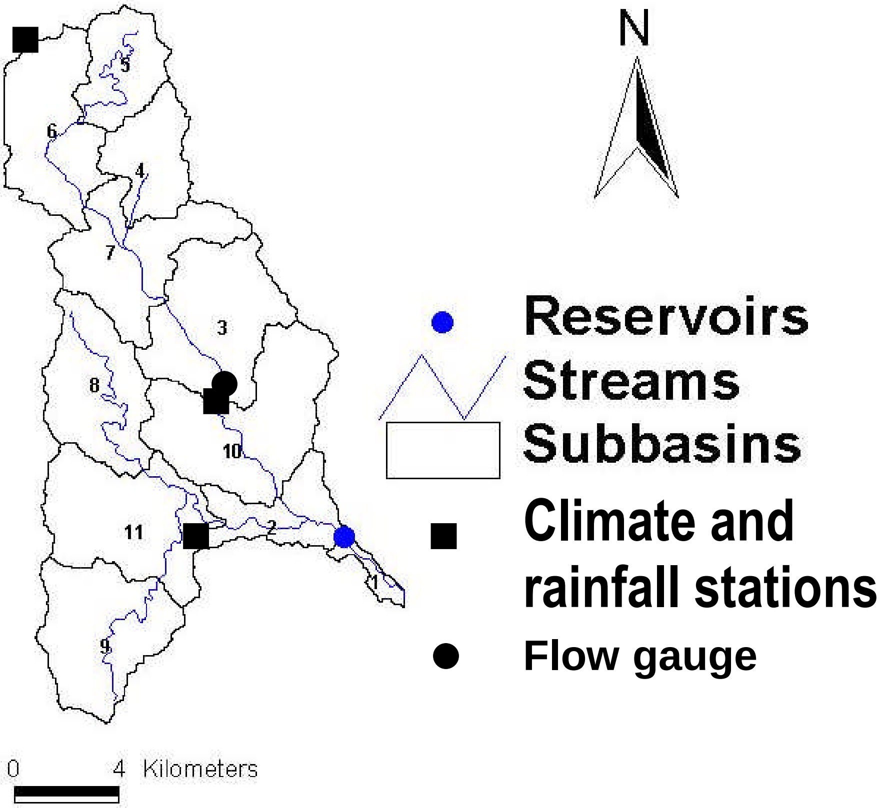


Figure 5.21 Streams, reservoir, sub-basins and climate and rainfall station set up for Wadi Ham catchment modelling.

6

Sensitivity analysis of the SWAT model

6.1 Introduction

Watershed models should pass through a careful calibration and validation procedure before they are used as a decision maker’s aid in the planning and management of water resources. To assist the calibration process, sensitivity analysis is generally applied to identify the parameters of the model that contribute most to the variability of its output e.g. streamflow and sediment yield, and thus, those that should be calibrated.

Sensitivity analysis of a hydrological model is the investigation of the relationship between model inputs and outputs, the results of which can be judged qualitatively (i.e. very sensitive, fairly sensitive or insensitive) or quantitatively as a percentage change in output given a percentage change in input (Heathcote, 1998). According to Bergstrom (1991), McCuem (1973) and Dubus et al. (2003), the results of, and understanding gained from, sensitivity analysis can be used in:

- model development and evaluation - to identify deficiencies in the theoretical structure of the model and problems in its operation;
- simplification- to identify parameters which show little effect on model output, and which can therefore be simplified and made into a constant;
- parameterisation - to identify the parameters which require the greatest accuracy in their determination and most attention when parameterising the model;
- Calibration- to select and prioritise parameters that need to be varied in the calibration procedure, and;
- Data collection - to highlight parameters for which additional research or field studies are needed.

A catchment will usually show a large variability and complexity with respect to soil, land cover, climate, topographic characteristics etc. To simulate such a system, spatially distributed hydrological models can suffer from a series of disadvantages owing to (1) high data demands, (2) exhaustion of computer power and data processing capability and finally (3) a lack of scientific understanding of the robustness in their simulation of hydrological processes under different catchment conditions (Abbott and Refsgaard, 1996). Thus, a number of sensitivity analysis studies of SWAT input parameters have been performed, leading to a better understanding of model behaviour and to better estimated values with an overall ranking into more and less sensitive parameters under different hydrological condition (Föhrer et al., 2005; Muleta and Nicklow, 2005; Francos et al., 2003; Kannan, 2003; and Lenhart et al., 2002). As a GIS-coupled hydrological model SWAT also shows sensitivity to its DEM input data and the aggregation of the spatial GIS data (Romanowicz, 2003 and Chaubey, 2005).

For this research, a sensitivity analysis is a fundamental initial component to the modelling to help understand the behaviour of the SWAT model in an environment (mountainous, arid climate) in which the model has not previously been used.

6.2 Approach to sensitivity analysis

According to Bergstrom (1991) “No matter what method (of sensitivity analysis) is being used it is important that the modeller bases the analysis (of sensitivity) on realistic assumptions of the uncertainties in the model conditions. Properly made, the sensitivity analysis is a very valuable tool for anyone who wants to build up confidence in a model structure” by identifying the stability of the results.

Many different sensitivity analysis techniques are available (Beven, 2001), such as one-at-a-time sensitivity measures (Dubus et al., 2003), the sensitivity index

(Bauer and Hamby, 1991) and standardised regression techniques (Iman and Helton, 1988).

The one-at-a-time (*ceteris paribus* approach) sensitivity analysis method (Hamby, 1994) has been chosen for the SWAT model sensitivity analysis in this research. In this method, the influence on the model prediction is observed by independently varying individual input parameters one at a time, while all other parameters remain constant. This method is simple and provides a direct assessment of sensitivity between model input and output. The main disadvantages of the approach are its computational intensity because of the large number of model runs, and its unsuitability for studying the effects of large variations in input parameter values on model prediction. However, in this study the variations in input parameter values will be restricted to ranges appropriate for arid region conditions and available input of dataset. Finally, the one-at-a-time method does not consider interactions that result from the simultaneous variation of multiple parameters (Dubus et. al., 2003). The choice of the one-at-a-time approach was based on its direct assessment of sensitivity between model input and output and to allow comparison of the results with other SWAT modellers' results who used similar approach to assess the sensitivity of SWAT input parameters (Chaubey et al., 2005 and Romanowicz et al., 2003).

Because the prime focus of this research is on the use of SWAT for simulating surface water flows, the sensitivity analysis was focussed on the simulated stream flow of the entire Wadi catchment as it flows into the Wadi Ham recharge dam and at the Bithna flow station. Based upon an examination of the earlier sensitivity analyses performed on SWAT in other climatic regions, this analysis investigated the sensitivity to the:

- DEM resolution,
- Sub-basin size created within the model set up, as determined by GIS functionalities of the model (number of sub-basins);
- Number of rainfall stations;
- Model input parameters.

The results of the sensitivity analysis will provide (1) a better understanding of the general model behaviour under Wadi Ham catchment condition, (2) help in the calibration of SWAT for Wadi Ham catchment, (3) identify sensitive parameters to aid future data collection activities in such arid data-poor catchments.

The sensitivity to the SWAT input parameters was based upon the relative variation in the model output to the relative variation in model input parameter:

Input variation = $\frac{I - IBC}{IBC} * 100$

Output variation = $\frac{O - OBC}{OBC} * 100$

Where I is value of the input parameter used in a given simulation, IBC is the value of the input parameter for the base-case simulation, O is the value of the output variable from the given simulation and OBC is the value of the output variable for the base-case simulation.

6.3 SWAT base-case configuration for sensitivity analysis

The Wadi Ham catchment base-case configuration used for the sensitivity analysis was derived using the spatial map themes and attributes described in Chapter 5. This base case represents the ‘best estimate’ of the catchment properties, prior to the calibration exercise. The weather data (rainfall and air temperature) for 1980 to 1982 for two stations were used.

A single HRU (Hydrological Response Unit) was created for the catchment by overlaying the dominant soil type of the catchment (loamy soil) and the dominant land use (natural vegetation of the arid range). Apart from the soil properties and land use datasets described in chapter 5, the other input data were given according to available literature about the study catchment, (MAF, 1993; UAEU, 1993 and Electrowatt Engineering Services Ltd, 1981), and similar areas (Luedeling, 2004; Al-Farsi and Cookson, 2002; Noman and Tahir, 2002 and Sorman et al., 1997) or the defaults values from the SWAT user manual.

The preliminary uncalibrated results from the base-case simulation show an acceptable hydrological behaviour for the catchment, based upon a reasonable visual relationship between the observed and simulated daily runoff (Figure 6.1). The daily potential ET values calculated by SWAT using the Hargreave's method are within the range of values reported in arid regions (Jones et al, 1981). The simulated actual ET values are generally significantly less than the potential ET values and show a characteristic peaky pattern linked to the availability of water in the catchment system following the sporadic rainfall events (Figure 6.2). The ratio between annual actual ET to annual potential ET is within limits (< 0.1) reported by Bremond et al, (2005) for some arid region vegetation.

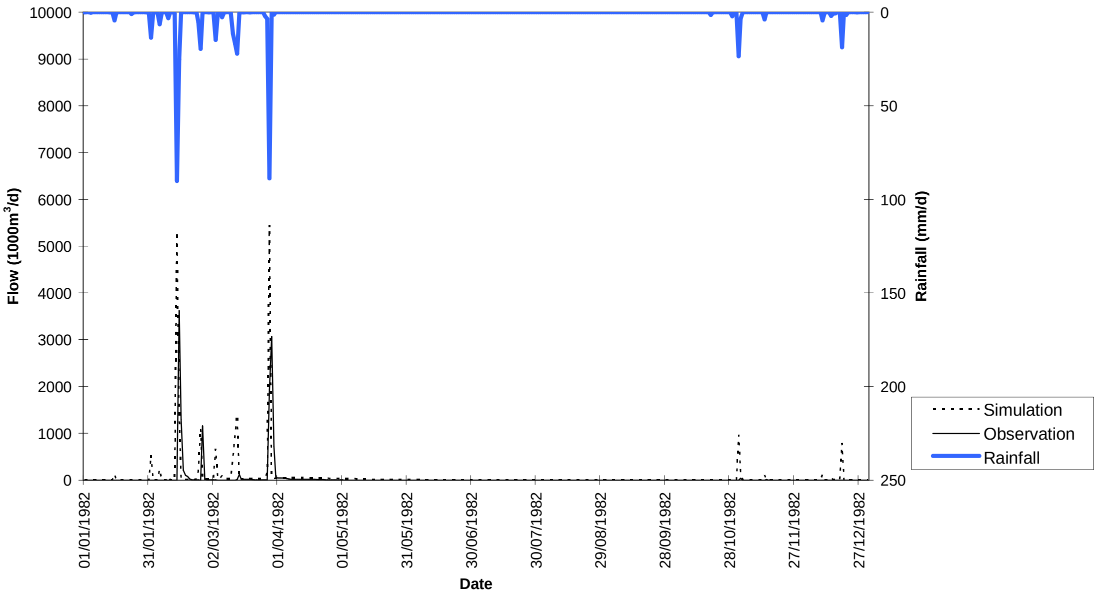


Figure 6.1 Observed and simulated streamflow at Bithna station for the base-case simulation for the wet year of 1982.

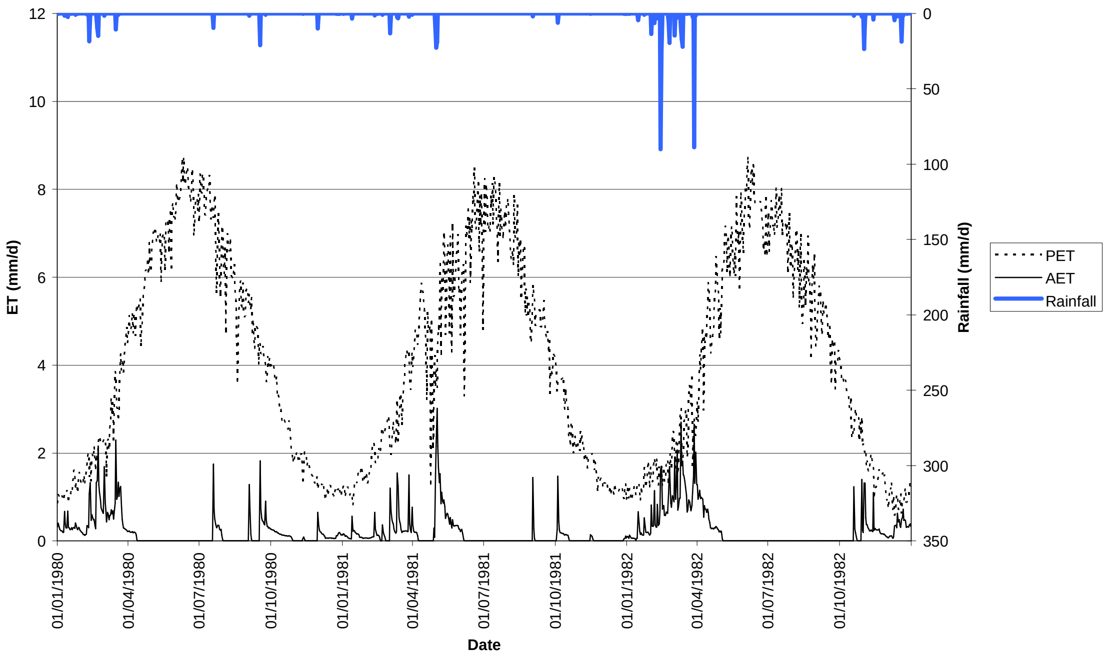


Figure 6.2 Simulated potential evapo-transpiration (PET) and actual evapo-transpiration (AET) for natural vegetation for the base-case simulation.

6.4 Sensitivity analysis of DEM resolution

Input DEM resolution has been shown to have a significant effect on distributed hydrological model outputs, mainly due to the inadequate representation of the landscape topography and the area of the catchment (Cochrane and Flanagan 2004; Armstrong and Martz, 2003; Cotter et al., 2003 and Wang et al., 2000).

The effect of the input DEM data resolution on the SWAT modelled flow for the Wadi catchment was therefore investigated by running the model with DEMs of eight different resolutions. The original DEM (which has a resolution of 50m x 50m) was resampled using the bilinear interpolation method (ERDAS, 2002) in the ERDAS IMAGINE software to create seven additional DEM resolutions (100 x 100 m, 150 x 150 m, 200 x 200 m, 250 x 250 m, 300 x 300 m, 400 x 400 m and 500 x 500 m). In this interpolation procedure, the new altitude value of a cell is based upon a weighted distance average of the four nearest input cell numbers.

Figure 6.3 shows the significant adverse effect on the catchment boundary, sub-catchments and stream network delineated by SWAT of going from the original 50mx50m resolution DEM to 300m x 300m and 500m x 500m resolution DEMs. The catchment area changes for each DEM resolution from 193.8 km' to 208.8 km^2 and 177.2 km^2 for the 50, 300 and 500 m resolution input DEM, respectively.

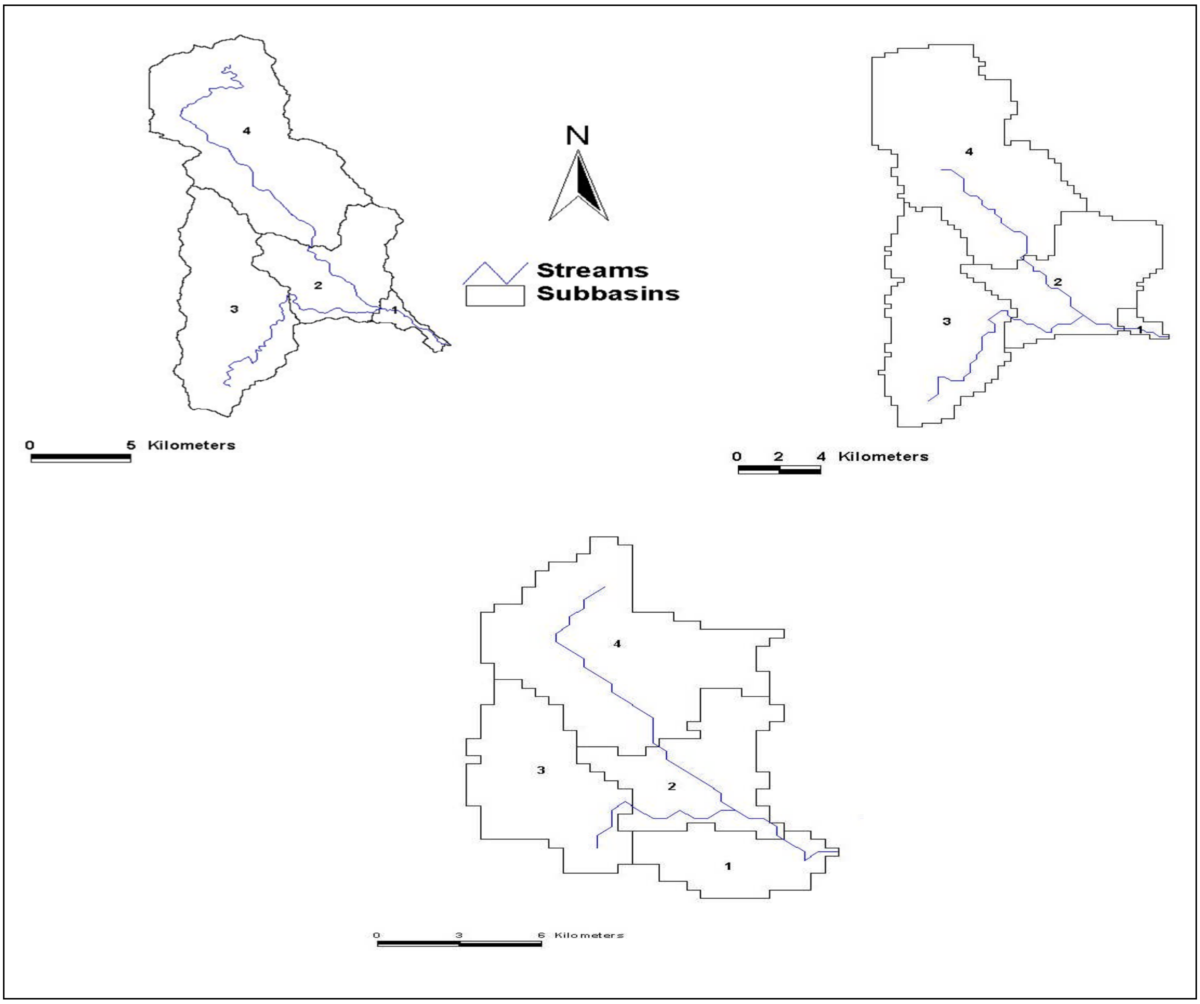


Figure 6.3 Examples of SWAT catchment delineation using (top left) 50mx50m, (top right) 300m x 300m and (bottom) 500m x 500m DEM resolution.

Figure 6.4 shows the resulting effect of the DEM resolution on the average simulated flow for the catchment, which decreases from 0.50 m^3/s for the 50m x 50m DEM to 0.18 m^3/s for 500m x 500m DEM resolution. The maximum simulated flow (Figure 6.5) also significantly decreases from 103.60 m^3/s for the 50m x 50m DEM to 15.79 m^3/s for the 500m x 500m DEM resolution. The number of days in which there is simulated stream flow at the catchment outlet during 1980-82 displays a similar trend and decreases from 312 days for the 50m x 50m DEM to 304 days of surface flow for the 500m x 500m DEM, although the number of flow days increased for the intermediate DEM resolutions (Figure 6.6).

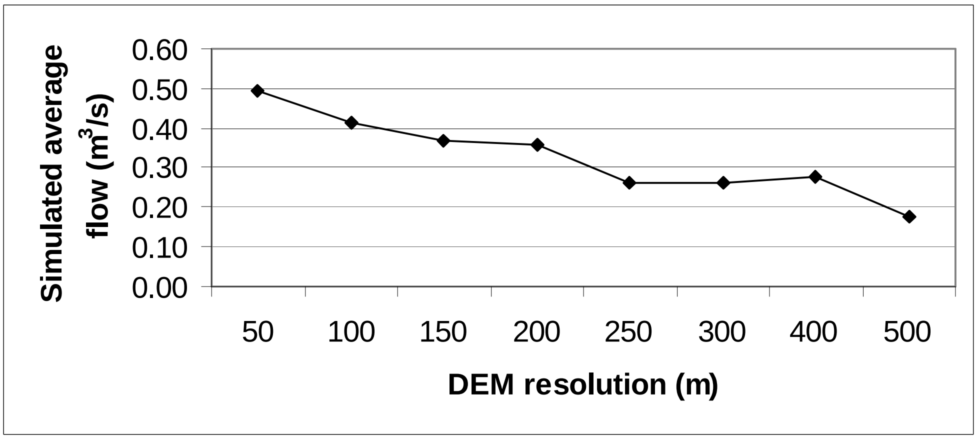


Figure 6.4 Simulated average daily flow (m^3/s) at the catchment outlet for the period 1980 to 1982 for varying DEM resolutions (m).

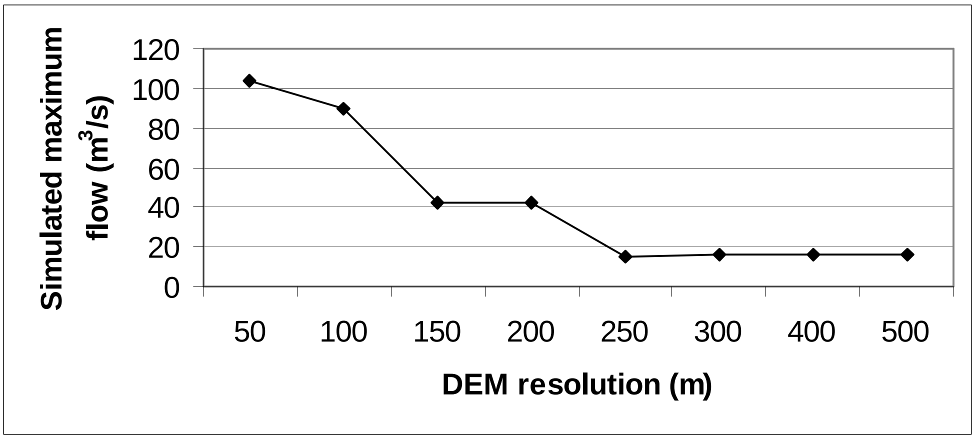


Figure 6.5 Simulated maximum daily flow (m^3/s) at the catchment outlet during the period 1980 to 1982 for varying DEM resolutions (m).

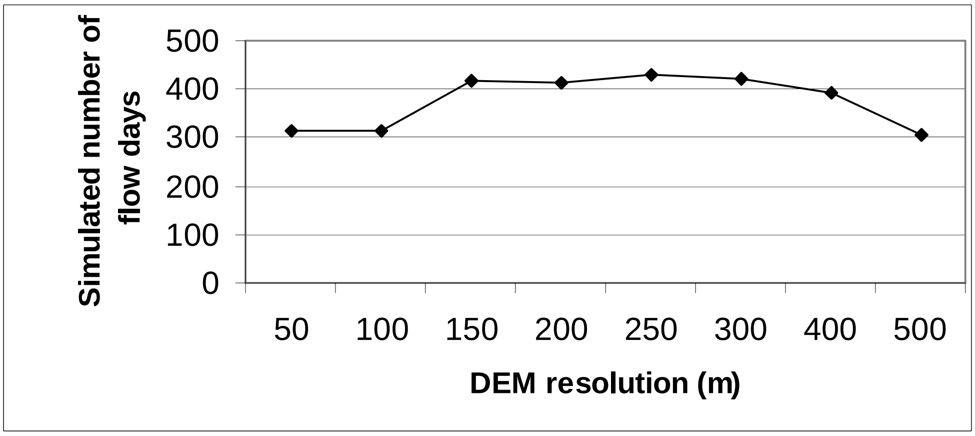


Figure 6.6 Catchment simulated number of flow days at the catchment outlet for the period 1980 to 1982 for varying DEM resolutions (m).

In order to identify the most appropriate DEM resolution to be used in the subsequent simulation of Wadi Ham, the simulated streamflow properties from sub-basin four were compared with the measured data at its outlet at the Bithna flow station which has a catchment area of about 90 km^2 (Table 6.1).

Table 6.1 Simulated average, maximum and days of flow (for1982) for sub-basin four compared with the associated measured flow at the Bithna flow station.

	average flow m^3/s	**maximum flow m^3/s**	**Flow days**
50 x 50 m	0.52	46.03	123
100 x 100 m	0.46	49.96	102
150 x 150 m	0.39	8.01	180
200 x 200 m	0.39	8.47	177
250 x 250 m	0.33	6.73	165
300 x 300 m	0.31	6.47	150
400 x 400 m	0.38	6.88	148
500 x 500 m	0.55	16.36	174
Bithna flow St.	0.41	41.93	73

From the previous results, it is obvious that the simulated flow of Wadi Ham catchment varies significantly with the change in DEM resolution. The general trend in the SWAT streamflow prediction that is associated with input DEM resolution shows a decrease in streamflow volume and maximum flow prediction, although there is no clear trend with flow days. A similar observation is reported by Chaubey et al. (2005) who used the same DEM resampling technique to study the effect of DEM resolution on SWAT output uncertainty for the 1890 ha agricultural watershed of Moores Creek in Northwest Arkansas (USA). Chaubey et al. (2005) found that reduced DEM resolution resulted in a smaller stream slope and longer slope lengths within the watershed and a smaller watershed area which affected the stream flow volume. On the basis of their analysis, Chaubey et. al. (2005) concluded that the minimum DEM data resolution should range from 100 to 200 m to achieve less than 10% error in the SWAT output for streamflow

From Table 6.1, it can be seen that the simulated average flow, maximum flow and number of flow days in the base-case simulation for sub-basin 4 depart from those measured at Bithna when the DEM resolution is greater than 100m x 100m. Figs. 6.5 and 6.6 show the significant discontinuities in the flow outputs for the catchment between a DEM resolution of 100m and 150m. The reason for such results may be due to the representation of the mountainous topography of the Wadi catchment within SWAT model, which is affected by the input DEM data. The coarser resolutions reduce the heterogeneity of the topography by smoothing, that affects the stream channel topographic properties and the total catchment area. Based upon the above analysis, it can be recommended that an input DEM of no poorer resolution than 100m x 100m should be used for the simulation of Wadi catchments using the SWAT model.

6.5 Sensitivity analysis of sub-basin size

AVSWAT applies ArcView® GIS functionalities to the input DEM to create the stream network, the catchment boundary and the sub-basin boundaries (Di Luzio et. al, 2001). It has been found by Romanowicz et. al. (2003) that the sub-basin size is a critical parameter in the AVSWAT model simulation, as it is the basis for the definition of the HRUs where the aggregation processes of all input data takes place. Therefore, it impacts on modelling performance of the model. Romanowicz et. al. (2003) showed that the Nash-Sutcliffe index for the prediction of streamflow varied significantly with the number of sub-basins delineated within the Thyle catchment in central Belgium.

In order to determine the acceptable size of sub-basins within the Wadi Ham catchment, the effect of the sub-basin size on the SWAT stream flow output for Wadi catchment modelling was investigated by manually subdividing the catchment into three different numbers (3, 10 and 20) of sub-basins (Figure 6.7) during the set-up of the catchment in SWAT. In addition, the model was also run as a single basin with no sub-basins. The results show that the simulated average flow and maximum flow for the catchment decrease with the increase in the number of sub-basins (Figure 6.8 and Figure 6.9), while the number of flow days increases (Figure 6.10).

To identify the appropriate number of sub-basins for the Wadi catchment, the simulated flow of the base-case with different numbers of sub-basins was compared with the stream flow measured at Bithna flow station (Figures 6.11, 6.12 and 6.13). The Bithna flow gauge is situated part-way down the Wadi Ham catchment, so that the numbers of sub-basins in Figures. 6.11-6.13 and Table 6.2 refer to the sub-basins upstream of Bithna in the model set-ups shown in Figure 6.7. From Table 6.2 it can be identified that simulated stream flow using five sub-basins is the closest match for the stream flow properties measured at Bithna flow station.

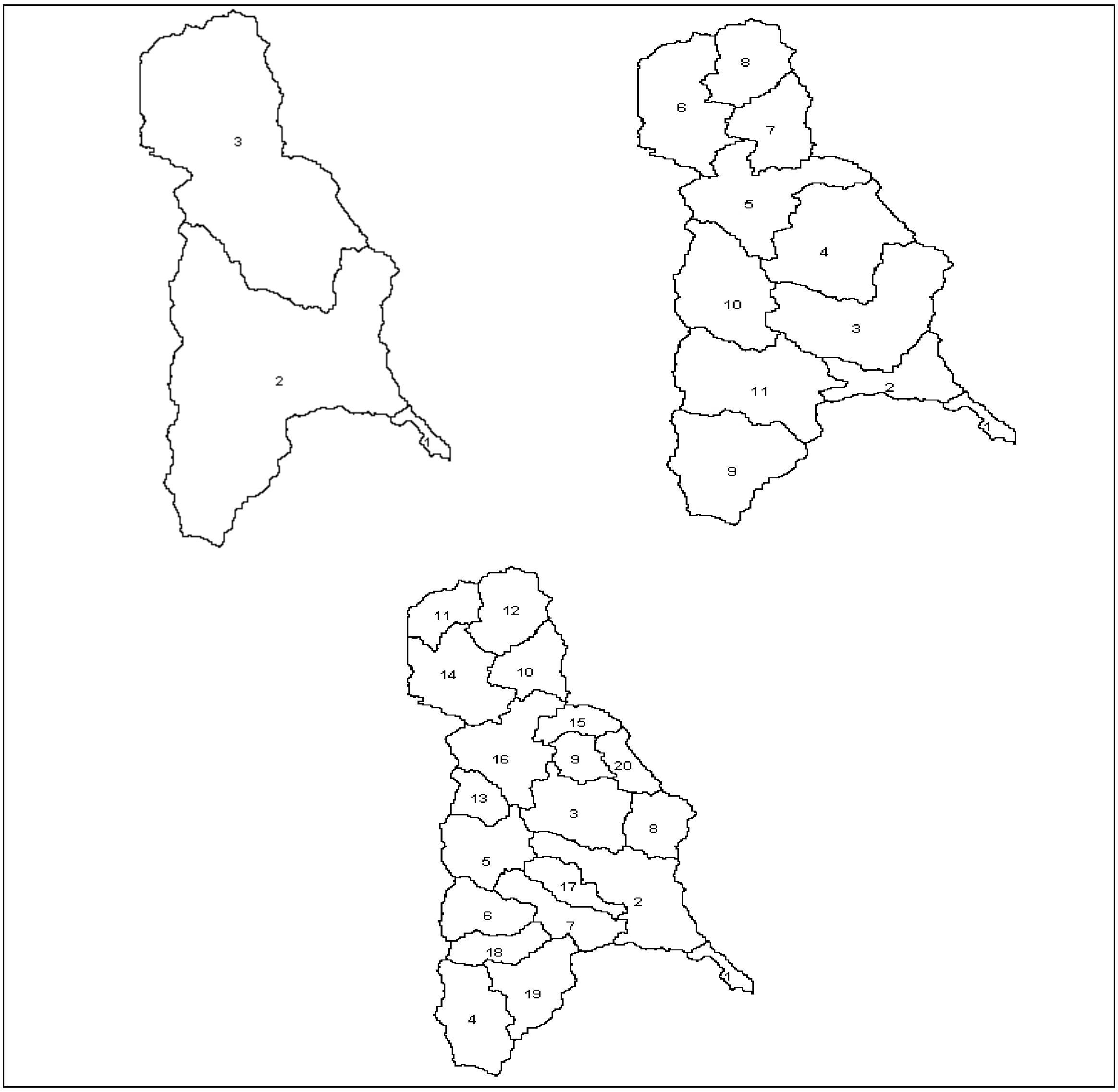


Figure 6.7 Three SWAT set-ups with different numbers of sub-basins for the Wadi catchment in AVSWAT.

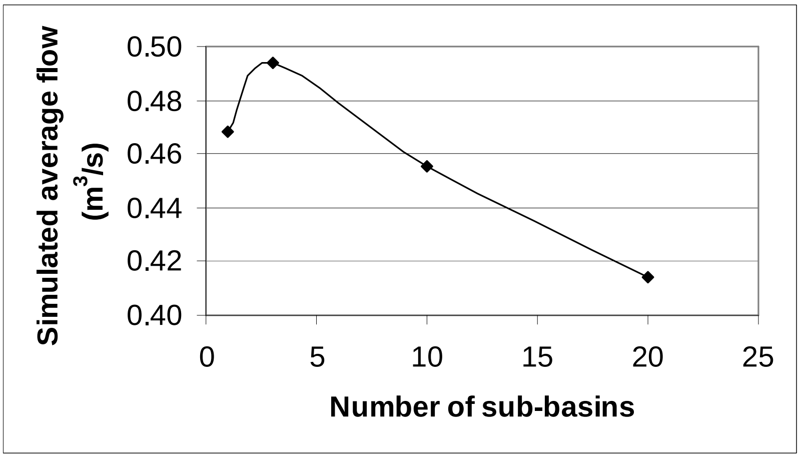


Figure 6. 8 Simulated average streamflow (m^3/s) at the catchment outlet for the period 1980 to 1982 with varying number of sub-basins.

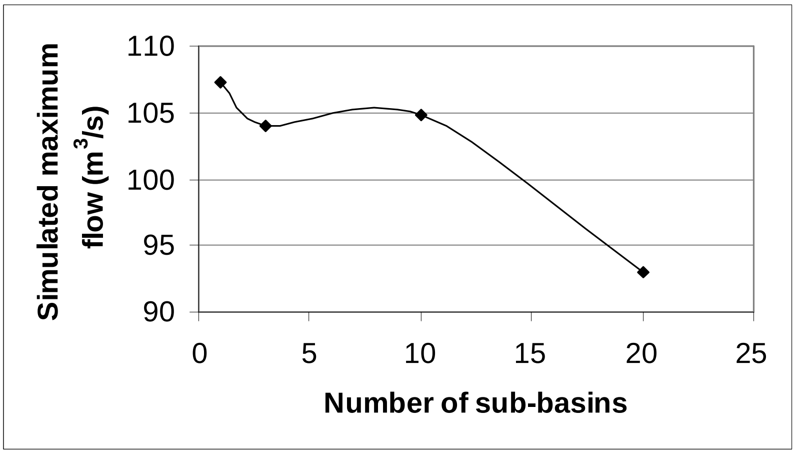


Figure 6.9 Simulated maximum flow (m^3/s) at the catchment outlet for the period 1980 to 1982 with varying number of sub-basins.

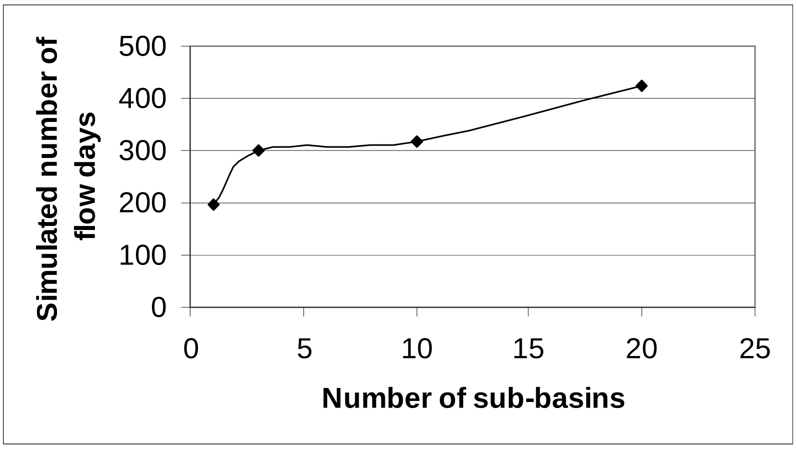


Figure 6.10 Simulated flow days at the catchment outlet for the period 1980 to 1982 with varying number of sub-basin.

Table 6.2 Simulated average, maximum and days of stream flow (1982) for different number of sub-basins compared with the associated measured stream flow at Bithna flow station.

Number of sub-basin set up / **Simulated flow**	**1**	**5**	**9**	**Bithna flow station**
Simulated average flow (m^3/s)	0.51	0.44	0.44	0.41
Simulated maximum flow (m^3/s)	45.32	43.08	42.82	41.93
Simulated flow days	108	142	199	73

The above table suggests that the 90 km^2 of the Bithna flow gauge catchment can be represented by about five sub-basins in AVSWAT for proper model prediction which is about 18 km^2 for each sub-basin within the catchment. This indicates that the entire Wadi Ham catchment can be represented by about ten sub-basins.

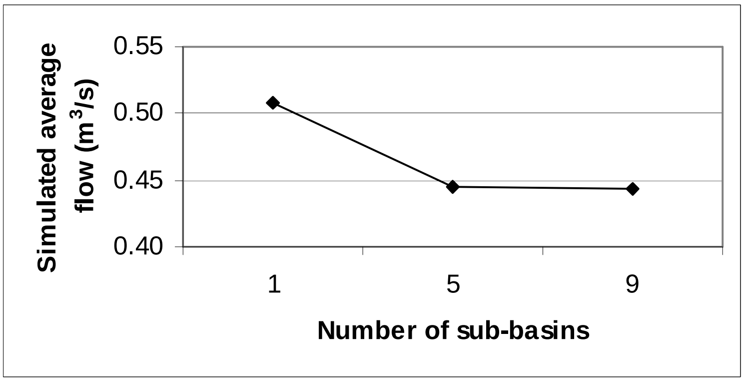


Figure 6.11 Simulated average flow (m^3/s) at the upper Bithna flow station in 1982 for varying numbers of sub-basins.

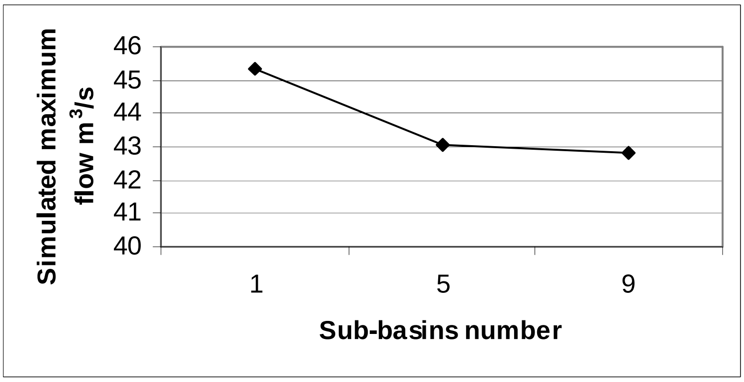


Figure 6.12 Simulated maximum flow (m^3/s) at the upper Bithna flow station in 1982 for varying numbers of sub-basins.

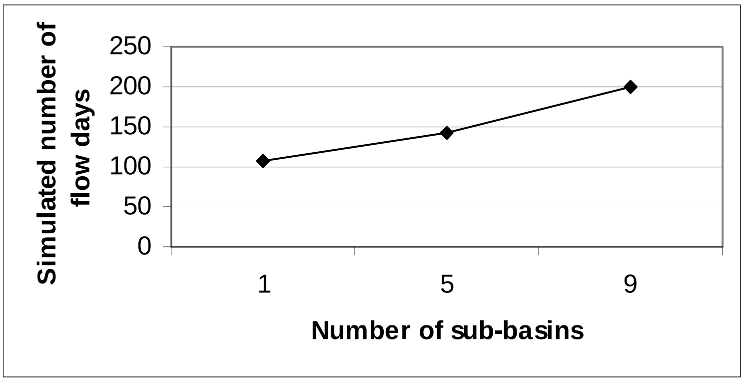


Figure 6.13 Simulated flow days at the upper Bithna flow station in 1982 for varying numbers of sub-basins.

6.6 Sensitivity analysis for rainfall

The realistic representation of rainfall over the catchment is obviously very important for correct model predictions. Because of the spatial/temporal variability in rainfall distribution in arid catchments (as discussed in Chapter 2), the effect of using rainfall data from different numbers of rainfall stations scattered within the Wadi catchment on SWAT stream flow was investigated, by using rainfall data from one, two and finally three rainfall stations.

The results show that average simulated stream flow from 1980 to 1982 for the catchment varied between 0.63 m^3/s for rainfall data from one station to 0.59 m^3/s for rainfall data from three stations (Figure 6.14). The maximum simulated flow for the same period increased from 120.50 m^3/s for one rainfall station to 134.70 m^3/s for rainfall data obtained from three rainfall stations (Figure 6.15). The catchment simulated number of stream flow days varied between 497, 488 and 499 days for rainfall data obtained from one, two and three rainfall stations respectively (Fig 6.16).

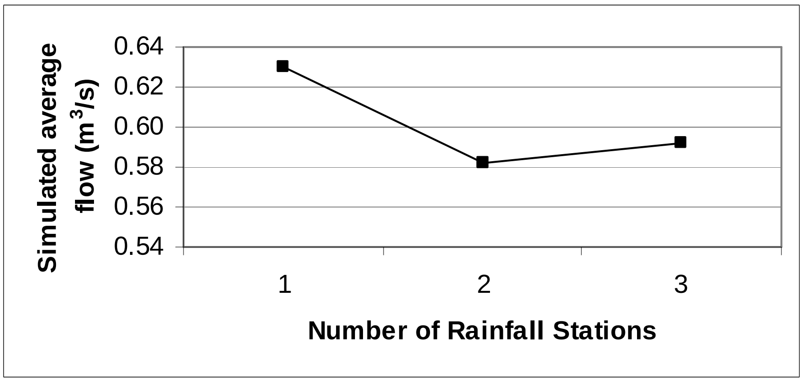


Figure 6.14 Simulated average flow (m^3/s) at the catchment outlet for the period 1980 to 1982 for varying numbers of rainfall stations.

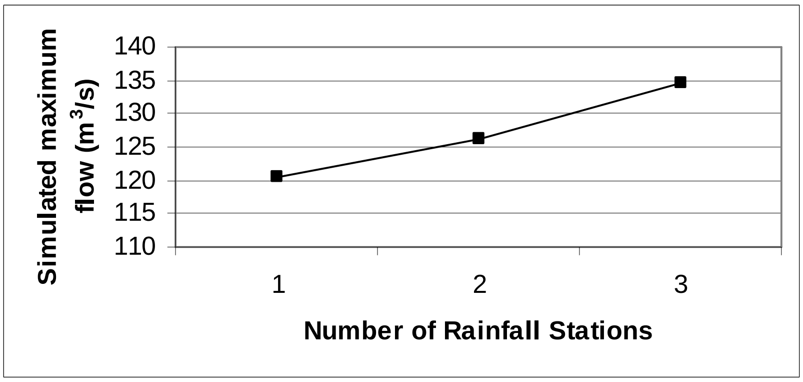


Figure 6.15 Simulated maximum flow (m^3/s) at the catchment outlet for the period 1980 to 1982 for varying numbers of rainfall stations.

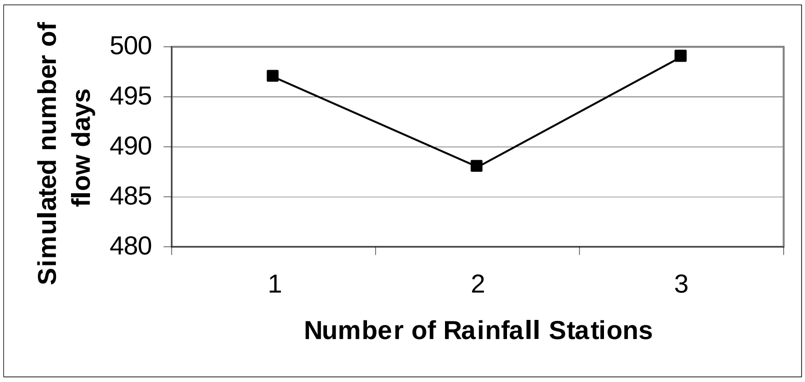


Figure 6.16 Simulated flow days at the catchment outlet for the period 1980 to 1982 for varying numbers of rainfall stations.

From the above results, it can be observed that SWAT is showing sensitivity to the number of rainfall stations used within the catchment. Therefore it is important to represent the rainfall with the highest number of available rainfall stations for an arid catchment.

6.7 Sensitivity analysis for SWAT model input parameters

As mentioned in section 6.2 the sensitivity analysis results for SWAT input parameters is graphically plotted based on the relative variation in the model output to the relative variation in model input parameter. The results obtained from the sensitivity analysis give a clear understanding of the relationship between SWAT input parameters and different outputs of hydrological processes under arid catchment conditions. The investigated parameters are listed in Table 6.3 with the range of values used in the sensitivity analysis. These parameters were chosen on the basis of sensitive parameters reported in the SWAT user manual, sensitivity analysis conducted for SWAT by some researchers (Kannan, 2004) and parameters associated with runoff and evaporation simulation in SWAT.

Table 6.3 Model parameters involved in the sensitivity analysis with their minimum and maximum values.

Name	Description	Min.	Max.
SOL_Z	Depth from soil surface to bottom of layer (mm)	100	1000
SOL_BD	Moist bulk density (Mg/m^3 or g/cm^3)	1.40	1.85
SOL_AWC	Available water capacity of the soil layer (mm H2O/mmsoil)	0.03	0.2
SOL_K	Saturated hydraulic conductivity (mm/hr)	5	65
CLAY	Clay content (% soil weight)	7	27
SILT	Silt content (% soil weight)	28	48
SAND	Sand content (% soil weight)	40	52
ROCK	Rock fragment content (% total weight)	5	90
SOL_ALB	Moist soil albedo	0.05	0.25
SOL_CBN	Organic carbon content (% soil weight)	0.05	0.25
USLE_K	USLE equation soil erodibility (K) factor (metric ton m2 hr)/(m3-metric ton cm).	0.10	0.65
ANION_EXCL	Fraction of porosity (void space) from which anions are excluded.	0.010	1
HYDGRP	Soil hydrologic group[Curve Number]	77	94
SOL_ZMX	Maximum rooting depth of soil profile (mm)	30	2000
CH_K1 (mm/hr)	Effective hydraulic conductivity in tributary channel alluvium.	0.05	150
CH_N1	Manning’s “n” value for the tributary channels.	0.010	0.056
OV_N	Manning's "n" value for overland flow.	0.040	0.170
ESCO	Soil evaporation compensation factor.	0.05	1
EPCO	Plant uptake compensation factor.	0.05	1
CH_K 2	Effective hydraulic conductivity in main channel alluvium (mm/hr).	50	150
CH_N 2	Manning's "n" value for the main channel.	0.010	0.065
CH_COV	Channel cover factor.	0.05	1
CH_EROD	Channel erodibility factor.	0.1	0.6
ALPHA_BNK	Base flow alpha factor for bank storage	0	1
SHALLST	Initial depth of water in the shallow aquifer (mm).	10	1000
DEEPST	Initial depth of water in the deep aquifer (mm)	10	3000
GW_DELAY	Groundwater delay time (days)	0	100
ALPHA_BF	Baseflow recession constant	0	1
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	10	3000
GW_REVAP	Groundwater "revap" coefficient.	0.020	0.2
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm)	0.05	375
RCHRG_DP	Deep aquifer percolation fraction.	0.05	1
GWHT	Initial groundwater height (m)	0.05	25
GW_SPYLD	Specific yield of the shallow aquifer (m^3/m^3)	0.05	0.4
EVRCH	Reach evaporation adjustment factor	0.5	1

The relationship between model input parameters and the simulated total stream flow, maximum flow, and number of stream flow days of the catchment can be obtained from Figures 6.17-21. Table 6.4 provides a provisional sensitivity ranking of the SWAT input parameters under arid conditions as suggested by the results for Wadi Ham catchment. The parameters that showed variation in output simulation of less than 10% were considered as lower influence parameters on the output simulation.

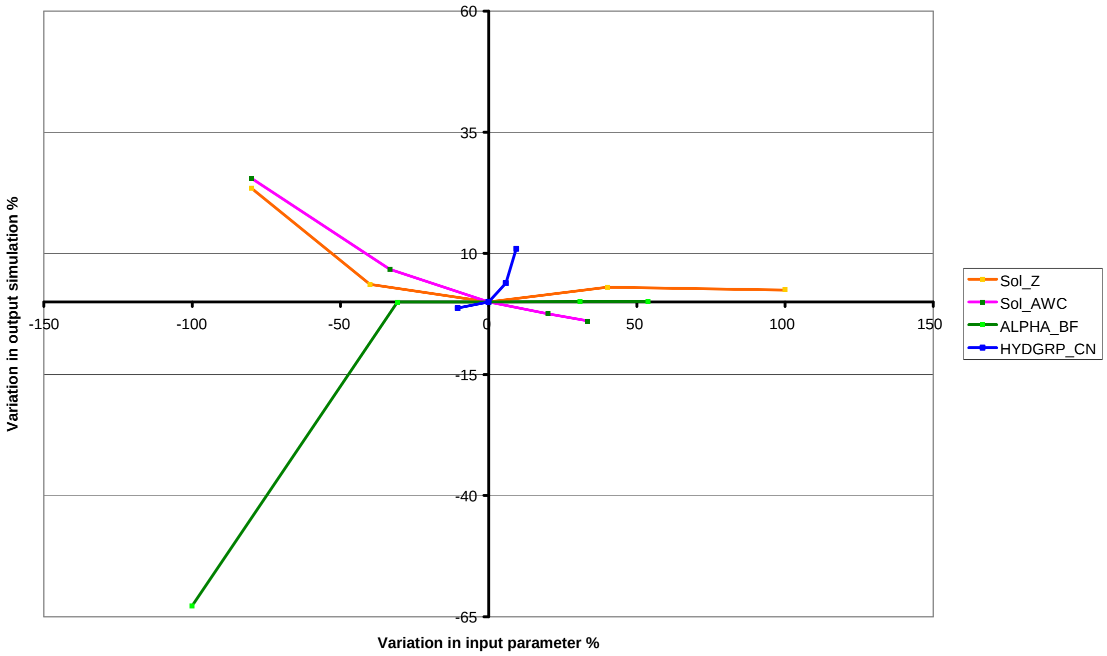


Figure 6.17 Variation in simulated mean stream flow (m^3/s) in response to the variation of input parameters (High influence parameters).

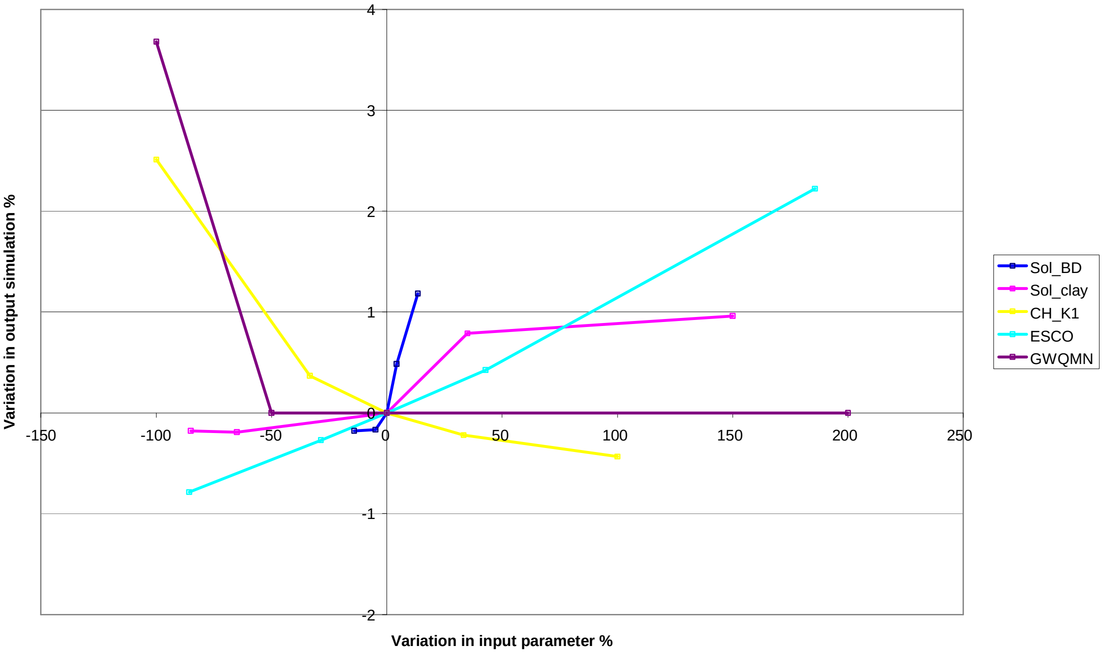


Figure 6.18 Variation in simulated mean stream flow (m^3/s) in response to the variation of input parameters (lower influence parameters).

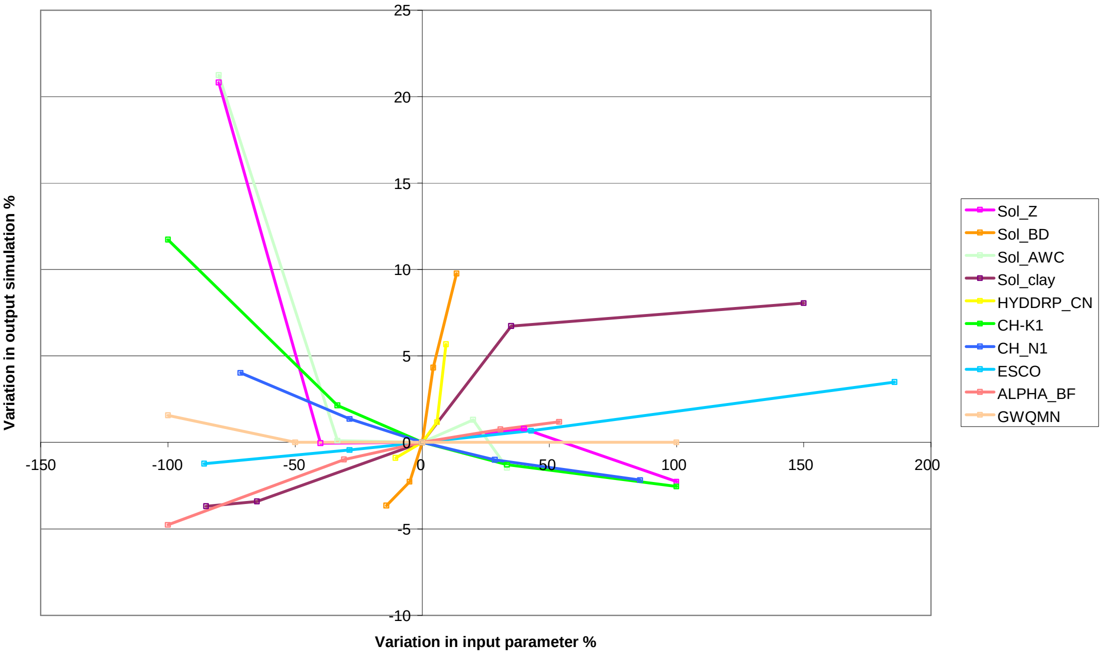


Figure 6.19 Variation in simulated maximum stream flow (m^3/s) in response to the variation of input parameters.

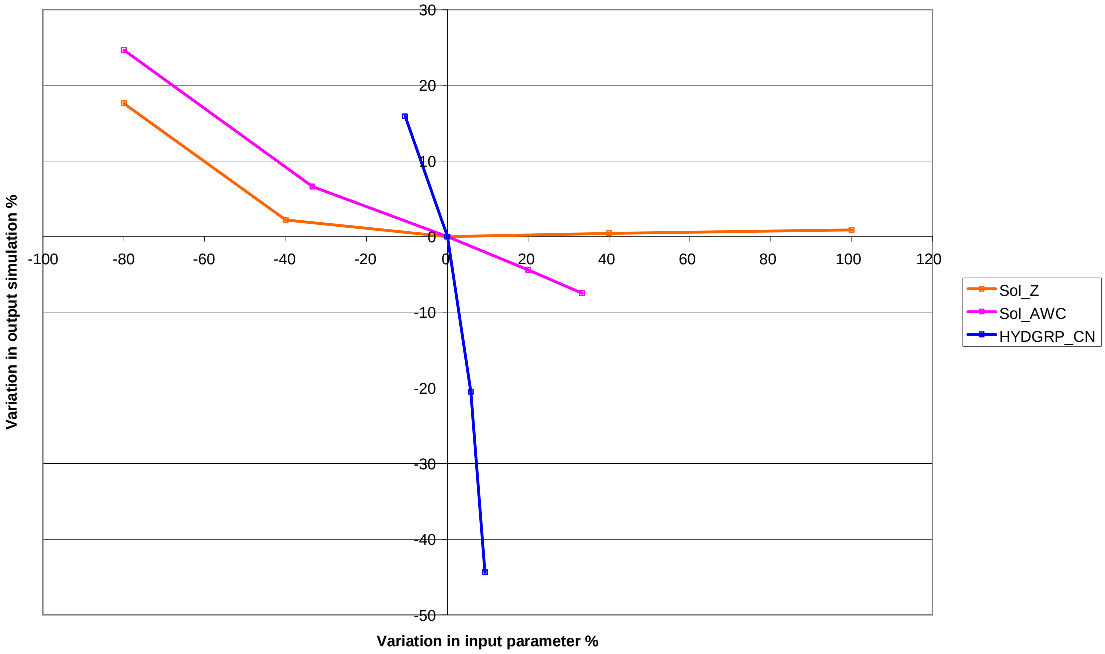


Figure 6.20 Variation in the simulated number of stream flow days in response to the variation of input parameters (High influence parameters).

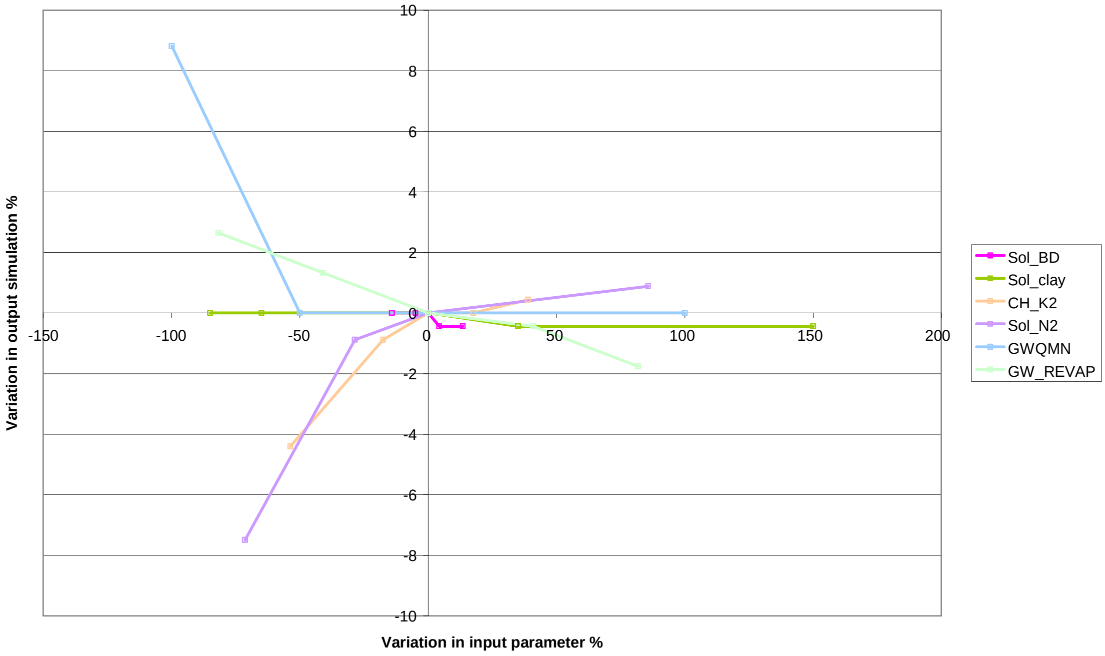


Figure 6.21 Variation in the simulated number of stream flow days in response to the variation of input parameters (lower influence parameters).

Table 6.4 Ranking of SWAT parameters according to the sensitivity of simulated stream flow of Wadi catchment.

Simulation	**High sensitivity**	**Low sensitivity**	**insignificant sensitivity**
Stream flow	Sol_z Sol_AWC ALPHA_BF HYDGRP_CN	Sol_BD Sol_clay CH_K ESCO GWQMN	ROCK SOL_ALB SOL_CBN SOL_CBN USLE_K ANION_EXCL SOL_ZMX OV_N EPCO CH_N 2 CH_COV CH_EROD ALPHA_BNK SHALLST DEEPST GW_DELAY GW_REVAP REVAPMN RCHRG_DP GWHT GW_SPYLD EVRCH
Maximum flow	Sol_z Sol_AWC Sol_clay HYDGRP_CN Sol_BD CH_K	CH_N ESCO ALPHA_BF GWQMN	
Flow days	Sol_z Sol_AWC HYDGRP_CN	Sol_BD Sol_clay CH_K CH_N GWQMN GWREVAP	

The SWAT user's manual (Neitsch et. al., 2001) lists the following parameters as the most sensitive SWAT parameters for streamflow simulation:

- available water capacity (AWC),
- soil evaporation compensation factor (ESCO),
- groundwater re-evaporation coefficient (GWREVAP),
- minimum depth of water in soil for base flow to occur (GWQMN),
- minimum depth of water in shallow aquifer for re-evaporation to occur (REVAPMN),
- saturated hydraulic conductivity (K_{SAT}), and;
- Curve number (CN).

Of the highly sensitivity parameters given in the SWAT user's manual, only the available water capacity (AWC) and curve number (CN) showed high sensitivity for all of the simulated stream flow characteristics investigated in this study.

However, a number of additional input parameters which are not identified as being of high sensitivity in Neitsch et. al. (2001) have been identified. The catchment soil depth and texture showed high sensitivity level. The variation in soil depth (Sol-z) and soil texture combination represented as percentage of clay appear to have a sensitive role in stream flow simulated processes since the clay percent content is used by SWAT in the calculation of water percolation from the soil layer when water content exceeds the field capacity. Under the ephemeral streamflow of the arid catchment conditions of the base-case scenario, the channel property of effective hydraulic conductivity (CH_K) affects the stream flow due to its important role in the calculation of transmission losses from surface runoff. In addition, the channel Manning's "n" number affects the stream flow characteristics because of its role in the calculation of peak runoff rate by SWAT.

Kannan (2003) found that the groundwater re-evaporation coefficient (GWREVAP) and minimum depth of water in shallow aquifer for re-evaporation to occur (REVAPMN) were not sensitive in a sensitivity analysis for a very small catchment in southern UK. This result is repeated in this study, although GWREVAP showed some degree of sensitivity to the simulated number of flow days for the catchment. The variation in saturated hydraulic conductivity (K_{SAT}) values of soil layer showed no sensitivity, consistent with Kannan (2003). The soil evaporation compensation factor (ESCO) and minimum depth of water in soil for base flow to occur (GWQMN) also showed low sensitivity under the base-case condition in this study. The baseflow recession constant (ALPHA_BF) appears to reduce the simulated mean and maximum flow mainly when its value is very low. This is because of its effect in the calculation of groundwater flow into the main channel.

6.8 Summary

The preliminary uncalibrated results from the base-case simulation (which uses the 'best estimates' of the catchment properties) show an acceptable hydrological behaviour for the catchment, based upon a reasonable visual relationship between the observed and simulated daily runoff, indicating that the SWAT model is capable of simulating streamflow of the arid Wadi Ham catchment. The analysis has demonstrated, for the first time, the sensitivity of SWAT streamflow outputs to the model inputs in a mountainous arid catchment. In particular the analysis has shown that a finer DEM resolution than previously reported for SWAT, of no more than 100 m x 100m, should be used. Also a different range of input parameters show sensitivity than those reported in the SWAT user's manual. The number of parameters that affect the ephemeral streamflow is limited and mainly relates to soil and channel properties. The acceptable representation of these in the SWAT parameterisation shall aid in the subsequent SWAT simulation set up, calibration and validation of the data poor Wadi Ham catchment.

7

Wadi Ham catchment modelling

This chapter describes the various modelling procedures implemented to achieve acceptable hydrological representation and modelling results for Wadi Ham catchment by the SWAT model. These include the calibration and validation of stream runoff and an assessment of the plausibility of the other hydrological processes simulated by SWAT.

7.1 Surface runoff simulation, calibration and validation

The objective of the model calibration in this research work was as described by Madsen (2000) - “Selection of model parameters so that the model simulates the hydrological behaviour of the catchment as closely as possible”. The simulation of surface runoff in Wadi Ham catchment was carried out from 1980 to 1988 due to data availability. The year 1980 was treated as a warm up period for the model in order for the model to realistically set-up the states of its internal hydrological compartments e.g. groundwater store, soil moisture content etc. The data from 1/1/1981 to 31/12/1982 were used as a calibration period and the remaining data from 1/1/1983 to 31/12/1988 were used for validation (Figure 7.1).

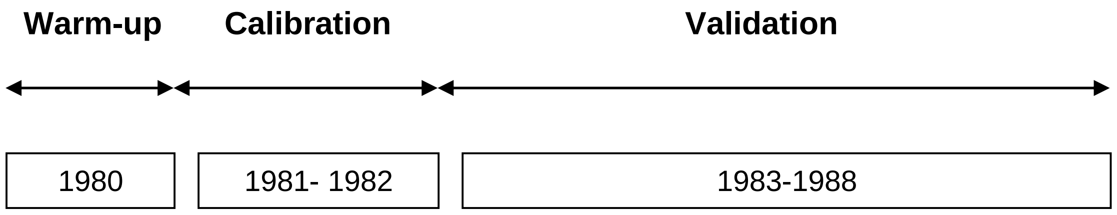


Figure 7.1 Calibration and validation calendar for SWAT modelling.

The unequal split of the years between the calibration and validation periods was to ensure the representation of both wet and dry years in both the calibration and validation procedures. In the calibration period, 1981 is a relatively dry year with total annual rainfall of 93 mm at Masafi station and 1982 is a wet year with total rainfall of 401 mm at Masafi station.

The model performance was evaluated qualitatively using visual inspection to assess the agreement between the observed and simulated hydrographs, and quantitatively by implementing a variety of different statistical measures. Gupta et al, (1999) described these statistics and illustrated their role in the model performance evaluation. The statistical measures selected were the:

- Daily Root Mean Square (DRMS) estimation criterion which computes the standard deviation of the model prediction error;
- Percent Bias (PBIAS) which measures the average tendency of the simulated flows to be larger or smaller than the observed flows
- Nash and Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) which measures the relative magnitude of the residual to the variance of the flows, and;
- Persistence Model Efficiency (PME) which measures the relative magnitude of the residual variance to the variance of the errors obtained by the use of a simple persistence model.

The previous model performance statistics can be written as follows:

$$DRMS = \sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(q_t^{sim} - q_t^{obs}\right)}^{2} \tag{7.1}$$

$$PBIAS = \sum_{t=1}^{N}\left(q_t^{obs} - q_t^{sim}\right) / \sum_{t}^{N} q_t^{obs} \times 100\% \tag{7.2}$$

$$NSE = 1 - \sum_{t=1}^{N}\left(q_t^{sim} - q_t^{obs}\right)^2 \Big/ \sum\left(q_t^{obs} - q_m{}^{obs}\right)^2 \tag{7.3}$$

$$PME = 1 - \sum_{t=1}^{N}\left(q_t^{sim} - q_t^{obs}\right)^2 \Big/ \sum_{t=1}^{N}\left(q_t^{obs} - q_{t-1}{}^{obs}\right)^2 \tag{7.4}$$

Where q_t^{sim} is the daily simulated flow, q_t^{obs} is the daily observed flow, q_m^{obs} is the mean of the observed flows and N is the number of days.

These performance statistics were chosen because of their ability to evaluate different features of the calibrated model in terms of its (1) agreement between the average simulated and observed catchment runoff volume (equation 7.1), (2) overall agreement of the shape of the hydrograph (equation 7.3), (3) and finally, agreement of the peaks with respect to timing, duration and volume (equation 7.2 and 7.4).

The calibration procedure for the Wadi Ham modelling involved manual adjustment, through the trial-and-error approach, for the key SWAT model parameters that had been identified in the sensitivity analysis procedure (Chapter 6) until acceptable simulation is achieved (Figure 7.2).

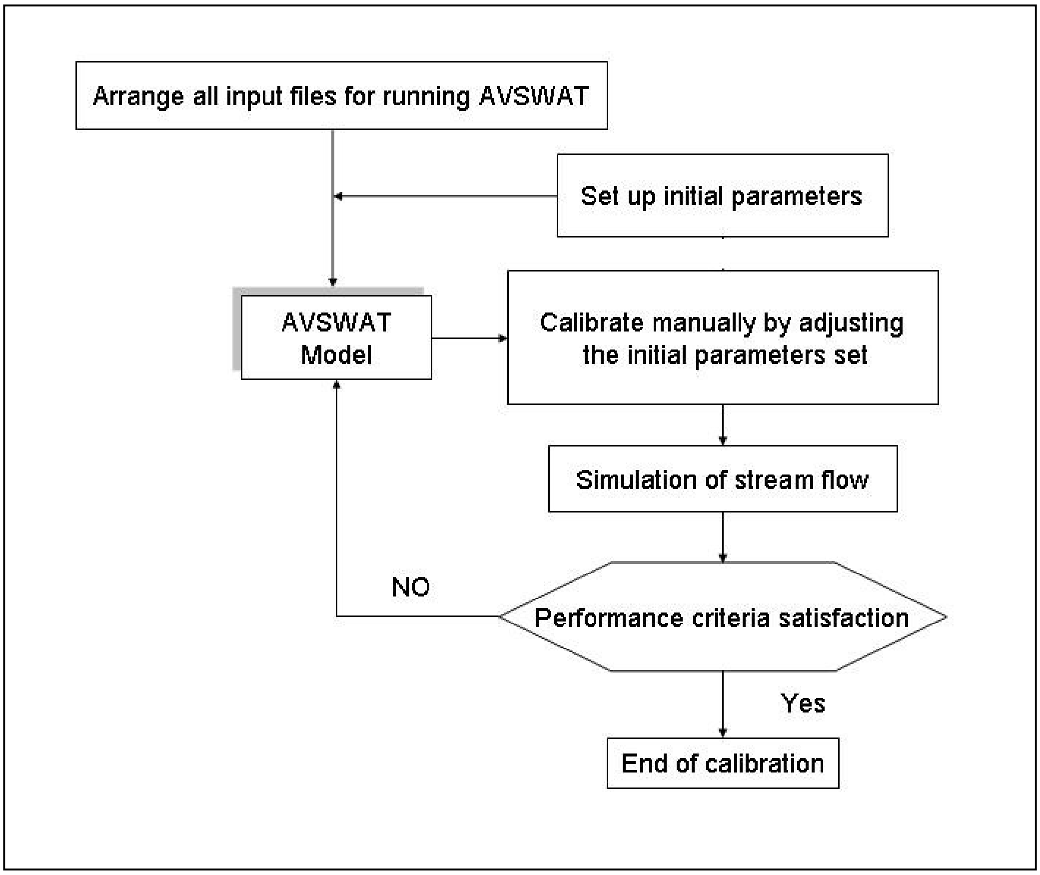


Figure 7.2 Flow diagram for SWAT stream flow manual calibration procedure for Wadi Ham catchment.

The model was prepared in its final set-up based on the primary set up and experience gained from the base case configuration used for the sensitivity analysis (chapter 6). The catchment was divided into 11 sub-basins, HRU's were created to represent all soil types and land uses within the catchment and the climate data and adjusted potential evapotranspiration values (as will be described later) from 1980 to 1988 were input to SWAT. Of the sensitive parameters identified in Chapter 6, the main parameters that required calibration in the case of Wadi Ham catchment to achieve acceptable performance by SWAT were the soil layer depth (sol_z), available water capacity (sol_AWC), soil hydrologic group (HYDGRP_CN), baseflow recession constant (ALPHA_BF) and the channel effective hydraulic conductivity (CH_k). The best model performance was achieved when Ch_k had been adjusted to the maximum permissible value (150 mm/hr) and ALPHA_BF to the minimum permissible value (0 days).

Figures 7.3 and 7.4 present a comparison between the observed and simulated daily runoff for the calibrated model for Bithna station in the upper Wadi Ham catchment. Both the calibration and validation graphs show good similarity between observed and simulated stream flow, with most observed runoff events being replicated by SWAT, although SWAT appears to have a slight tendency to over-predict the frequency of small (< 4 m^3/s) events. Table 7.1 gives the results of the performance statistics that indicate the goodness of fit between the observed and simulated stream flow by the SWAT model.

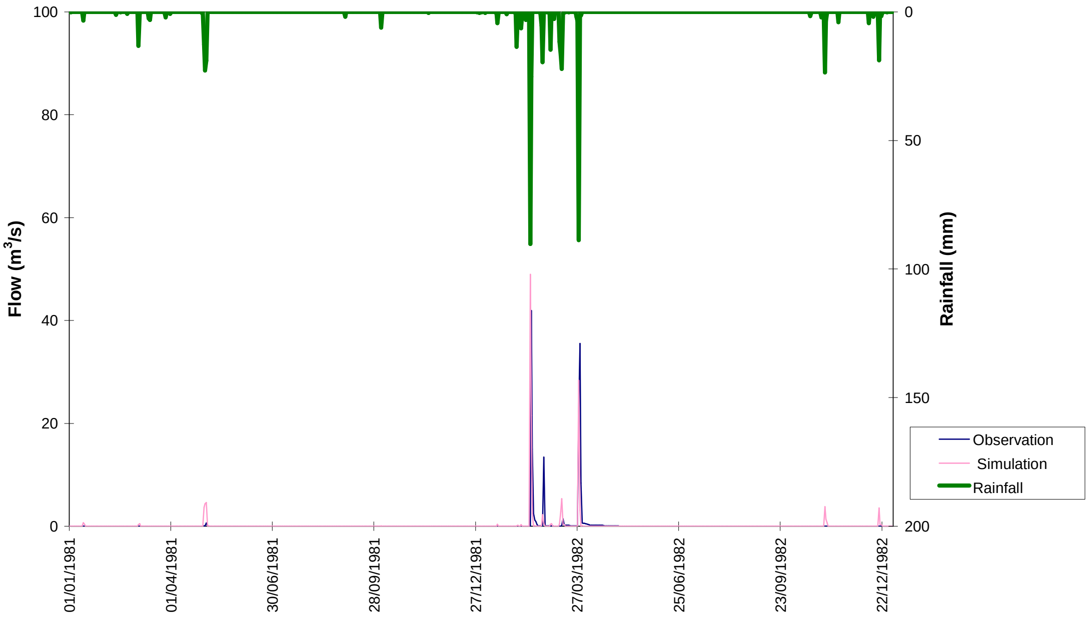


Figure 7.3 Comparison between observed and simulated daily stream flow at the Bithna station in the upper Wadi Ham catchment during the calibration period.

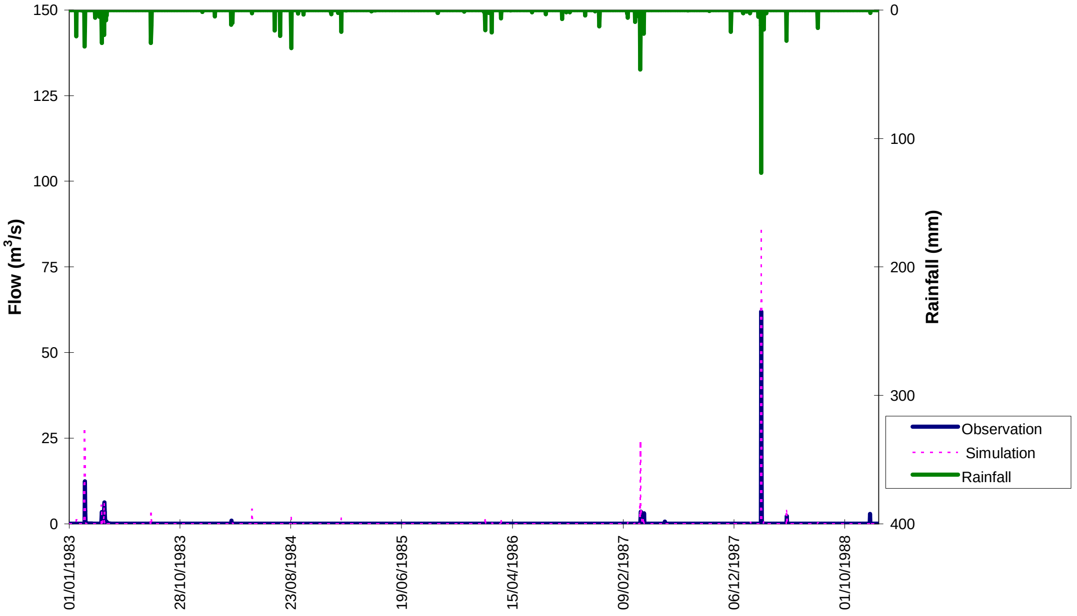


Figure 7.4 Comparison between observed and simulated daily stream flow at the Bithna station in the upper Wadi Ham catchment during the validation period.

Table 7.1 Results of Performance statistics of SWAT model for Wadi Ham catchment simulation at Bithna Station.

	Calibration	**Validation**
statistics	1981-1982	1983-1988
DRMS (m^3/s)	1.10	0.93
PBIAS (%)	27.12	-27.30
NSE	0.78	0.57
PME	0.80	0.70

From the Figure 7.3, Figure 7.4 and Table 7.1 it can be seen that the overall performance of SWAT model rainfall-runoff prediction is within the acceptable range. The NSE and PME for both calibration and validation periods indicate that the model performance is good. Although the overall model performance deteriorated slightly according to the NSE from 0.78 for the calibration period to 0.57 for the validation period, the DRMS decreased from 1.10 to 0.93 m^3/s. The model appears to have a tendency to under estimate or over estimate the total stream flow according to the influence of low or high base flow component in the rainfall-runoff simulation.

7.2 Plausibility of processes simulated by SWAT

The daily streamflow at the Bithna flow station represents the only quantitative data against which to statistically assess the model performance. However, because of the multiple processes separately simulated within SWAT, it is possible to qualitatively or semi-quantitatively assess the performance of these SWAT components against other data or knowledge from the catchment or region in order to increase the confidence in the ability of SWAT to simulate the arid zone processes. The subsequent sections therefore demonstrate the results from Wadi Ham catchment of hydrological processes that have been simulated without extensive datasets. According to Carter et al. (2002) simulation without extensive datasets can provide valuable insights into complex systems where the credibility of results can be established through criteria of ‘plausibility’ based on quantitative and qualitative observations.

The validation of the hydrological model was based upon (1) realistic representation of the different processes in the SWAT model and on (2) semi-quantitative knowledge/information and available data about the Wadi Ham catchment and other arid region catchments. For instance, the representation of natural grass land use in the catchment in SWAT has used data related to arid range grass from the United States. The model simulation results were validated using information relevant to Wadi Ham catchment i.e. growing period and from other arid regions i.e. biomass values reported from the arid state of Kuwait. The previous methodology was also used to validate the SWAT components of simulation of reservoir sedimentation, plant growth, irrigation application and groundwater recharge.

7.3 Sedimentation simulation

Information about sedimentation rates within the Wadi Ham dam reservoir is very limited. It is known that the reservoir has only been cleaned once, since its construction in 1982, in late 1998, and it is reported that the local farmers tend to collect sediment from the reservoir bed to use as a fertile soil in their farms (MAF, 1993). However, the volumes removed by both these formal and informal means are unknown.

SWAT is able to simulate the transport of sediment into the reservoir. Figure 7.5 shows the sediment inflows to the Wadi Ham dam reservoir for 1982 to 1988. It can be seen that the sedimentation occurs in wet years in relation to the high flood events during the simulation period. The highest event sediment quantity is 10.5 t/ha/y which occurred in 1988. The average annual simulated sediment yield of the reservoir (1982-88) is 4.1 t/ha/y. This quantity is close to the average annual sediment yield of 3.2 t/ha/y estimated by MAF for Wadi Ham catchment recharge dam using the non calibrated Fleming design curves method (MAF, 1993). It is reported by Bureau of Reclamation (1988) also that a conservative sedimentation rate of 26000 m^3/y was estimated based upon some field observations of the reservoir in 1987. Using an average bulk density of 1500 kg/m^3 this volume is equivalent to 39000/a tonne of sediment. Based on the above tentative estimations of reservoir sedimentation it seems that SWAT is giving a reasonable estimate. There may be a tendency to overestimate the reservoir sedimentation, based upon the overestimation of some of the high runoff events apparent in Figures 7.3 and 7.4, but there is insufficient sedimentation data to verify this.

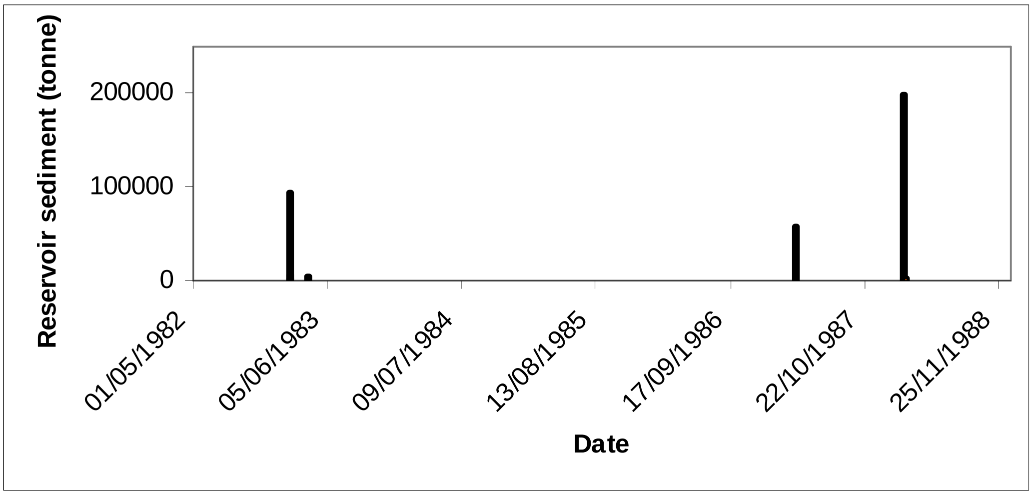


Figure 7.5 Simulated sediment yield to Wadi Ham catchment dam from 1981 to 1988.

7.4 Evapotranspiration and Plant growth simulation

7.4.1 Evapotranspiration

Potential evapotranspiration (PET) was calculated by SWAT using the Hargreaves method (Neitsch, 2002) which requires only daily minimum and maximum air temperature data. The PET values calculated by SWAT for Wadi Ham catchment appeared to under estimate the real PET values when compared with the reported monthly PET data for Eastern region (Prashar , 1978) and general PET values under UAE conditions (MAF, 1993). In general the calculated values ranged between 2 - 8mm/d as average monthly PET values, an apparent 2 mm/d underestimation for most months, which suggest that PET calculated by the Hargreaves method needed to be adjusted for the catchment conditions. The ET calculator software (Allen, 1998) was used to calculate the average monthly PET using the available published climate dataset for Dubai Airport (ICBA, 2000) with both Hargreaves-85 and Penman-Montieth (FAO, 1998) methods (Figure 7.6). An adjustment factor, derived using a regression analysis from the relationship between the two methods

(Figure 7.7), was used to adjust the daily PET valued calculated by the Hargreaves-85 method before they were imported into SWAT. A possible reason for the underestimation of PET values by Hargreaves-85 method could be the high mean wind speed values (2 m/s) that occur in the region, that are not considered in this method.

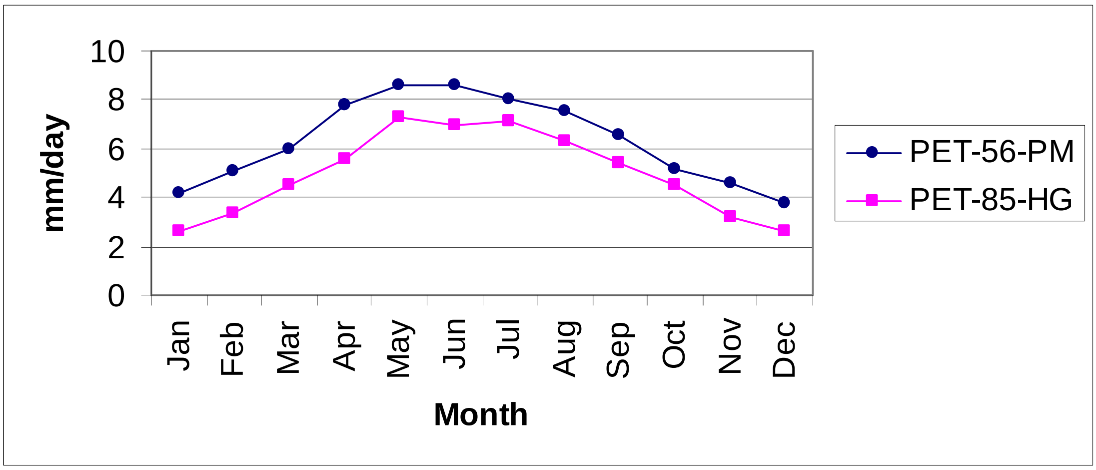


Figure 7.6 Average monthly potential evapotranspiration for Dubai Airport calculated using the Hargreaves (1985) [PET-85-HG] and Penman-Monteith [PET-56-PM] methods.

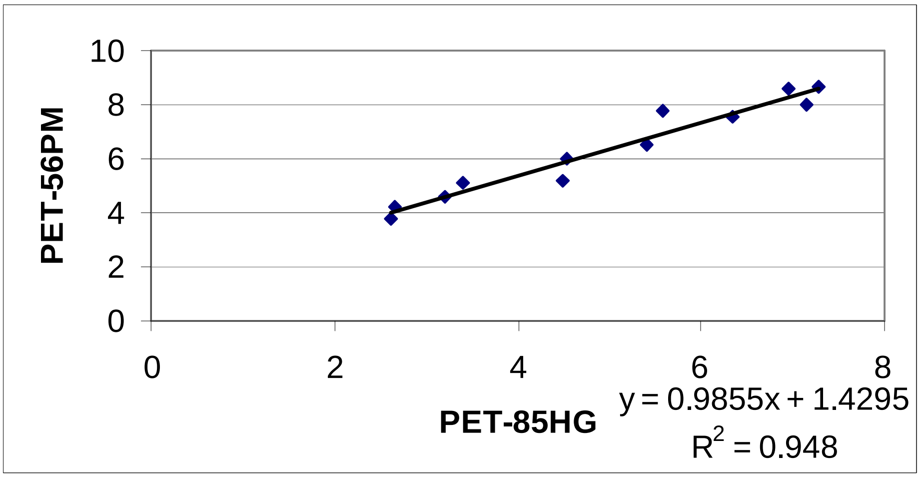


Figure 7.7 Relationship between average monthly PET values calculated by Hargreaves-85 [PET-85HG] method and Penman-Montieth [PET-56PM] using data from Dubai Airport.

As a comparison, Figure 7.8 presents calculated PET for different regions of UAE, including the eastern region where Wadi Ham catchment is located by Prashar et al. (1978) while Figure 7.9 shows the average monthly PET values calculated for Wadi Ham catchment after the adjustment. It should be noted that Prashar et al. (1978) calculated PET using the available pan evaporation (Epan) data in every region and Pan Coefficient values as tabulated in the FAO irrigation and drainage paper No. 24, (FAO, 1977) that relate to weather stations which are generally located on dry bare soil. The agreement between the PET values in both calculations is observable, where the minimum values are around 4 mm/day and maximum values are more than 8 mm/day in both estimations. However, the slight over-estimation in winter and under-estimation in summer of the calibrated PET that can be observed may very slightly affect the water balance and the irrigation water demand in the catchment.

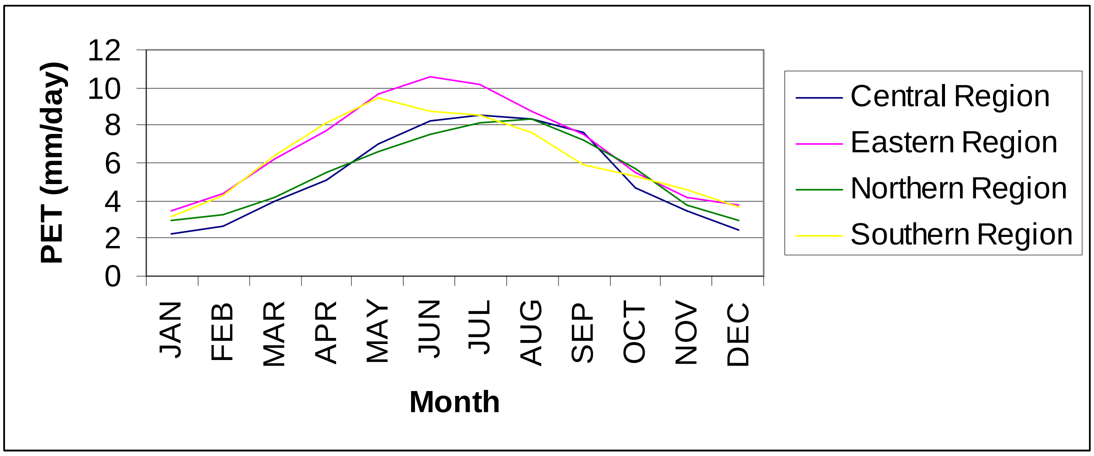


Figure 7.8 Average monthly potential evapotranspiration values calculated for UAE regions by Prashar (1978) using pan evaporation method.

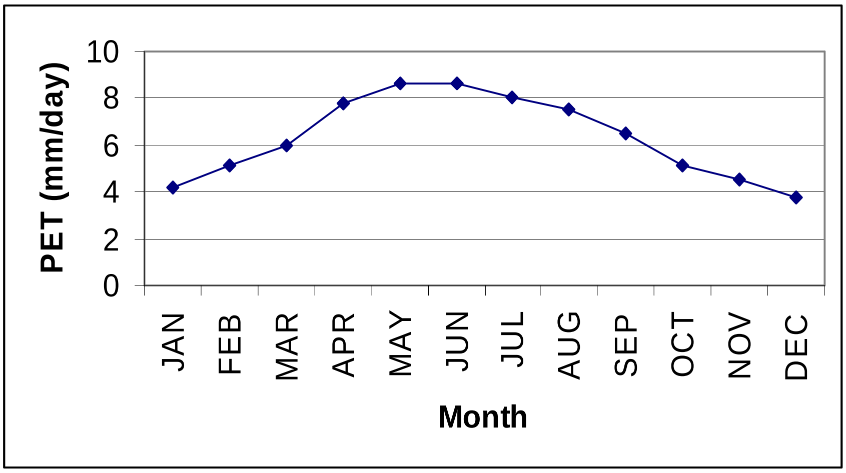


Figure 7.9 Calibrated average monthly potential evapotranspiration for the period 1980-88 calculated for Wadi Ham catchment.

7.4.2 Plant growth simulation

The plant growth simulation component in SWAT is a simplified version of the EPIC (Williams, 1995) plant growth model (Neitsch et al., 2001). Four types of plants were simulated in Wadi Ham by the SWAT model. These plants are a natural arid zone perennial grass (represented by the arid perennial range grass of south-western US- SWRN), Alfalfa (ALFA), tomato (TOMA) and date palm (PALM). Default crop growth parameters included in the SWAT model were initially used for the first three crops, while information for date palm was developed and added to the SWAT land cover database (Chapter 5).

In terms of the overall catchment water balance, the behaviour of the natural arid zone vegetation is highly important to the model performance as they are the most spatially extensive of the represented plants, covering about 98.5% of the catchment. Figure 7.10 shows the simulated Leaf Area Index (LAI) development curve of the arid perennial range grass. It can be observed that the emergence and growth of the range grass in the HRU is strongly related to the rainfall events. The grass usually takes a few days after the first significant rainfall event to start growing. After a short growth period, the grass wilts due to the rapidly increasing soil moisture deficit during the dry periods (Fig. 7.11). The duration of plant development in the HRU during the rainy season (Fig. 7. 12) is about three to four months which is similar to the flowering period of many indigenous perennial and annual grass and herbs in UAE. For example, *Asphodelus tenuiflius* (January-April), *Phalaris minor* (February-May) and *Plantago amplexicaulis* (January-April) (Karim, 1995).

Brown (2002) estimated biomass values using a regression equation developed from a three year field study of annual plants (Predominated by *Plantago boissieri*) in Kuwait that grow in the season between November and April (Figure7.13). During the three growing seasons, the rainfall was 72 mm, 170 mm and 87 mm per season. The simulated biomass values of natural grass for Wadi Ham from SWAT (Figure 7.12) are comparable with values obtained from this previous study (Figure 7.13).

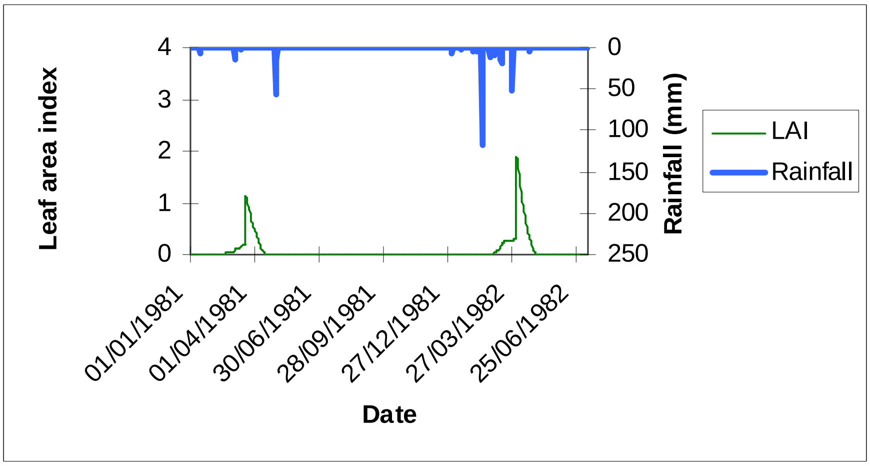


Figure 7.10 Simulated development of Leaf Area Index of an arid range grass as modelled by SWAT for a loamy soil type in Wadi Ham catchment.

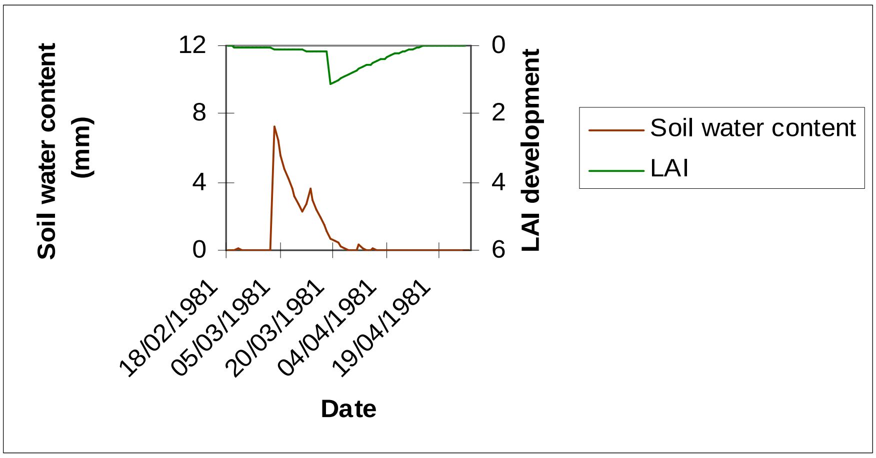


Figure 7.11 Simulated development of LAI of an arid range grass and soil moisture depletion by SWAT for loamy soil type in Wadi Ham catchment.

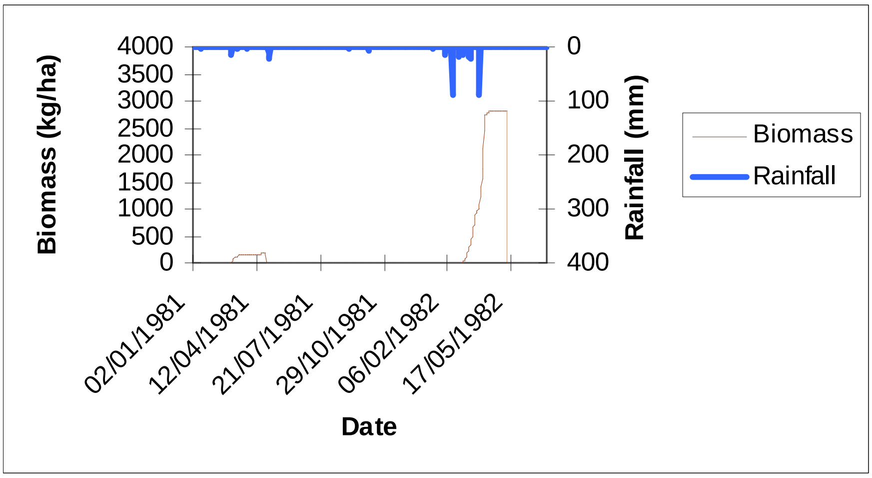


Figure 7.12 Biomass development and growth duration of arid range grass as simulated by SWAT for a loamy soil type in Wadi Ham catchment.

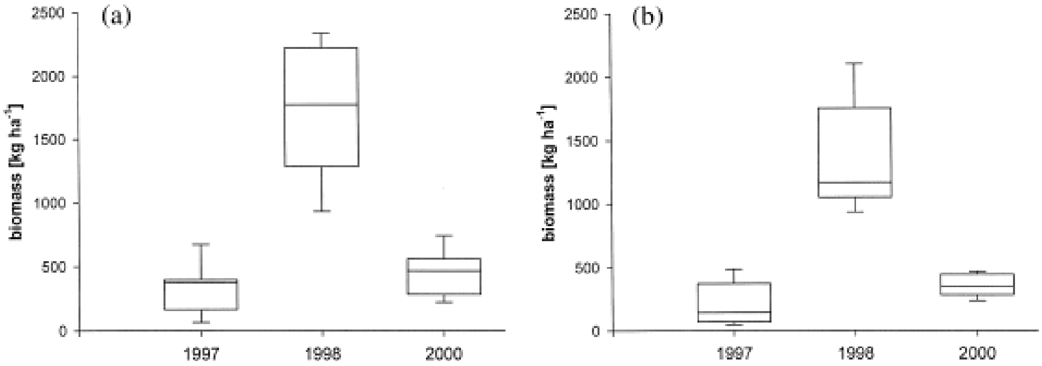


Figure 7.13 Estimated biomass production in the three observation years for two plots of natural vegetation during the growth period in Kuwait. Plots give the median, 10th, 25th, 75th and 90th percentile. (after Brown, 2002).

Alfalfa (*Medicago sativa*), a perennial legume, is the main fodder crop in Wadi Ham catchment and in many other arid region farm lands. The harvest of the green part of the plant takes place on a monthly basis under field practices. Figure 7.14 and figure 7.15 show the development of leaf area and biomass of alfalfa as simulated by the SWAT model.

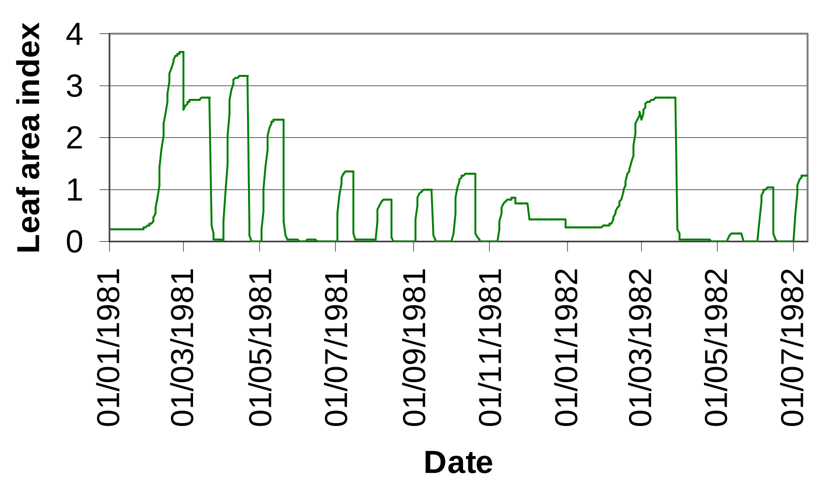


Figure 7.14 Simulated leaf growth of irrigated alfalfa for the agricultural loamy soil type in HRU 7 as modelled by SWAT.

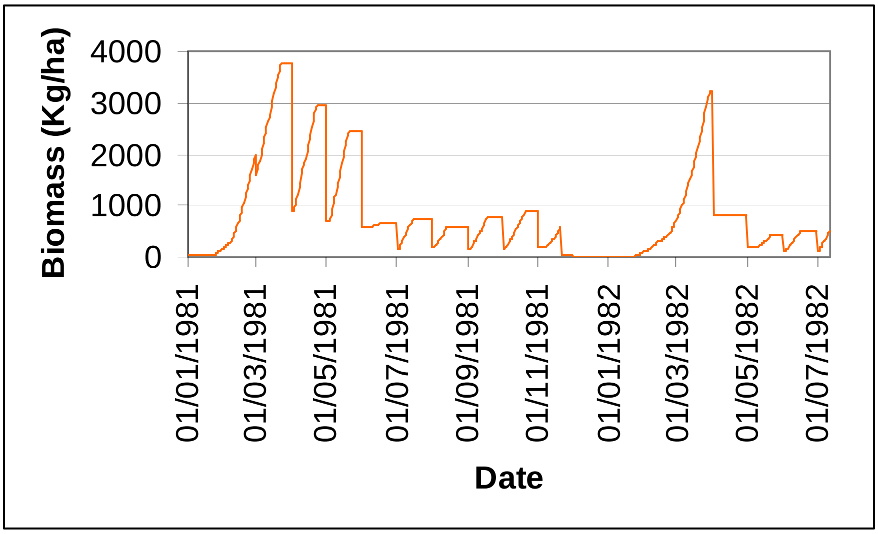


Figure 7.15 Simulated biomass growth of irrigated alfalfa for the agricultural loamy soil type in HRU 7 as modelled by SWAT.

The general SWAT model performance for alfalfa growth simulation under Wadi Ham catchment condition appears to be acceptable when compared with simulated results obtained by Probert (1998) for alfalfa growth using the Agricultural Production Systems SIMulator (APSIM) model under irrigation in Australia (Figure 7.17). SWAT simulated the regular harvest pattern of the green leaf, but it also shows progressive degradation in LAI and biomass growth, mainly in the summer months. For example, in 1981 after several harvests at a LAI of 2-4 and biomass of 2500-4000 kg/ha, the LAI and biomass fail to grow back to these levels, reaching a LAI of around 1-1.5 and a biomass of less than 1000 kg/ha. Figure 7.16 shows simulated phosphorus stress and temperature stress during the year of growth and a short period of water stress on alfalfa during the month of July as result of insufficient irrigation application by the model which is likely to have contributed to the reduced yield. The phosphorus stress to alfalfa was removed by applying the required amount of the fertilizer by manual application option in the model (Figure 7.17). Figure 7.18 shows that temperature is a real constraint for alfalfa growth simulation by SWAT. Figure 7.19 shows that the observed alfalfa LAI is less than 4 which is similar to SWAT simulation (Figure 7.13) for the early part of the growing season under Wadi Ham catchment conditions.

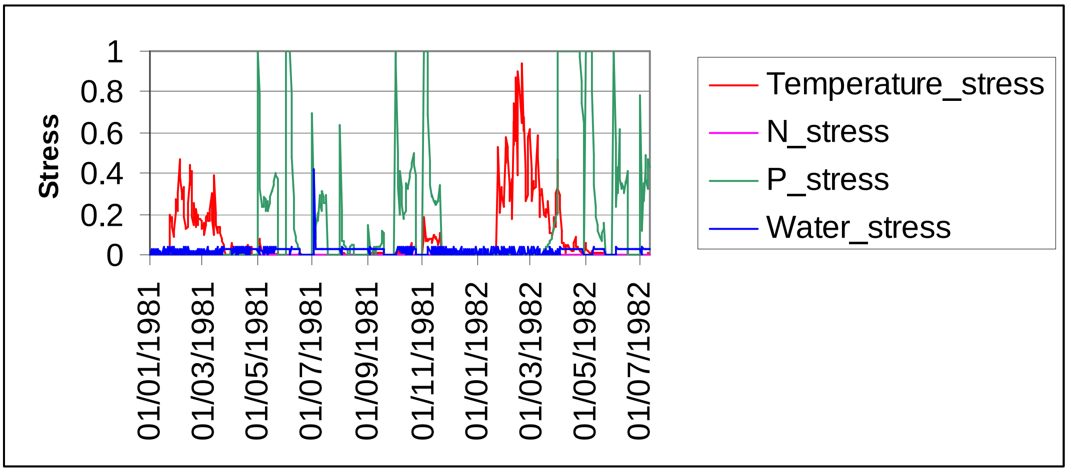


Figure 7.16 Simulated Temperature, nitrogen, phosphorus and water stresses for irrigated alfalfa on agricultural loamy soil type in HRU 7.

The degradation in alfalfa biomass growth affects the simulated annual yield of the plant estimated by SWAT which, at 12.28 t/ha is about half the yield observed by Sattar et al. (2002) in a field experiment to obtain the optimal level of irrigation water needs for alfalfa crop under UAE environmental conditions. Using three levels of irrigation water applied (2000mm, 1800mm and 1600mm per growing season, twelve cuts of alfalfa yielded 30.3, 27.5 and 24.3 t/ha (15% moisture content) for the three treatments (Sattar et al., 2002). SWAT continued the same simulation pattern of under estimating the yield for the following simulated years e.g. 11.58, 12.66 and 12.97 t/ha for 1986, 1987 and 1988 respectively.

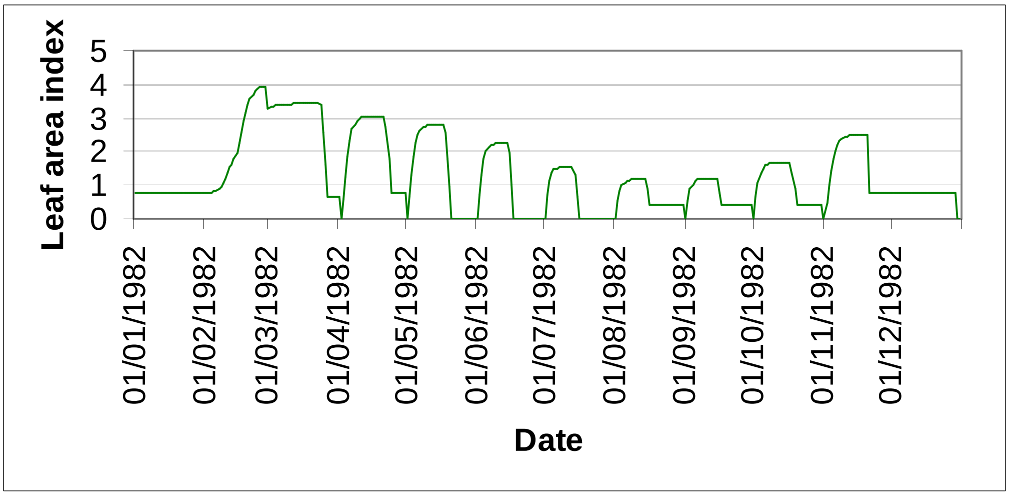


Figure 7.17 Simulated leaf growth of irrigated alfalfa for the agricultural loamy soil type in HRU 7 after the removal of phosphorus stress.

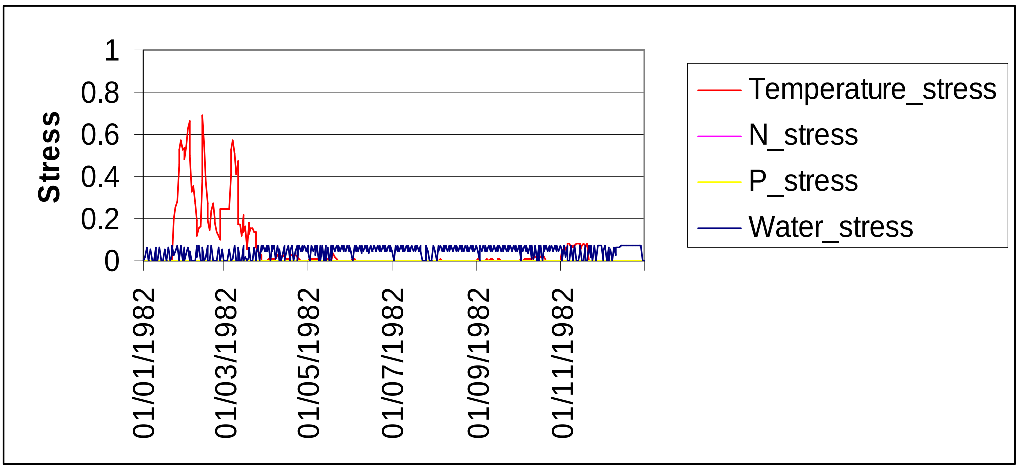


Figure 7.18 Simulated Temperature stress for irrigated alfalfa on agricultural loamy soil type in HRU 7 after the removal of phosphorus stress.

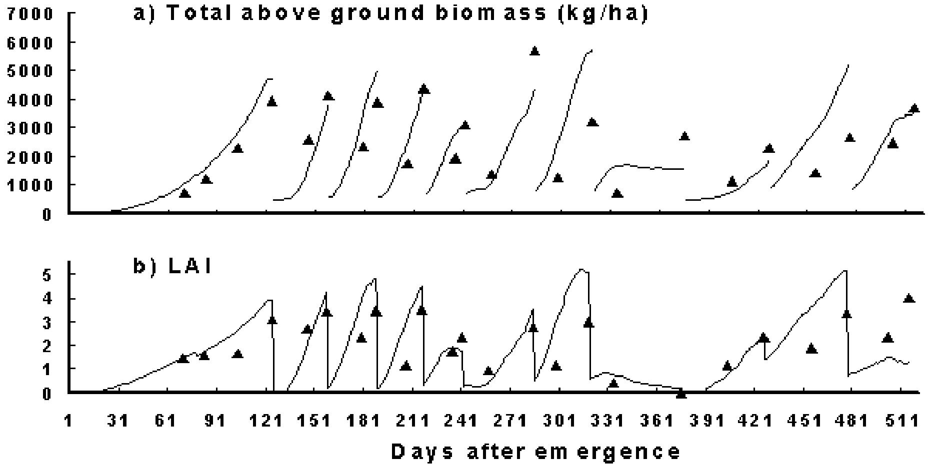


Figure 7.19 Simulated biomass growth and leaf area index (LAI) for irrigated alfalfa by APSIM model (triangles are observed data) (Probert et al., 1998).

Tomato (*Lycopersicon spp)* is the main vegetable crop grown in the catchment. The simulation of tomato by SWAT shows acceptable leaf area development during the growth period (Figure 7.20). The general trend of the simulation graph corresponds with that of a tomato growth simulation by Irmak and Jones (2000) (Figure 7. 21). The number of days to the maximum LAI is 60 days which is reasonable for the study area species (Hussain, personal comunication). But the graph also shows that the simulated plant is not reaching its maximum LAI of 3 and Figure 7.22 shows temperature stress on tomato during the growing season.

The simulated biomass development graph (Figure 7.23) for tomato shows acceptable values in comparison with literature (e.g. Figure 7.24), with a maximum simulated biomass in 1982 of 9000 kg/ha being equivalent to 900 g/m^2. However, a problem in the simulation of tomato growth is apparent, as SWAT appears to let the tomato keep growing after the harvesting date (Figure 7.23), although the LAI has been reduced to zero after harvest (Figure 7.20). Such a problem was identified by Kannan (2003) in other crops (i.e. peas) simulated by SWAT in a UK case study.

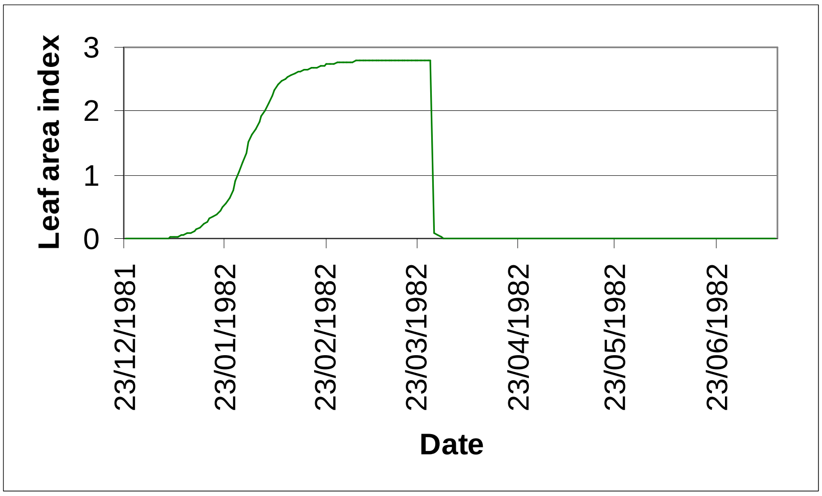


Figure 7.20 Simulated LAI developments for irrigated tomato for the agricultural loamy soil type in HRU 8 as modelled by SWAT.

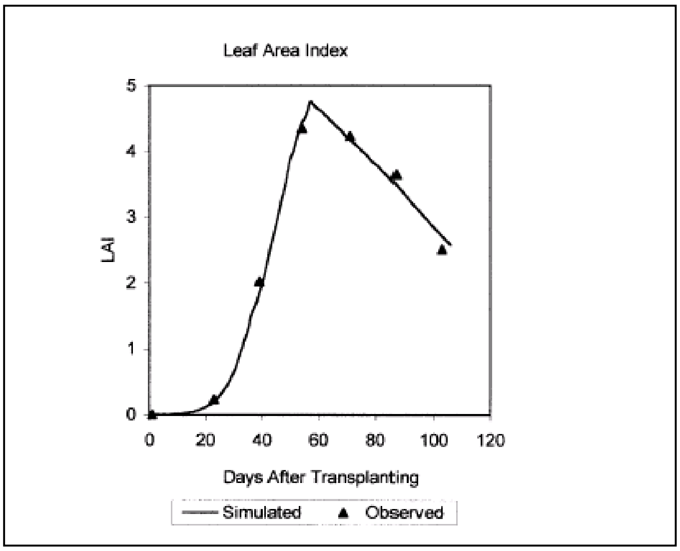


Figure 7.21 Simulated and observed leaf area index of tomato in Florida (USA) as reported by Irmak and Jones (2000).

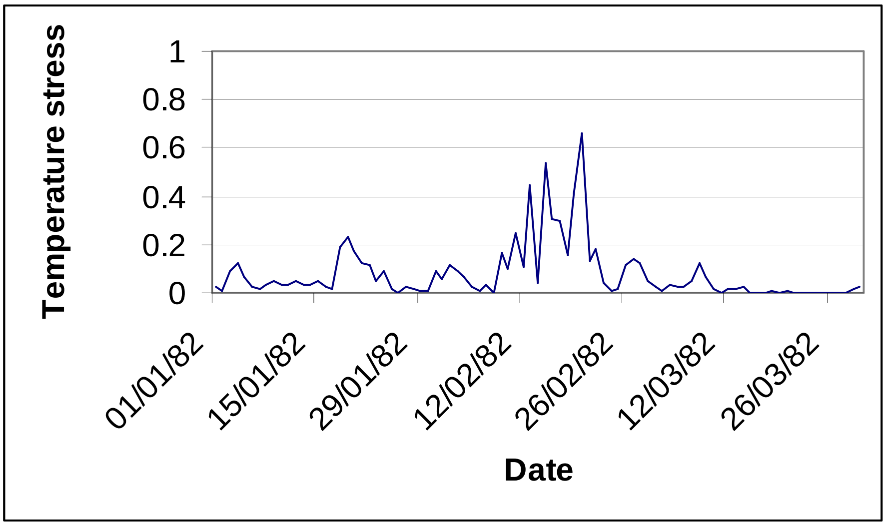


Figure 7.22 Temperature stress for tomato during the growing season.

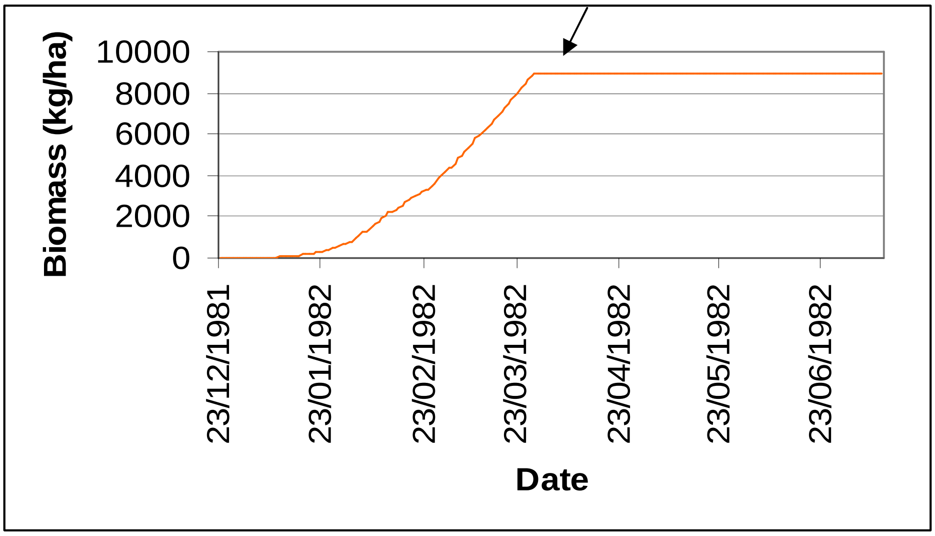


Figure 7.23 Simulated biomass of tomato by SWAT model (the arrow shows harvest date).

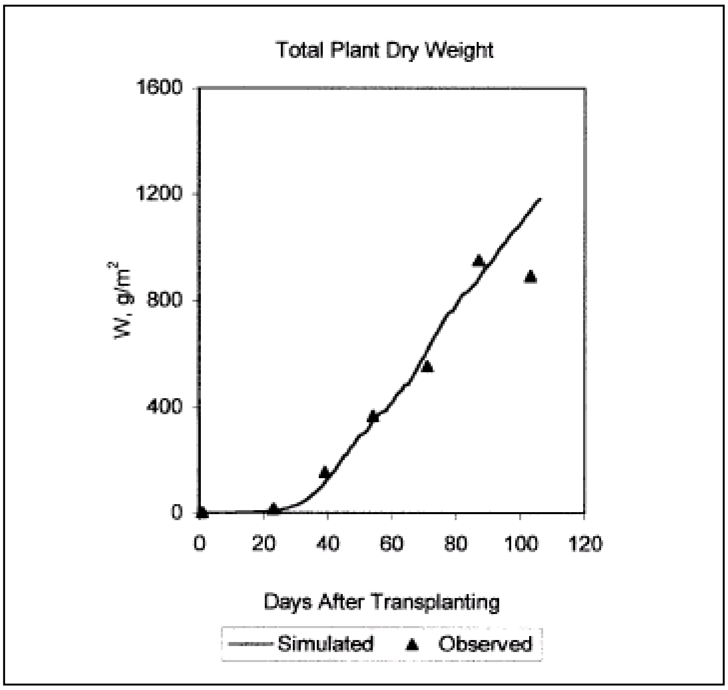


Figure 7.24 Simulated and observed biomass development of tomato in Florida (USA) as reported by Irmak and Jones (2000).

The simulation of the growth of the date palm tree *(Phoenix dactylifera)* that has been added to the SWAT crop and land use database was not totally successful (Figure 7.25). SWAT was not able to produce the correct continuous leaf growth although the maximum simulated biomass of the plant at about 13000 kg/ha is very close to annual dry matter production of oil palm (14.3 t/ha) (Corley and Tinker, 2003). In regard to the overall catchment modelling this shortcoming is unlikely to be significant since date palm occupies only 0.5 % of total catchment area and generally requires less irrigation than alfalfa and vegetables during the year.

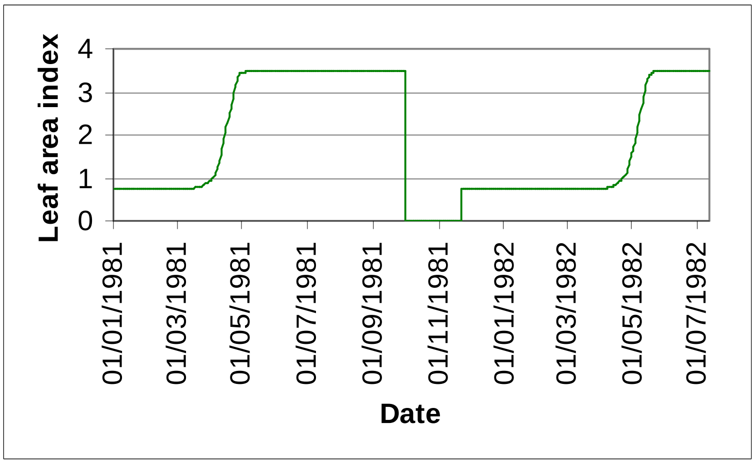


Figure 7.25 Simulated LAI development of date palm tree.

7.5 Irrigation application

The SWAT model has an irrigation auto-application procedure, where irrigation water amount is calculated and applied to the appropriate crop in an HRU. A water stress threshold value must be specified by the user. Anytime actual plant growth falls below this threshold fraction due to the water stress the model will automatically apply water to the HRU to fill the soil layers up to the field capacity.

The irrigation schedule was set up for the crops in Wadi Ham catchment based on the actual frequency of irrigation practiced by the local farmers. Date palm is normally irrigated each 6 days, alfalfa each 3 days and tomato is irrigated on a daily basis (Hussain, Personal communication). The irrigation application in SWAT was set up to represent these irrigation frequencies for each crop by setting up the different water stress threshold for each crop.

Estimates of crops water requirements under UAE condition are available from two references. Prashar and Thanki (1978) estimated the crop water requirements for different agricultural regions in UAE using the pan evaporation method with climate data ranging from 8 to 5 years. While Hassbini (2003) implemented longer climate datasets (20 years) to estimate the crop water requirements using CROPWAT (Hassbini, personal communication). Table 7.2 gives the estimated crop water requirements for crops cultivated in Wadi Ham catchment from these sources.

Table 7.2 Estimated crop water requirements under UAE conditions using Pan method by Prashar and Thanki (1978) and Penman-Monteith by (Hassbini, 2003).

	Pan method m³/ha	**Penman-Monteith** m³/ha	***Average*** m³/ha
Alfalfa	21151	26770	23961
Tomato	6058	6360	6209
Date Palm	8553	12780	10667

Figure 7.26 shows the average volumes of water that were applied to the three irrigated plants in Wadi Ham catchment by SWAT against the average crop water requirement estimated under UAE condition from Table 7.2. It can be seen that the alfalfa irrigation water amount is within the range of estimated water requirements under UAE condition. However, tomato and date palm had higher irrigation amounts than that estimated under average UAE conditions.

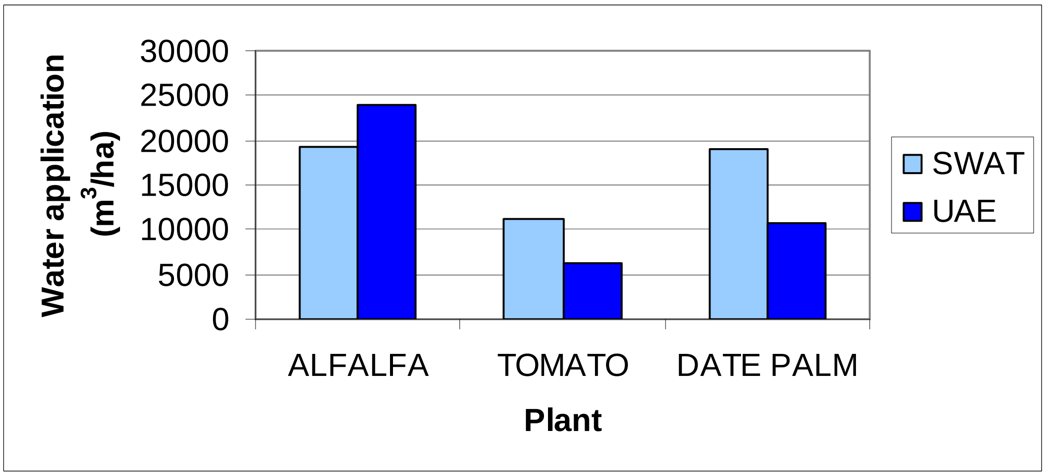


Figure 7.26 Average annual irrigation application in Wadi Ham catchment as simulated by SWAT and estimated average crop water requirements for UAE as estimated by Prashar and Thanki (1978) and Hassbini (2003).

7.6 Groundwater recharge simulation

The United States Geolgoical Survey define an aquifer as “a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs”(USGS, 2005). However, rather than representing aquifers, the groundwater system in SWAT is represented by shallow and deep groundwater stores which underlie the entire catchment. It is therefore necessary to relate the conceptual model of groundwater recharge processes and aquifers in Wadi Ham catchment with the SWAT output variables in order to ensure that the correct SWAT elements are being considered.

7. 6. 1 Wadi alluvial aquifer recharge

In the mountainous part of an arid region Wadi catchment, the part of the plain in which alluvial materials are saturated below a water table is called the aquifer area (Khazaei et al., 2003). The Wadi Ham catchment local alluvial aquifer system consists of (a) old gravel which is weathered gravel, cobbles and boulders that is overlying conglomerate and also benches and terraces cut into the Semail bedrock, (b) new gravel which has been deposited on lower benches in the Wadi fan area and finally (c) the channel gravel which are the deposits of the active channels in the drainage network of the Wadi catchment (MAF, 1988). In such an aquifer system the main recharge mechanism is transmission loss from the bed of the Wadi streams to the underlying alluvial aquifer (Figure 7.27).

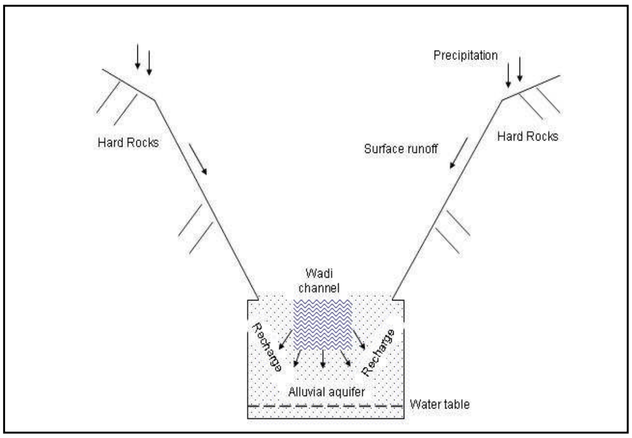


Figure 7.27 Conceptual model of recharge to the alluvial aquifer via transmission loss mechanism from Wadi channels in Wadi Ham catchment.

The recharge to the alluvial aquifer underlying the main Wadi channel is represented in SWAT by the transmission losses from the reach in each sub-basin. SWAT estimates the water lost from the channel via transmission through the side and bottom of the channel using the following equation:

$$tloss = K_{ch} \cdot TT \cdot P_{ch} \cdot L_{ch} \tag{7.5}$$

Where *tloss* is the channel transmission losses (m^3/hr), K_{ch} is the effective hydraulic conductivity of the channel alluvium (mm/hr), *TT* is the flow travel time (hr), P_{ch} is the wetted perimeter (m), and L_{ch} is the channel length (km).

Figure 7.28 shows the simulated volume of recharge to the alluvial aquifer of Wadi Ham provided by transmission losses. It can be seen that the simulated volume of recharge varies significantly between years, in relation to the runoff events throughout the simulated years. The highest simulated recharge volumes occur in 1982 and 1983, which were the years with longest observed stream flow duration of 78 days and 68 days, respectively.

Additional support for the SWAT modelled recharge volume is provided by the simulated irrigation water volume applied to the plants in the Wadi catchment (Figure 7.29). This shows a stable annual pattern of pumped irrigation water, with slight annual variation due to weather differences. Comparison of Figures 7.28 and 7.29 shows that, in most years, simulated irrigation abstraction is less than simulated recharge to the alluvial aquifer (as given by transmission losses). This matches the balance between the groundwater supply and demand in such traditional agriculture practices in arid Wadi catchments that have historically kept such cultivation practices and production areas sustainable. A comparison of simulated cumulative irrigation water and simulated cumulative recharge represents the balance that had been maintained between groundwater demand and supply during the simulation period that kept the supply sustainable for the irrigation demand in Wadi Ham catchment (Figure 7.30).

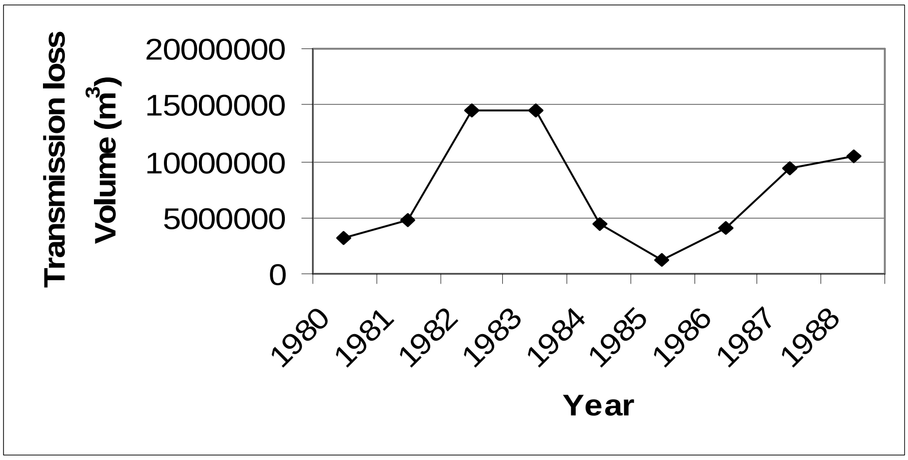


Figure 7.28 Simulated annual groundwater recharge via transmission losses to the Wadi Ham alluvial aquifer by the SWAT model.

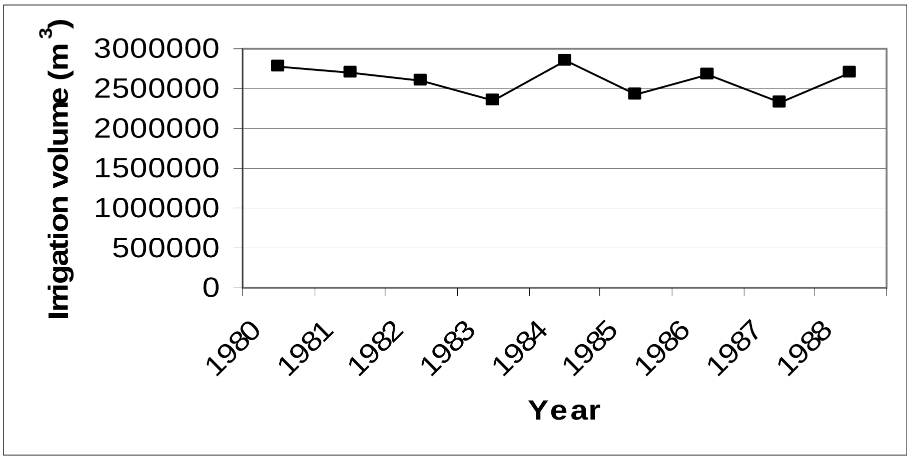


Figure 7.29 Simulated annual irrigation water volume for Wadi Ham catchment.

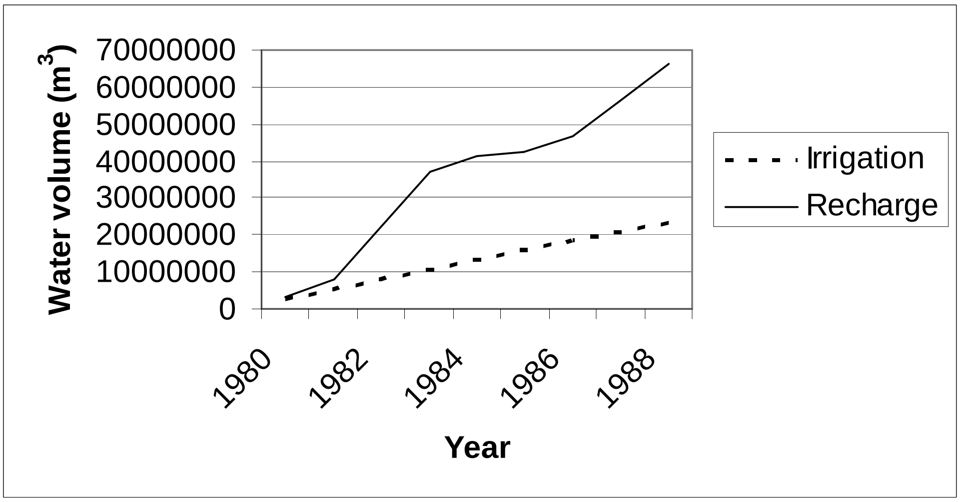


Figure 7.30 Simulated cumulative irrigation water and simulated cumulative recharge via transmission losses in the Wadi Ham catchment.

IWACO (1986) reported a tentative study of recharge of groundwater in Wadi Ham in which, using the chloride contents of rainwater and groundwater in the region, they estimated that the recharge is about 10% of precipitation. Karanjac (1995) suggested recharge of 20% of rainfall, from results from a calibrated groundwater model of downstream Wadi Ham and the gravel plain. The average percentage of recharge (via transmission losses) of the aerial rainfall over the catchment from 1981 to 1988 from the SWAT simulation is 26%. Figure 7.31 shows the percentage of recharge from precipitation for the individual years of simulation, which varies between about 19 and 30%.

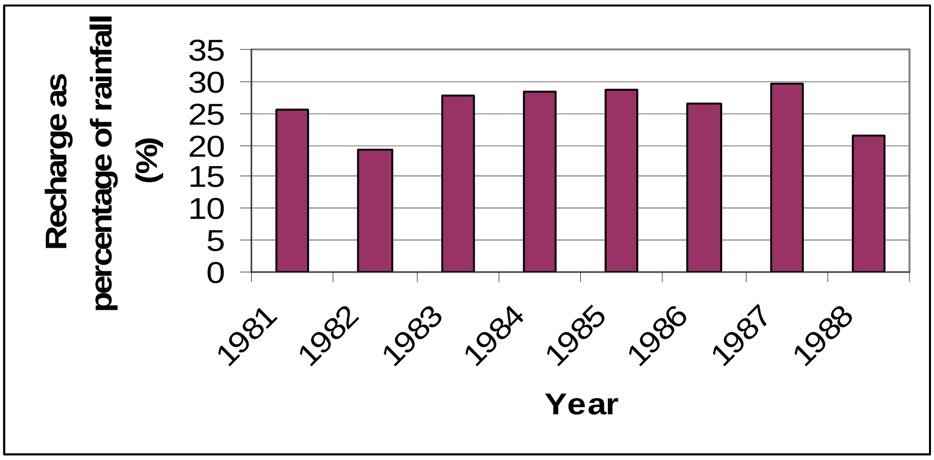


Figure 7.31 Recharge as a percentage of areal rainfall over Wadi Ham catchment.

If the relative balance of irrigation abstraction and recharge simulated by SWAT are correct, the simulated groundwater recharge to the alluvial aquifer in excess of the simulated irrigation abstraction would generate groundwater flow down the alluvial aquifer towards the gravel plain (Bajada). That this occurs in reality is supported by Figure 7.32 which shows the groundwater head downstream in Wadi Ham catchment observed by Entec (1996). These show decreasing heads down the valley and into the Bajada indicating groundwater flow from the Wadi into the gravel plain aquifer.

Using data in Entec (1996), an estimate of the groundwater flow into the Bajada can be obtained by appling Darcy’s law to a cross-sectional area of the Wadi aquifer (Figure 7.33).

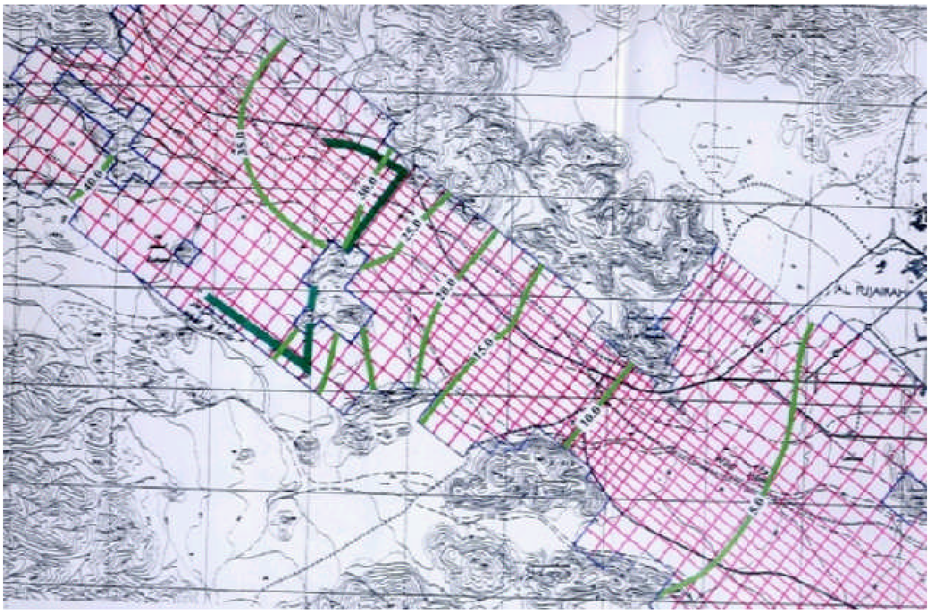


Figure 7.32 Groundwater level contour downstream of the Wadi Ham recharge dam (Entec, 1996).

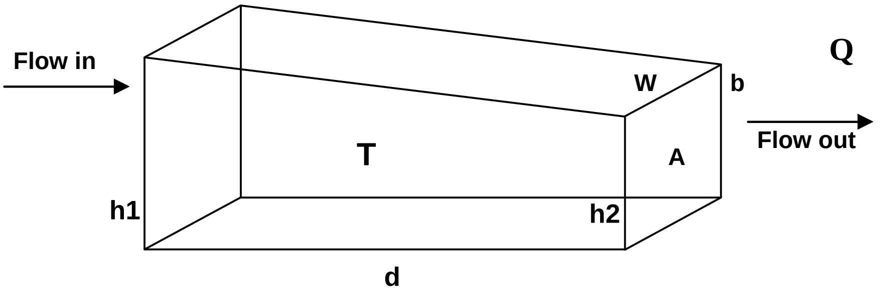


Figure 7.33 A cross-sectional area of the Wadi aquifer

The equation is as follows:

$$Q = K\,i\,A \tag{7.6}$$

Where Q is flow rate in (m^3/d), K is hydraulic conductivity (m/d), i is hydraulic gradient [(h1-h2)/d] and A in cross-sectional area (m^2).

And since

$$T = K\,b \tag{7.7}$$

Where T is the transmissivity (m^2/d), K is hydraulic conductivity (m/d) and b is thickness of the saturated aquifer (m).

$$Q = T\,w\,i \qquad (7.8)$$

By applying the above equation to a cross-sectional width of Wadi Ham aquifer using data reported by Entec (1996) where T = 200 m^2/d, w = 3000 m, and groundwater heads decline by approximately 20m over a lateral distance of 3000m

$$Q = 200 \times 3000 \times (20/3000)$$
$$= 4000\ m^3/d = 1460000\ m^3/y$$

This volume of water flowing downstream in the aquifer is close to the difference between recharge and irrigation abstraction volume of water simulated by SWAT. In 1986 SWAT simulated the difference between irrigation abstraction volume and recharge at 1412994 m^3/y, and the cumulative difference between the irrigation abstraction and recharge volume for the simulation period (1981-1988) is 5345751 m^3/y.

7. 6. 2 Recharge dam reservoir simulation

Wadi Ham recharge dam is an artificial recharge facility for augmentation of groundwater recharge in the shallow gravel plain (Bajada) aquifer of the catchment. Groundwater recharge by the dam can be simulated by the SWAT model on a daily basis. The water balance for a reservoir as modelled in SWAT is:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \qquad (7.9)$$

Where V is the volume of water in the impoundment at the end of the day (m^3), V_{stored} is the volume of water stored in the water body at the beginning of the day (m^3), V_{flowin} is the volume of water entering the water body during the day (m^3), $V_{flowout}$ is the volume of water flowing out of the water body during the day (m^3), V_{pcp} is the volume of precipitation falling on the water body during the day (m^3), V_{evap} is the volume of water removed from the water body by evaporation during the day (m^3), and V_{seep} is the volume of water lost from the water body by seepage (m^3).

The component of water seepage in the equation can be considered as the recharge entering the shallow aquifer of the catchment. SWAT calculates the volume of water lost by seepage through the bottom of the reservoir on a given day as:

$$V_{seep} = 240 \,.\, K_{sat} \,.\, SA \qquad (7.10)$$

Where K_{sat} is the effective saturated hydraulic conductivity of the reservoir bottom (mm/hr), and *SA* is the surface area of the water body (ha).

Figure 7.34 shows the simulated volume of water in the dam reservoir. For both years shown (1987 and 1988) the maximum volume of water in the reservoir reaches the emergency spillway threshold volume of 3.4 MCM. Based on observations of the maximum Wadi Ham reservoir water volume during different flood events, it can be seen that the model overestimated the maximum reservoir water volume (Figure 7.35) due to the overestimation of the total stream flow and flood magnitude for some events.

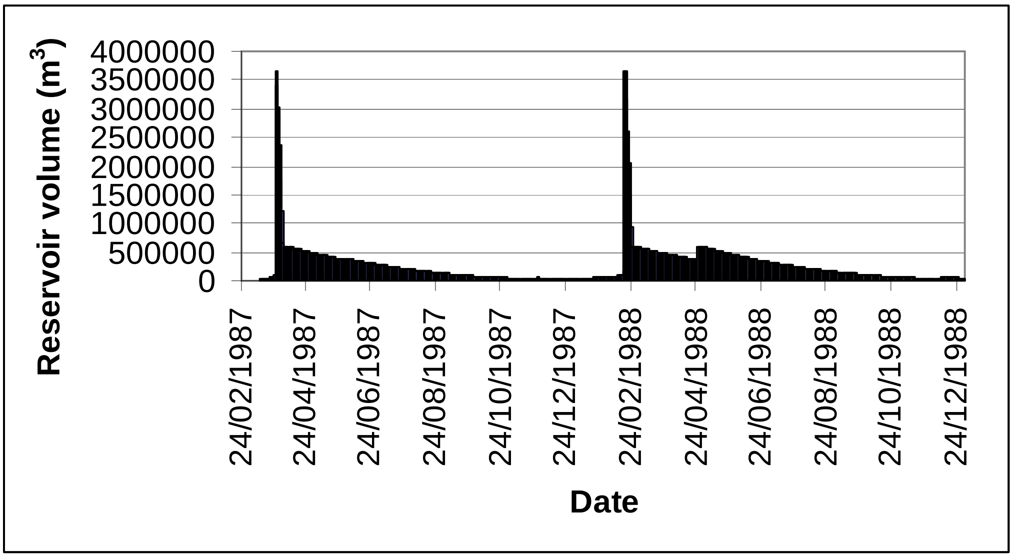


Figure 7.34 Simulated Wadi Ham reservoir water volume for 1987 and 1988.

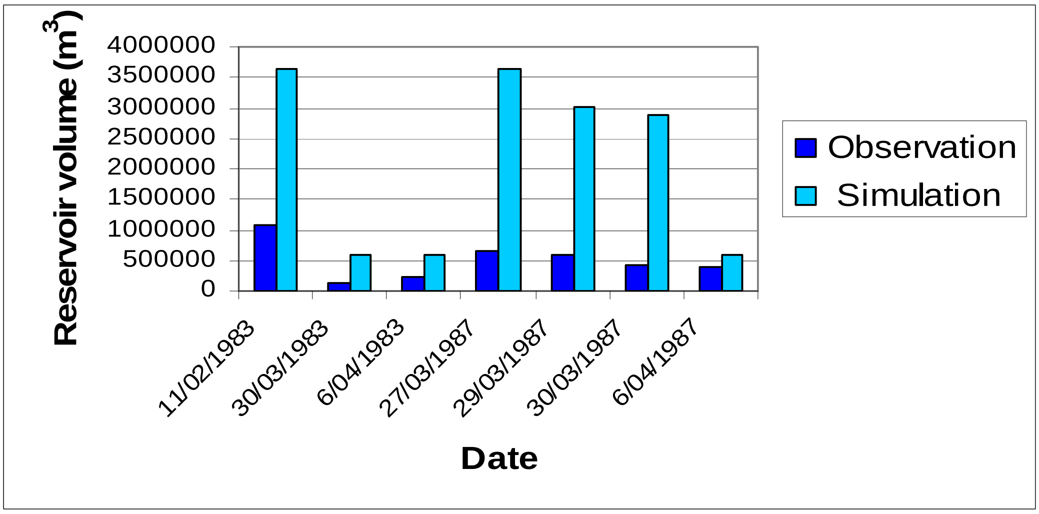


Figure 7.35 Observed vs simulated maximum Wadi Ham reservoir water volume during flood events in 1983 and 1987

Also it can be seen from Figure 7.34 that some water remained in the reservoir for the duration of the entire two simulated years. Under actual Wadi Ham conditions, the infiltration rate from the reservoir bottom allows the reservoir to empty sooner than simulated, notwithstanding the overestimation of simulated volumes. For example it is reported that during the floods of March 28 and April 6, both in 1987, the ponded water in the reservoir had infiltrated fully after approximately a week (Bureau of Reclamation, 1988). Figure 7.36 shows the simulated seepage rates from the bottom of the reservoir for the same floods, which appear to be low for such recharge dam reservoir bottoms. The maximum value of effective saturated hydraulic conductivity of the reservoir bottom allowable by SWAT (1 mm/hr) in seepage calculations seems to be very low for the condition of a recharge dam.

Support for higher infiltration rates than those simulated is given by the groundwater behaviour downstream of the dam (Figure 7.37). Groundwater hydrographs for two observation wells downstream of the dam (Figure 7.38) during 1988 shows that the recharge to the aquifer following the flood event of 17-18/2/1988 which can be observed in the simulated reservoir seepage volume in Figure 7.35 occurs during February/March, as seen by the rapid increase in groundwater levels. Prolonged ponding of water in the reservoir is unlikely as groundwater levels decline soon after.

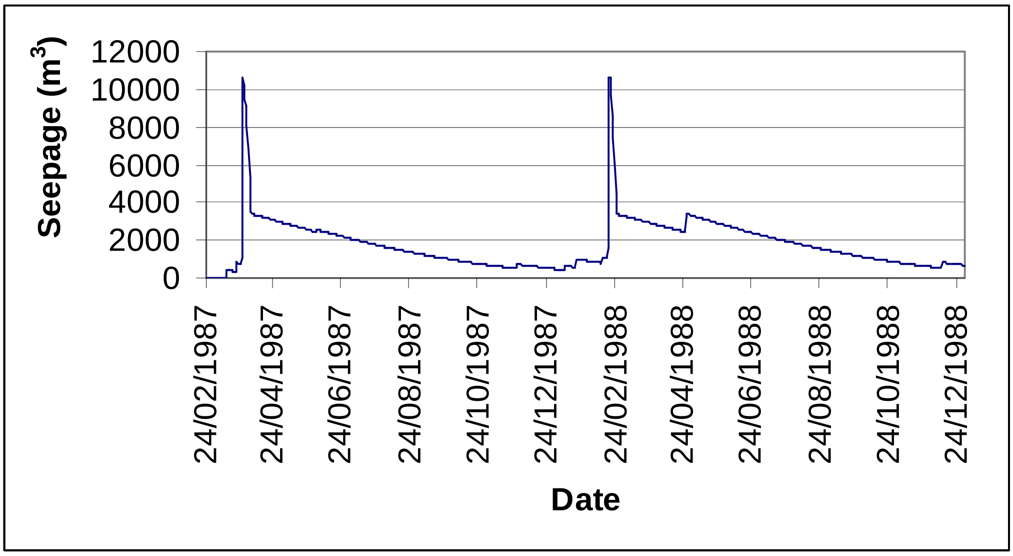


Figure 7.36 Simulated volume of water as seepage from Wadi Ham recharge dam.

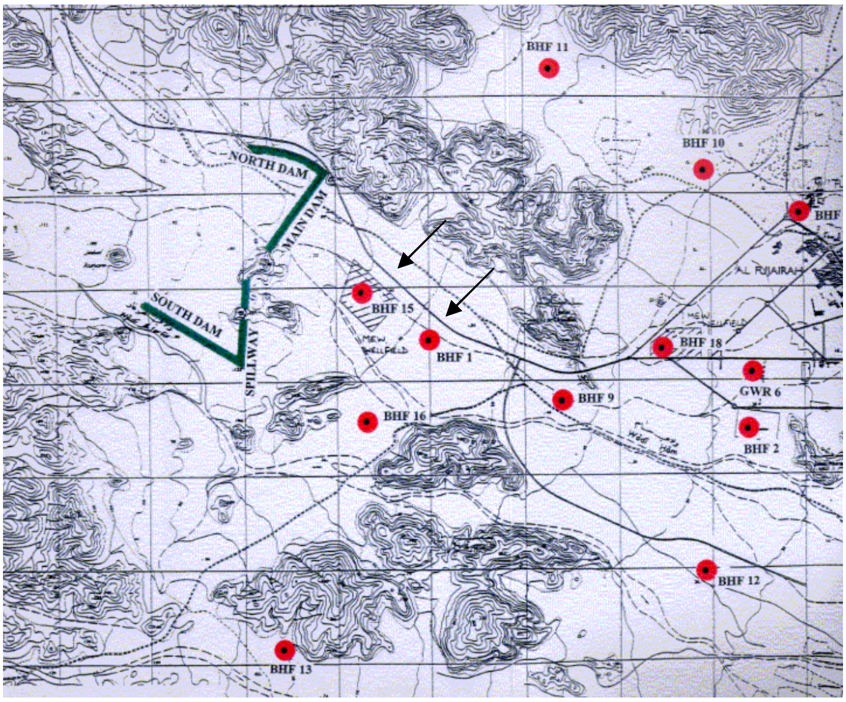


Figure 7.37 Location map of groundwater observation wells downstream of Wadi Ham dam.

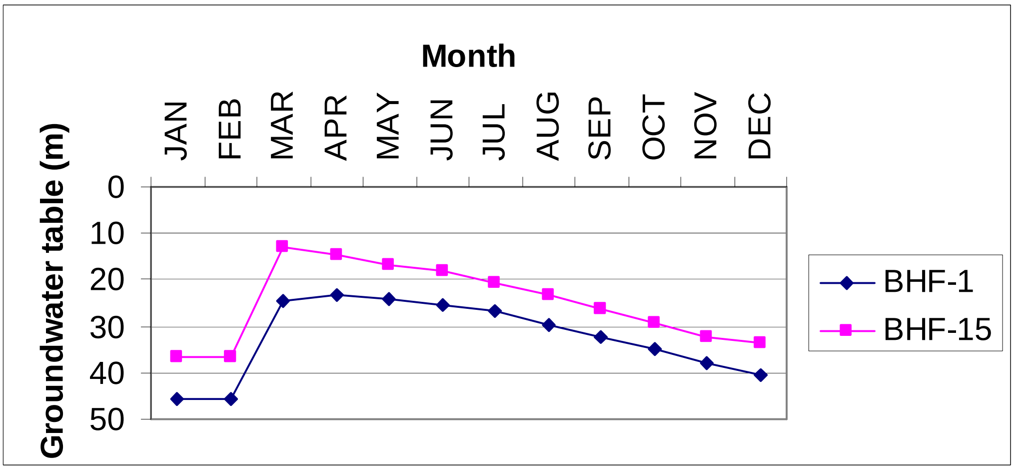


Figure 7.38 Depth to groundwater table in observation wells BHF-1 and BHF-15 in 1988 downstream of the Wadi Ham recharge dam (MAF, 1998).

7.7 Wadi Ham catchment management scenarios

Having successfully calibrated and validated SWAT against measured runoff data and demonstrated the realistic simulation of many other hydrological processes within the catchment (e.g. crop growth, sedimentation, irrigation, recharge etc.), SWAT has been used to simulate the effects of two management scenarios that have been proposed or applied in the Wadi Ham catchment:

1. The effect of an additional dam on the main dam reservoir sedimentation.
2. The discharge of treated wastewater as a recharge mechanism within the catchment.

The purposes of these simulations are to demonstrate the ability of the SWAT model to be used in conducting different management scenarios related to water resources management and development under arid catchment conditions, and to examine the effect of such scenarios on the water resources of Wadi Ham catchment (Figure 7.39).

7.7.1 Effect of additional dam on main dam reservoir sedimentation

SWAT has been used to study the effect on reservoir sedimentation of the main recharge dam of a new proposed dam within Wadi Ham catchment. The new dam site was implemented at a location suggested by NESPAK (1997) in a study for potential sites for the construction of groundwater recharge and management of water resources facilities in Wadi catchments of UAE.

SWAT was used to simulate the effect of the proposed dam on reservoir sedimentation of the main recharge dam for the flood years of 1987 and 1988. According to the SWAT model results the reservoir sedimentation of the main dam could reduce by 56% in 1987 and 29% in 1988 as result of the construction of the new dam (Figure 7.40)

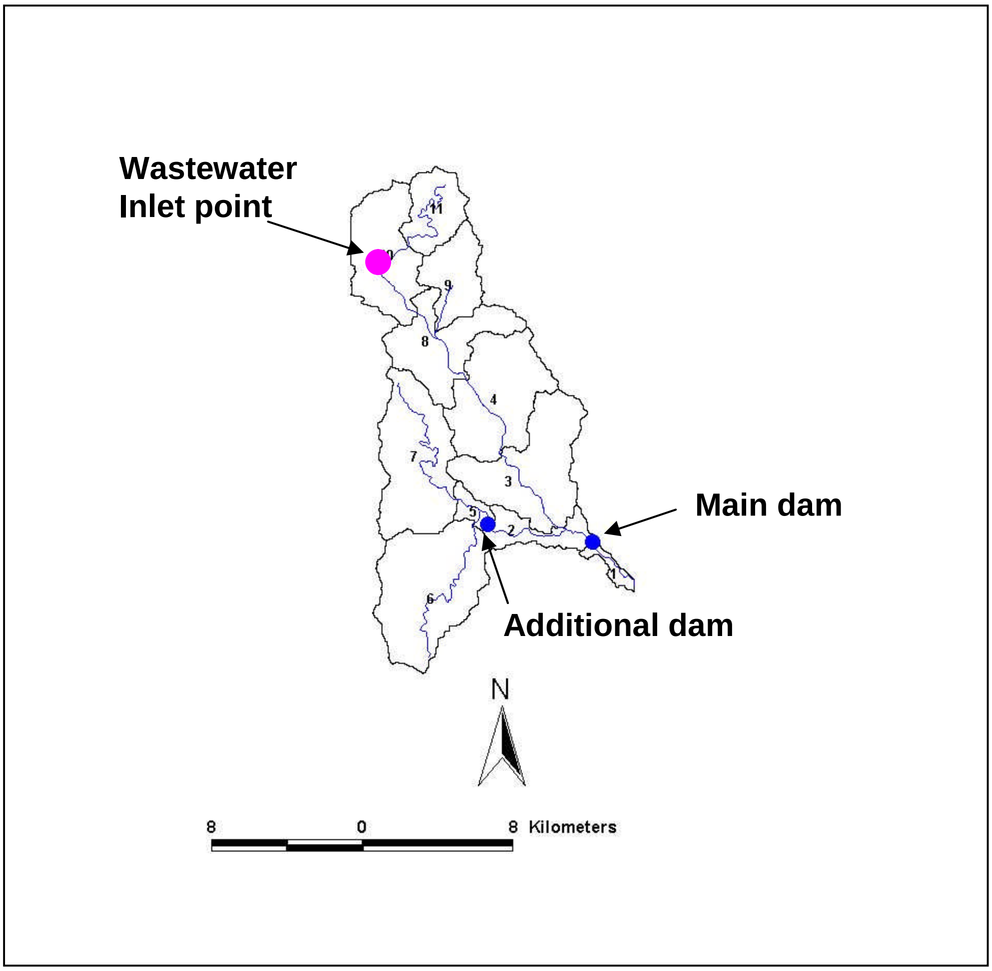


Figure 7.39 Location map of main dam, the additional dam and the wastewater inlet point into the main stream channel of Wadi Ham catchment.

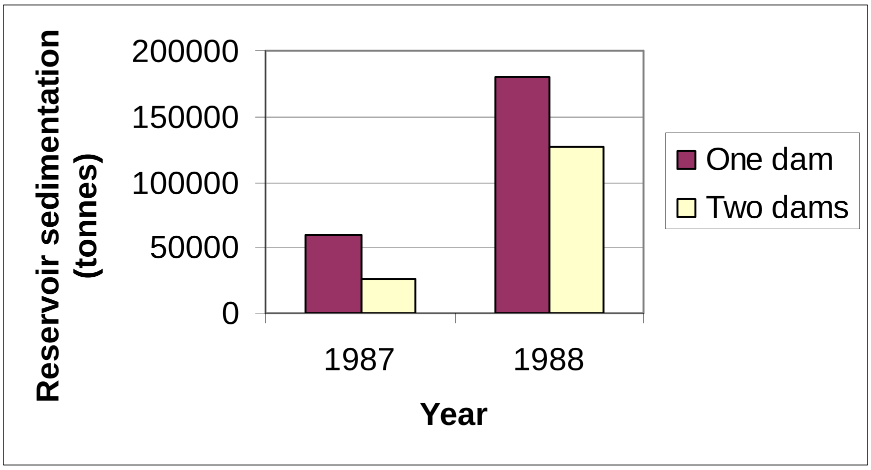


Figure 7.40 Simulated reservoir sedimentation of the main dam in 1987 and 1988 in the case of the existence of the existing dam (one dam) and with construction of a new dam (two dams) upstream.

7. 7. 2 Treated wastewater discharge as recharge mechanism

Groundwater abstraction from wells in the catchment includes the upstream farming areas along the main Wadi stream and its tributaries and the larger farming areas and domestic well fields downstream near the coast. Due to over pumping from the gravel aquifer, which occurs mainly in the downstream areas of the gravel plain, many studies have found a drawdown in the water table in some places (Rizk and Alsharhan 2000; IWACO 1985) and suggested the risk of seawater intrusion into the coastal aquifers (Rizk and Alsharhan, 1999).

This scenario suggests the discharge of treated wastewater, collected from the urban areas near the head of the Wadi Ham catchment, into the main stream channel as an artificial recharge water resource. SWAT can simulate the discharge of water at any point along the channel network (Neitsch et al., 2001). Three daily discharge rates of 0.25, 0.50 and 2 m^3/s were simulated, representing the lower and upper boundaries of the discharge volumes that can be obtained from the urban areas and villages upstream in the catchment. Four years (1985-1988) were simulated; as the first two years are considered dry years, while the last two years are wet years. Figure 7.41 shows simulated recharge volume via transmission losses to the aquifer underlying the main channel.

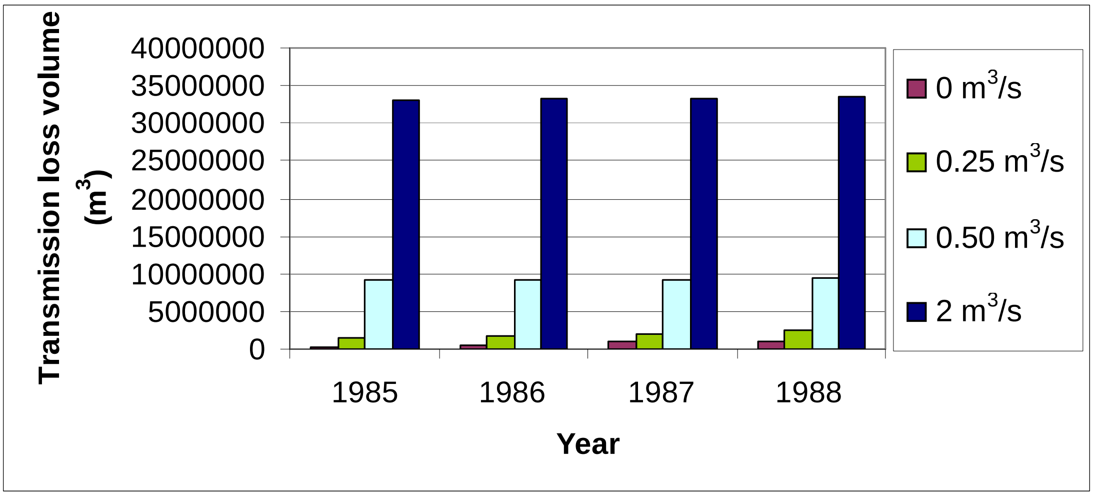


Figure 7.41 Simulated recharge volumes by different discharge rates for sub-basin 4 located on the main stream channel of the Wadi Ham catchment.

From the above results it can be seen that discharge of treated wastewater can provide a constant recharge resource within the catchment, even with minimum discharge rate, that can provide a recharge volume that exceeds the natural recharge in some wet years. The discharge rate of 0.25 m^3/s can provide the total irrigation water requirement for the catchment as simulated by SWAT.

7.8 Summary

From the simulation results of Wadi Ham catchment obtained by SWAT under the data limited condition, it can be concluded that SWAT was able to simulate the surface runoff as demonstrated by the calibrated and validated stream flow at Bithna station. The other hydrological processes were simulated acceptably based on the realistic representation and semi-quantitative validation of the model. On this basis, SWAT has been applied to demonstrate its utility in assessing the possible consequences of two contrasting management options for Wadi Ham catchment

8

Discussion

As demonstrated in chapter 7 SWAT was able to simulate the hydrological processes of Wadi Ham catchment acceptably. In this chapter the discussion will be related to the overall performance and shortcomings of SWAT within an arid Wadi catchment, aspects of data provision in arid region catchment modelling and the future use of SWAT as a management and decision making aid for arid Wadi catchments.

8.1 The structure of the model

The structure of the model is an important criterion in the selection of an appropriate model to be used as a simulation and management tool under a particular set of catchment conditions. Available hydrological models simulate the phases of the hydrologic cycle using either an empirical, semi-mechanistic (conceptual) or fully mechanistic (physically based) approach, while the level of spatial detail for describing the different hydrological processes is either lumped, semi-distributed or fully distributed (Davie, 2003). The SWAT model is described as a watershed scale, conceptual and semi-distributed spatial model that simulates a number of different hydrological processes (Abu El-Nasr, 2005 and Neitsch et al., 2001). Being a comprehensive watershed model, SWAT was able to simulate all of the relevant hydrological processes of the arid Wadi Ham catchment e.g. rainfall-runoff, channel transmission losses, ephemeral streamflow, dam reservoir recharge etc. under the available data conditions. This is because the SWAT model is structured in a way that makes it able to simulate processes related to both perennial streams (e.g. baseflow) and ephemeral streams (e.g. transmission losses). In addition it has flexibility in simulating processes with different alternative methods such as for PET and surface runoff.

The empirical modelling (black box) approach, which is based on using observed data to calibrate simulations, is simple and successful in making predictions by relating a series of available inputs to a series of available outputs under the catchment conditions that have been developed. But their emphasis on data availability is a major limitation for their application in ungauged or data-poor catchments (Marechal, 2004). As a conceptual model SWAT has been shown to be able to adequately simulate and represent all the physical hydrological processes occurring under the catchment conditions of Wadi Ham. The parameterization of the SWAT model for Wadi Ham required the very limited available measured data from the catchment together with supportive information obtained from other catchments under similar condition such as, for example, appropriate Manning “n” value for channel and overland flow from Wadi Surdud catchment in Yemen (Noman and Tahir, 2002).

SWAT is a semi-distributed model which means the model defines hydrological units with similar behaviour in the catchment and groups them i.e. into HRUs. In this way the model simplifies the computation and demands less data input when compared to fully distributed models. Despite this simplification in the representation of spatial heterogeneity, SWAT is able to produce comparable simulation results to a fully distributed model as concluded by Abu El-Nasr (2005). The performance of SWAT was tested with the fully distributed MIKE SHE model for the Jeker river basin (465 km^2) in Belgium. The land use is mainly farmland, and the soils vary from sandy-loam to clay-loam. Analysis revealed that both models were able to simulate the hydrology of the catchment as given by the average daily discharge in an acceptable way, despite the difference in concept and spatial distribution of the models.

Finally, it can be seen that the SWAT structure of a comprehensive watershed, conceptual and semi-distributed model enables it to simulate different hydrological processes occurring in arid catchments, relevant to improved water management decision making. Being a conceptual model it can simulate outside its zone of calibration unlike a black-box model, and dose this as well as more detailed distributed models.

8.2 SWAT conceptualisation

8.2.1 Curve Number method for rainfall-runoff simulation in arid data-poor catchments

SWAT applies the SCS curve number method (SCS, 1972) as one option to estimate surface runoff volume (Neitsch et al., 2001). The method mainly depends on the value of the curve number, which is a function of the soil's permeability, land use, land management practices and antecedent soil water conditions. Default values of Curve Number for different combinations of these properties are tabulated in SCS (1972). This makes the method potentially suitable for use in data-poor regions. It has been stated that the method seems to work best in agricultural watersheds, next best for range lands and worst for forested watersheds (Woodward et al., 2002). Most of the arid region Wadi catchment lands can be described as range lands.

The Curve Number method has a major advantage as concluded by Beven (2001) which is that the original formulation of the method was not on the basis of point scale measurements but directly from small catchment measurements describing the rainfall-runoff relationship. As a semi-distributed model SWAT represents the catchment on the basis of HRU's whose areas are expected to have similar hydrological behaviour within the catchment. This set up makes it potentially suitable for poor data conditions where point data are not available, but more suitable to be used at larger scales such as HRU's. However, a limitation of the method, due to it describing average conditions, could lead to decreases in the accuracy of modelling historical rainfall events that depart from average conditions (ASCE, 1996).

The performance of the Curve Number method for simulating rainfall-runoff in a semi-arid region was evaluated by Michaud and Soroohains (1994). They compared the accuracy of rainfall-runoff simulation using the complex distributed KINEROS model versus SCS model (based on the SCS curve number) in both lumped and distributed mode at the Walnut Gulch experimental catchment (100 km^2) in Arizona (USA). The results suggested that none of the models simulated the peak discharges and runoff volume adequately for the individual 24 thunderstorms with raingauge density of one per 20 km^2, which suggests the difficulty of accurately simulating the arid flash floods with normally available datasets. But they also showed that the calibrated simple distributed SCS curve number-based model proved to be as accurate as a complex distributed model in simulating peak flows and runoff volumes for the events (Michaud and Soroohains, 1994).

The accuracy of surface runoff simulation by CN method in arid catchments may be affected by the rainfall intensity over the catchment. In arid catchments when rainfall intensity is high, the CN method is reported by Mertens et al. (2002) to underestimate runoff during periods of high rainfall intensities and overestimate surface runoff during periods of low rainfall intensity. For Wadi Ham, it is difficult to have a clear idea about rainfall intensity during the simulation period since the rainfall data is on a daily basis, but since intensive rainfall is common in the region it can be observe that for the calibration period SWAT under estimated the runoff volume during the events of February and March 1982 that can be related to the high intensity of these rainfall events.

Another issue that may affect the accuracy of runoff simulation by CN method in arid Wadi catchments is the vegetation interception of rainfall. The CN method always approximates the initial abstraction (I_a), which includes interception from rainfall, as 20% of the retention parameter (s). In arid Wadi catchments of the UAE, the natural range land vegetation is highly patchy especially during the early period of the rainy season as opposed to the continuous nature of the United States range land vegetation where the CN was developed originally. Furthermore, in the summer season the Wadi catchments suffer from a lack of ground cover until the rainy season when the vegetation emerges.

The generation of surface runoff in arid regions is due to the infiltration-excess mechanism, although the basis of surface runoff generation in the CN method is consistent with both infiltration-excess and saturation-excess theories (Lyon et al., 2004). Mishra and Singh (2004) stated that the method in its current form is not suitable as an infiltration model from which to derive infiltration-excess runoff. However, they have found that the existing CN is applicable to a given rainfall–runoff event in a watershed if the watershed's potential maximum retention parameter S, is less than, or equal to, twice the total rainfall amount. This observation is found to be applicable for Wadi Ham surface runoff generation from a given rainfall event for the land use dominated with natural vegetation.

Based on the scale which curve number represents and the available tabulated curve number values, the method is a suitable choice for data poor conditions. Also it can be stated that the performance of the SWAT model for rainfall-runoff simulation under the case study catchment condition using the curve number produced acceptable simulation performance (NSE of 0.78 and 0.57 for calibration and validation respectively).

8.2.2 Crop parameterisation

A plant database for crop parameterization that corresponds to appropriate plant species, local climatic conditions and agronomic practices is essential for correct plant growth simulation. Breuer et al., (2003) overviewed plant parameters comprehensively and constructed a database of plant parameter values for temperate climates to be used in hydrological models including the SWAT model. However, it was found that data for tropical and sub-tropical regions where many of arid region crops originate (e.g. date palm) is comparatively difficult to find in the literature.

Based on a sensitivity analysis for parameters governing the plant growth in SWAT model conducted by Kannan (2003) in a UK catchment, the most sensitive parameters affecting crop growth were found to be biomass conversion efficiency, parameters controlling leaf area development, base temperature and optimal temperature. In this research, in the absence of local plant physiological data, default SWAT crop growth parameters were used, which resulted in temperature stress in all of the simulated plants. This affected the proper growth and biomass production of the simulated plants under the arid catchment conditions. This indicates that temperature is a key parameter for proper simulated plant growth under arid conditions.

In the arid region Wadi catchment, the majority of the catchment is covered by natural range grass. For Wadi Ham catchment, the natural vegetation which covers most of the catchment (98%) was represented by the arid perennial range grass of south-western US- SWRN, that appears to be simulated acceptably by the model (chapter 7). This was reflected in the satisfactory simulation of the catchment runoff by SWAT. This suggests a weak relationship between surface runoff and the plant cover in the catchment. Since the runoff is generated via infiltration-excess mechanism, the effect of the plant cover in the catchment on the antecedent moisture condition of the catchment has little effect in simulating the surface runoff.

From the model plant growth simulation results (chapter 7), the necessity to have correct parameterisation data of some key plants under the condition of arid region catchments can be seen. The simulation of irrigation water abstraction within the catchment is affected by the quality of growth simulation of the irrigated crops (trees, forages and vegetables). The proper parameterization of plant growth under arid region conditions will lead to accurate simulation of plant growth, that gives higher confidence in the overall model outputs as they will be based on a proper hydrological modelling of all components of the plant, soil and atmosphere relationships and this provides a robust tool for assessment and prediction of impacts of different land management practices within arid Wadi catchments.

8.2.3. Groundwater recharge via transmission losses

As demonstrated in chapter 2, natural groundwater recharge in Wadi catchments occurs mainly by transmission losses through the Wadi beds and as direct rainfall-recharge in the alluvial material in the lower Wadi plains. The

SWAT model has components to simulate the above mechanisms. It estimates transmission losses using Lane's method and percolation of water into the soil profile after input of water via precipitation or irrigation (Neitsch et al., 2001).

SWAT uses Lane's method as described in USDA Soil Conservation Services (1983) cited in the model manual (Neitsch et al., 2001). Water losses from the stream channel are a function of channel width, length and flow duration. This method was developed using an ordinary differential equation with empirical and statistical techniques and the SCS method, to study transmission losses in 14 channels reaches in Arizona and Texas (USA) and was recommended for use in small semi-arid watersheds (El-Hames and Richards, 1994). To assess the transmission losses from Wadi Ham estimated by SWAT using Lane's method, the values were compared with transmission losses from other arid catchments. Data on transmission losses published by Walters (1990) including data published by Lane (1983) were used and compared with mean first-mile losses of sub-basin 10 of Wadi Ham catchment as estimated by SWAT. The transmission loss for the first-mile is a method to standardise the data as shown by Jordan (1997):

$$V_1= V_A\ [1- (V_x/V_A)^{1/x}]$$

Where V_1 is the loss in the first mile (acre-ft); V_A is the flow volume at the upper station (acre-ft) and V_x is the volume of flow (acre-ft) at distance x in miles.

Table 8.1 shows calculated mean first-mile transmission losses calculated for sub-basin 10 for 1988 compared with published data from arid catchments in Saudi Arabia and the USA. Figure 8.1 shows that the relationship between calculated mean first-mile transmission losses and upstream flow volume for the reach of sub-basin 10 using the SWAT simulation results for Wadi Ham are well within the limits of other similar arid catchments.

Table 8.1 First mile transmission losses (TL) from runoff events for different arid catchments (After Walters, 1990)

Catchment	Reach	Reach Length (mile)	Up stream flow volume (acre-ft)	TL1st mile (acre-ft)
USA Walnut Gulch	11-8	4.1	16.5	2.4
	8-6	0.9	13.7	2.5
	8-1	7.8	16.3	4.2
	6-2	2.7	75.1	6
	6-1	6.9	48.3	6.7
	2-1	4.2	49.3	7.6
Qween Creek	Upper-Lower	20	4283	101
Elm Fork	Elm Fork-1	9.6	454	1.4
	Elm Fork-2	21.3	441	0.8
	Elm Fork-3	30.9	451	1
Kansas Neb	Prairie Dog Creek	26	1890	24.8
	Beaver Creek	39	2201	31
	Sappa Creek	35	6189	83.3
	Smoky Hill River	47	1217	16.2
Saudi Arabia	Tabalah-1	27.2	236	1.7
	Tabalah-2	16.6	325	12
	Habawanah-1	12.2	1262	70.2
	Habawanah-2	11.5	157	1.5
	Habawanah-3	22.2	293	3.9
	Yiba-1	20.7	826	38.4
	Yiba-2	6.7	301	29.1
UAE- Wadi Ham	Sub-basin- 10	5.96	26.3	2.2

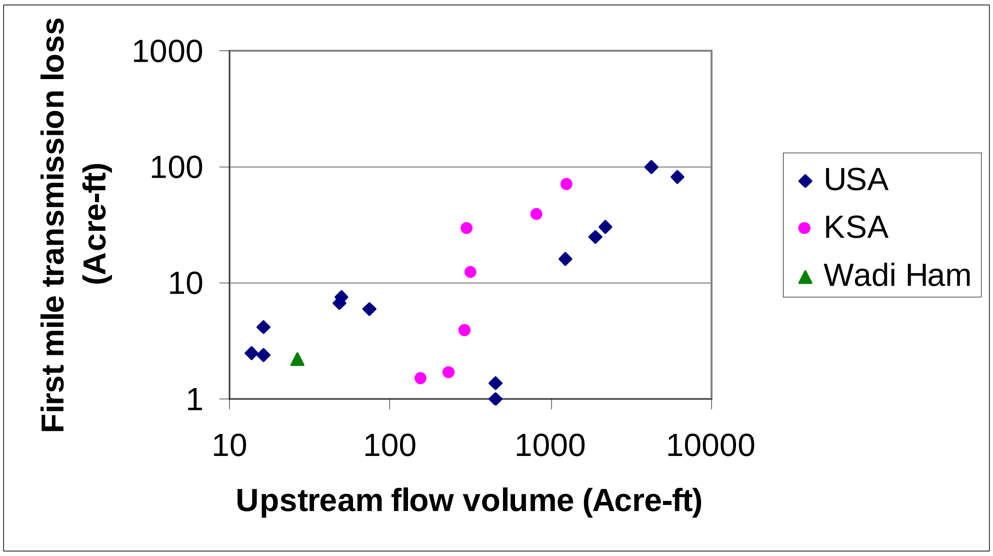


Figure 8.1 Mean transmission losses versus upstream flow volumes for various arid region streams.

Walters (1990) developed a regression equation relating transmission losses to channel characteristics for a single arid catchment in southwest Saudi Arabia. He stated that the following equation can provide reliable estimates for losses associated with large floods:

$$V_1 = 0.0006225W^{1.216}\ V_A^{0.0507}$$

Where V_A is upstream flow volume in (acre-ft); V_1 is the transmission loss for the first mile in (acre-ft) and W is active channel width in (ft).

Applying the above equation to the large flood event that occurred in Wadi Ham in 17/2/1988 using data simulated by the SWAT model, the calculated transmission loss for the first mile for a reach with a channel width of 30.8 ft (in sub-basin 10) is 3.78 acre-ft, while the transmission loss for the first mile calculated by Jordan’s methods based on the outputs of SWAT is 3.52 acre-ft. This indicates that the simulation of transmission losses by SWAT is comparable with arid hydrological conditions observed in the Saudi Arabian catchment.

Overall the standardised transmission losses in Wadi Ham calculated by SWAT compare well with observations in other arid catchments and with other methods, suggesting that this important recharge process is adequately simulated by SWAT

8.2.3.2. Simulation of recharge from the recharge dam reservoir

SWAT provides the user with several options for setting up a dam and reservoir. The model offers three alternatives for estimating outflow from the reservoir. The first option allows the user to input measured outflow. The second option, designed for small, uncontrolled reservoirs, requires the users to specify a water release rate. When the reservoir volume exceeds the principle storage, the extra water is released at the specified rate. Volume exceeding the emergency spillway level is released within one day. The third option, designed for larger, managed reservoirs, has the user specify monthly target volumes for the reservoir.

However, despite these different set-up options, the conceptual model of the reservoir within SWAT is that of a permanent reservoir fed by a perennial river, rather than the ephemeral water body which characterizes a recharge dam reservoir. In simulating the recharge dam reservoir in SWAT, several problems were identified with:

- Dam design;
- Reservoir initialization;
- Leakage.

The first problem relates to representing the recharge dam design in SWAT, as SWAT only allows for a principle spillway and an emergency spillway. The emergency spillway for the Wadi Ham dam can be considered to be at the level of the dam crest (88.5 masl) for very big flood events, while the principle spillway of the dam is composed of two sections both with an elevation of 84.50 masl. However, the Wadi Ham recharge dam also includes two important additional outlets which cannot be parameterised with the above set-up. These two 0.80 m diameter culverts, with intakes at elevations of 78 and 76 masl, are used for controlling and managing the water release from the bottom of the reservoir (Figure 8.2). These two outlets are kept open to continually release water downstream from the reservoir, according to the design report (Electrowatt Engineering Services Ltd, 1981). For the uncontrolled reservoir option which was used in Wadi Ham, when the reservoir volume exceeds the principle spillway volume; the extra water is released at the constant specified rate. However, in the case of the Wadi Ham dam, the water will be released at different rates from three outlets which are the spillway at an elevation of 84.50 masl, the first outlet at an elevation of 78 masl and the second outlet at an elevation of 76 masl.

After trying various options, the Wadi Ham reservoir was modelled in SWAT with the spillway at an elevation 84.50 masl being considered as the emergency spillway from which any volume of additional water is released within one day. The two outlets were considered to be the principle spillways with an elevation midway between the two and the water release rate was specified as the average rate for both outlets. These shortcomings in the dam set-up will undoubtedly affect the accuracy of calculating the reservoir water volume and the rate of water released to the downstream sub-basin from the reservoir.

Figure 8.2 Wadi Ham dam outlet.

The second problem with the reservoir paramterization stems again from the conceptual model of the permanent reservoir SWAT demands that an initial reservoir volume is specified for the reservoir, for which the minimum volume is 100000 m^3. In the arid region, a recharge dam reservoir is usually empty until one of the infrequent run-off an event occurs which is able to start to fill it. To overcome this problem it is important that the warm-up period for the model is sufficiently long to allow the recharge dam to empty, and the effects of the additional recharge induced to the shallow groundwater store by this initial volume diminished. For Wadi Ham dam reservoir, the simulation started in the month of November where an initial volume very close to the SWAT minimum volume was already stored in the reservoir.

The final problem is related to the calculation of the recharge amount from the reservoir, which originates through leakage from the reservoir base. In general, the losses from man-made reservoirs formed by the construction of a dam across a stream valley in the arid region are high due to the significant leakage occurring from the bed and sides of the reservoir (Rushton, 1997). This can be because of the deep water table, which creates a deep unsaturated zone beneath the soil surface and because of the high permeability of bed material that forms from the alluvial deposits. According to the E.E.S., (1980), field testing of the recent and young alluvial deposits in the dam area gave unsaturated hydraulic conductivity (K) values which ranged from 360 mm/hr to 3600 mm/hr on the surface and decreased with depth to a range of 36 mm/hr to 3.6 mm/hr. Further evidence of high K_{sat} values for reservoir bottoms under arid catchment conditions is provided by Al-Turbak (1990). He used K_{sat} = 2.2 mm/hr to simulate the infiltration in a recharge dam reservoir using the Green and Ampt model in central Saudi Arabia.

The recharge from the reservoir is simulated by SWAT as the volume of water lost by seepage through the bottom of the reservoir on a given day by:

$V_{seep} = 240 \,.\, K_{sat} \,.\, SA$

Where V_{seep} is the volume of water lost through the bottom of the reservoir by seepage in (m^3); K_{sat} is the effective saturated hydraulic conductivity of the reservoir bottom in (mm/hr) and SA is the surface of the area of the water body in (ha).

The maximum value for K_{sat} in SWAT is set at 1 mm/hr. This maximum value for K_{sat} is considered to be too small for the material measured at the Wadi Ham recharge dam reservoir and by Al-Turbak (1990). A maximum value of K_{sat} = 5 mm/hr can be suggested to be used in other studies of recharge dam reservoir simulation until a proper value is finalized.

8.3 SWAT model code stability

SWAT is a collection of about 220 computer programs written in the FORTRAN 90 language (Arnold and Föhrer, 2005). This high number of programs results in some model instability and crashes during running because of bugs in the source code of the model. Such problems have been faced by many SWAT modellers e. g. Kannan (2003) who reported bugs in the SWAT source code related to plant growth simulation, soil water routing and root growth. The SWAT user forum (http://sslgtw08.tamu.edu/forum/) contains a lot of such experiences cited by SWAT users.

From the experience of running SWAT for Wadi Ham catchment, the following problems in the code occurred:

- Sudden and repeated crashes of the model during simulation
- Difficulties in adding new crops to the SWAT data base.
- Miscalculation of the average slope length (SLSUBBSN) parameter for some of the sub-basins

- Difficulties with the irrigation application; SWAT ceased the irrigation application after the first year during the simulation and kept irrigating the crop after kill and harvesting operation.
- Crop auto fertilizer option doesn’t work.

The previous problems were overcome either by personal communication with the developer to provide a corrected .exe file such as for crop database and irrigation auto application or by trying alternative data input, such as for SLSUBBSN parameter, where a new temporary model set up with a higher number of sub-basins is created. In this way the original sub-basin were subdivided to many sub-basins in the new set up. The value for SLSUBBSN parameter that occurred in these sub-basins were averaged and used as an input for the related sub-basin in the original model set up.

8.4 Data availability issues

Data availability is a major issue for all water resources assessment, development and management activities. In arid region hydrological modelling, the quality of data can have a greater effect on the accuracy of results than the quality of the model used (Pilgrim et al., 1988). Thus, the paucity of available data constitutes the greatest problem in arid region hydrological modelling.

8.4. 1 Rainfall data requirements

In hydrological modelling, rainfall is the primary input. The problem of interpolation of point raingauge data to estimate spatial rainfall over a catchment is well recognised among modellers (Beven, 2001 and Wheater et al., 1991). Such problems can be particularly obvious in arid regions where 10 km inter-gauge spacing is still not adequate for the representation of spatial rainfall variation (Wheater, 1991a and Wheater, 1991b) as illustrated in chapter 2. Allthough the SWAT model was able to produce an acceptable rainfall-runoff relationship, based on the calibration and validation performed at the Bithna runoff gauge station (chapter 7), the sensitivity analysis (chapter

6) showed that the SWAT model outputs are sensitive to the number of raingauge stations in the catchment. According to Arnold (2006) (personal communication), for each sub-basin, AVSWAT assigns the data from the raingauge that is nearest to the sub-basin centroid. This can also explain the sensitivity of SWAT outputs to the input DEM resolution and the number of sub-basins delineated within the catchment. Both the DEM resolution and number of sub-basins affect the boundaries and area of each sub-basin within the catchment and thus the particular raingauge that is assigned to a given sub-basin. Thus the more raingauges providing input data to the model, the better the representation of spatial rainfall variability over the catchment. Alternatively, the introduction of areal rainfall interpolation techniques such as spatial methods e.g. thiessen polygon, isohyetal method (Shaw, 2002), or an altitudinal correction technique (Brunsdon et al., 2001 and Smith, 1976) can improve the association between the raingauge, point measurements, and the derivation of the areal rainfall over the catchment. Another alternative for modelling the highly spatial variable rainfall over Wadi catchments is the use of rainfall radar data (Lange et al., 1999).

Another problem which appears to affect the runoff hydrograph is the relative timing of rainfall and runoff events, associated with the time of the rainfall data collection. Figure 8.3 shows that the surface runoff hydrograph is lagged by one day compared to the observation data. SWAT uses daily rainfall which is assumed to occur between 00:00 to 23:59 as an input for the Curve Number surface runoff simulation (Neitsch et al., 2001), whilst daily rainfall measurements are taken from 08:00 to 08:00. In the arid region where convective rainfall occurs as short events, the timing of such events by conventional manual raingauges can be subject to error, since the amount of rainfall which falls in the early morning (before 08:00) will be added to the previous day's rainfall record. This can affect the response of the simulated runoff hydrograph and its relationship with the observed one. It may cause a shift between the simulated and observed runoff due to the differential time between when the model assumes the rain falls and when it actually does.

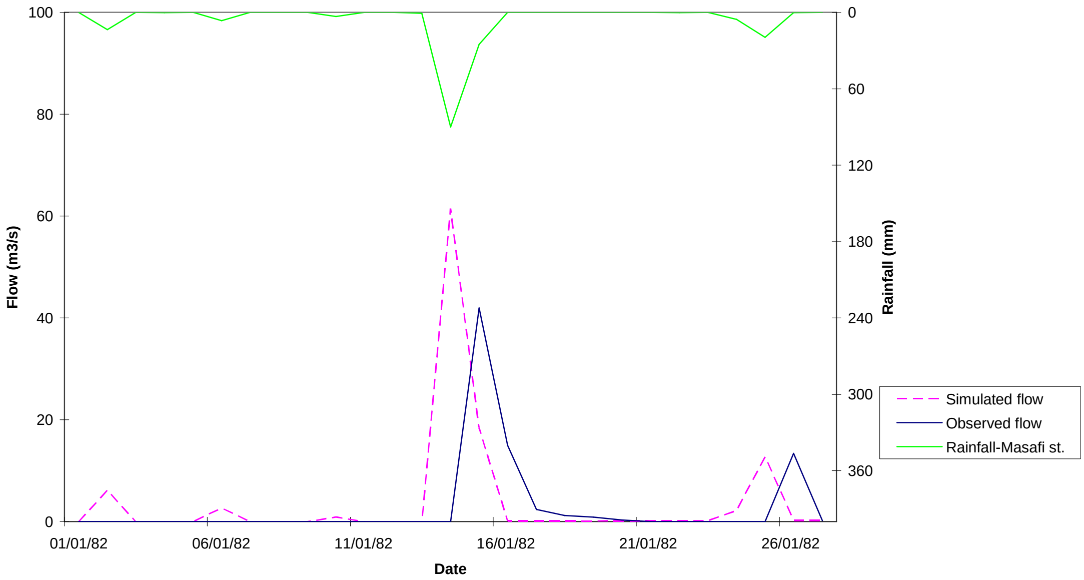


Figure 8.3 Time shift between simulated and observed stream flow at the Bithna flow station in Wadi Ham.

8.4. 2. DEM data requirements

DEM data in developed countries are available at different, but generally high, resolutions, for example 25 m in Switzerland; 30 m in USA; 50 m in UK and France (Beven, 2001). In the case of developing countries, many of which are in arid regions, the availability of high resolution DEM data can be very limited. It has been shown in the sensitivity analysis in chapter 6, that the globally available, but low resolution, DEM datasets such as HYDRO-1k are inappropriate for SWAT modelling. But, this situation could be improved by generating finer resolution DEM from different sources such as aircraft or satellite derived stereo image DEM using photogrammetric analysis techniques (Aguilar et al., 2005; Buyuksalih et al., 2005 and Cuartero et al., 2005) or by aircraft-borne laser altimetry (Vosselman et al., 2005). Another alternative is the Shuttle Radar Topography Mission (SRTM) DEM dataset which provides 3 arc second (90 metre) SRTM "Finished" data covering the globe between 60 degrees N and 56 degrees S latitude(http://edcwww.cr.usgs.gov/srtm/index.html). The use of such DEM source data as an input can have a good potential for hydrological modelling as demonstrated by Bundela (2004).

Since the resolution of input DEM data has a major affect on the uncertainty of hydrological model outputs (Chapter 6), Cotter et al. (2003) recommended that the minimum DEM data resolution should range up to 300 m for the SWAT model. Chaubey et al. (2005) on the basis of their analysis concluded that the minimum input DEM data resolution for SWAT should range from 100 to 200 m to achieve less than 10% error in the SWAT output for stream flow. However, based on results obtained from the sensitivity analysis of SWAT input DEM resolution in this research work (chapter 6), it can be concluded that for arid mountainous catchments, a finer minimum input DEM resolution of no more than 100 m is needed for simulation in SWAT.

8.4. 3. Soil mapping

At the outset of this project, there was no soil map available for Wadi Ham. The development of a soil map for the Wadi Ham catchment was based on DEM data as the main input, with properties for the different soil types derived from published literature. The accuracy of DEM-derived products depends on a number of factors, such as the horizontal resolution and vertical precision at which the elevation data are represented, the source of the elevation data including the techniques for measuring elevation, the algorithms used to calculate different terrain attributes and the topographic complexity of the landscape being represented (Thompson et al., 2001). Boer et al. (1996) reported an attempt to develop soil maps for two semi-arid catchments in south east Spain, where terrain attributes derived from a digital elevation model at 30 m resolution were used with a modest set of georeferenced field soil plot observations to predict soil depth classes across three lithological units with different terrain characteristics. Results showed accuracies ranged from 40% to 81% for soil depth classes predicted for the different lithological units. According to the conclusion, the spatial variation of soil properties that can be detected at a specific spatial resolution and which can be explained by topographic variation depends on

(1) spatial scale of topographic variation in the catchment;
(2) the nature of processes that cause the spatial variation in soil depth in which these processes depend on topography as the driving force;

(3) the degree to which the terrain-soil relationship has been disturbed by human land use.

In chapter 5, the soil map for the case study (Wadi Ham catchment) was developed based on a conceptual understanding of the distribution of the different soil types in relation to the topographical exposures extracted from DEM data of the catchment. The derived soil map was intended to only show the distribution of soil thickness and soil texture classes within the catchment. The soil map was linked to knowledge extracted from the 1:5,000,000 scale FAO-UNESCO (1974) soil map and the 1:5,00,000 scale soil map in the national atlas of the UAE (UAEU, 1993). From the overall modelling results (chapter 7), the approach seems to have produced an acceptable overall representation of the soil hydrological response and erosivity of the catchment, but the accuracy of the spatial soil distribution within the catchment cannot be ascertained.

However, accurate representation of a catchment's soils can lead to better simulation results due to the hydrological importance of the soil units in the SWAT model e. g. Curve Number values for different soil types in the simulation of rainfall-runoff (Romanowicz et al., 2005). Thus better soil mapping techniques can be proposed, based on remote sensing (Scull et al., 2003) or combination of remote sensing and DEM data (Ryan et al., 2000). Remote sensing can provide a spatially contiguous quantitative measure of surface reflectance, which is related to soil physical properties i.e. particle size and surface roughness and chemical properties i.e. surface mineralogy, organic matter and moisture content (Scull et al., 2003). Literature provides successful attempts to develop detailed soil maps using Landsat TM images and topographic data for arid and semi-arid areas (Ziadat et al., 2003), which have the advantage of relative cloud-free remote sensing images.

8.5 Applicability of SWAT model for arid region catchment simulation and as a management tool.

SWAT is a continuous time model that was developed to assist water resource managers in assessing the impact of management and climate on water supplies and non-point source pollution in watersheds and large river basins (Arnold and Fohrer. 2005). It has been applied in many different climatic regions, such as temperate (e.g. Bosch et al., 2004), cold (e.g. Huisman et al., 2004) and semi-arid regions (e.g. Muttiah and Wurbs, 2002).

This current study is considered to be the first attempt to apply SWAT for arid region catchment simulation with data scarce conditions. The successful calibration and validation of the model suggest the potential utility of SWAT in arid regions. Based upon its use in this study, SWAT can potentially be used as a management tool in arid region catchments to support sustainable land and water management in a number of ways, informing:

- engineering and planning;
- water resources management, and;
- water policy and land use management.

SWAT can assist in locating major groundwater recharge dam sites in a catchment or locating small check dams to control flood volumes or to create small surface water bodies as water harvesting facilities for small agricultural areas in a catchment. Check dams can control the sediment volume that is transported downstream to the main dam, which is major problem affecting recharge dam efficiency (Benbiba, 2002). The sedimentation process decreases the infiltration rate and storage capacity of the dam. For example in the Al-Kabir wadi recharge dam in Oman which has a storage capacity of about 0.5 million m^3, the sedimentation volume reached 110,000 m^3 within five years of operation. The identification of suitable locations for the construction of a check dam can be assisted by SWAT by identifying spatially within the catchment, the sub-basin or sub-basins which deliver the highest sediment loads to the recharge dam facility. A similar management approach has been used by Mishra et. al. (2003) who used SWAT to model the effects of check dams constructed in the semi-arid Banha watershed (16.95 km^2) in India as onstream reservoir type impoundment structures. Results showed a 70% sediment reduction from the watershed due to check dam construction. Similarly, this current study shows that a single check dam in Wadi Ham was able to reduce annual sediment delivery to the main reservoir by 56 to 29%. However, utilisation of SWAT is dependent on the spatial and attribute quality of the soil map which determines the soil erosivity within the MUSLE to derive erosion within SWAT. Thus, accurate soil map development for Wadi catchments is an essential input into SWAT for such management scenarios to be confidently simulated.

There are examples in the literature of the use of SWAT to model the effects of land use management (e.g. proceedings of the second and third international SWAT conferences). For example, Pandey et al. (2005) implemented SWAT to evaluate the use of different tillage practices of disc plough, mouldboard plough and field cultivator compared to conventional tillage in generating sediment and pollutants in the agricultural Banikdih watershed (89.5 km^2) of eastern India; Varanou et. al. (2003) used SWAT to study the effects of land use change, by implementing different deforestation scenarios, on the daily and monthly total discharge in Pinios river chatchment (2796 km^2) in central Greece; while Lenhart et al. (2003) used SWAT to study the effect of land use change and average field size scenarios in Dill catchment (70 km^2) in Germany on sediment yield and nutrient concentration. In arid regions as discussed in chapter 4, the expansion of the irrigated agricultural areas within recent years has severely affected the water resources of many catchments i.e. Saudi Arabia (Abderrahman, 2005) and Yemen (Al-Sakkaf et al., 1999). This land use change has had consequent effects on groundwater quantity by lowering the water table and quality due to salinity intrusion. The effect of landuse change can be simulated and evaluated by SWAT model (Qi and Grunwald, 2005 and Santhi et al., 2005). As a continuous model, increasing irrigated areas can be simulated within a catchment, so that SWAT can estimate the irrigation requirements and future abstraction from the groundwater aquifer which can aid in management and decision making. Furthermore, this can be enhanced by coupling the SWAT model to a specific ground water model (Sophocleous et al., 1999).

Furthermore the development of crop parameterisation data for the arid region in the SWAT database can help in applying scenarios of different cropping patterns and combinations that can lead to better agricultural practices. This can be achieved by conducting scenarios of growing different crops or different cropping patterns within the catchment and evaluating their effect on irrigation requirements and groundwater abstraction for a number of simulated years including dry and wet years.

For many arid catchments, water resource plans and policies have not been implemented or developed. In such regions, SWAT can be used as a decision support tool to assist the decision makers in designing and implementing policies that lead to better water resources usage. The model can aid in estimating applied irrigation water for different crops and in different locations in the catchment. Also it can be used to estimate the amount of groundwater abstracted for irrigation purposes in unmonitored areas. Such information is a vital input for decision making and policy implementation since it improves the understanding of the current situation. Pappagallo et al. (2003) attempted to use SWAT to analyse the human impacts of intensive agriculture practices on water resources quality and quantity in the Celone Creek basin in Italy. They confirmed the reliability of SWAT outputs in comparison with their available experimental data. They concluded that decision making has been supported by defining, within the modelling, the location and types of activities which are damaging to water resources and ecosystems. This helps to identify the most effective rehabilitation works and the most economical approach.

As well as helping to inform the development of current to medium term policy, SWAT can also be used to inform longer term policy or to help make current policies robust to future change. SWAT has been involved in many climate change studies e. g. Arnold and Föhrer (2005); Jha et al. (2004); Bouraoui et al. (2004); Eckhardt and Ulbrich (2003) and Fontaine et al.

(2001). As demonstrated by Abderrahman and Al-Harazin (2003) climate change can have a great effect on reference crop evapotranspiration, irrigation water demands, soil salinity and desertification in the Arabian Peninsula. Since they studied this impact based on point data, SWAT can be proposed to study climate change impacts on different hydrological cycle components at the catchment scale in such arid areas.

9

Conclusion and recommendations

9.1 Conclusions

The overall aim of this study was to assess the feasibility of using an available watershed scale hydrological model for integrated simulation and Wadi management under arid, data-poor catchment conditions in the Arabian Gulf Region. The Wadi Ham catchment, located in northeast UAE, was selected as a representative catchment because of its relative availability of data and being facilitated with a recharge dam. A review of the hydrological processes occurring under arid catchment environments identified a range of important processes or characteristics which needed to be taken into account by the hydrological model used. These were the spatiotemporal representation of rainfall over the catchment; the high potential evapotranspiration; ephemeral surface runoff in the form of flash floods with the chance of partial-area runoff occurrence; high soil erosion and sedimentation rates; transmission losses that are associated with stream channel flow and are an important recharge mechanism within Wadi catchments and finally the groundwater recharge from the bottom of recharge dam reservoir which is an important further recharge mechanism in many Wadi catchments in the Arabian Gulf region.

Based upon the review of hydrological processes, previous modelling approaches taken in arid regions and the aim and objectives of this research project, a list of model criteria were developed to aid in the selection of an appropriate model. The main criteria were:

1- The model should simulate ET, rainfall-runoff, transmission losses, catchment erosion, channel and reservoir sedimentation, reservoir performance and groundwater, as well as crop growth and irrigation practices.
2- Be physically or conceptually based and semi-distributed.

3- Be able to be parameterised and validated with the limited datasets typically available in arid region Wadi catchments.
4- Have a daily time-step in order to capture the short timescale runoff events
5- Have been used in a wide range of climatic regions, especially arid region or semi-arid regions.
6- Be able to predict the effects of different land management practices (such as land use change), excessive groundwater abstraction and different reservoir operations on water resources within the catchment).
7- The model should be continuous, rather than event-based in order to be used in long term simulation.
8- The model should have a GIS interface to be used in catchment data management and model parameterisation and calibration.

A review of potential models identified the AVSWAT GIS interface version of the Soil and Water Assessment Tool (SWAT) model as an appropriate watershed scale model that satisfied all of the listed criteria, in addition to the availability of its source code for any future development and the existence of an active user group for providing technical support. This study represents the first application of AVSWAT in both a truly arid environment and in the mountainous arid Wadi catchments of the Arabian Peninsula.

The necessary data to initially parameterise SWAT were either directly available or could be derived from the SWAT databases. The main exception to this was spatial and property information for the soils of the catchment. A landscape-based soil map for the Wadi Ham catchment was developed based on a conceptual understanding of soil development and distribution in the catchment. The properties for the resulting different soil types were derived from published literature.

As this was the first application of SWAT in an arid environment, a detailed sensitivity analysis of the effects of a range of soil and channel parameter values and model set-up on total runoff, maximum runoff and days of runoff was conducted using a simplified spatial representation of the Wadi Ham catchment of a single soil and vegetation type. The previous flow characteristics are most important features of arid catchment hydrology. The analysis showed that a DEM resolution of no more than 100 m should be used for proper representation of such mountainous catchments, which is of finer resolution than that suggested by previous researchers elsewhere. As sub-basin size has been previously found to be a critical parameter in AVSWAT model results, the sensitivity of the model outputs to the size of defined sub-basins showed that no more than 18 km^2 is an appropriate size for such a catchment. Compared to previous sensitivity analyses in temperate climates, a different range of input parameters were shown to be sensitive under arid conditions. The parameters that affect the ephemeral streamflow in Wadi Ham are mainly related to the soil and channel properties of the catchment. The most sensitive parameters are the soil depth, soil available water capacity, soil bulk density, soil clay percentage, soil curve number, baseflow recession constant and channel effective hydraulic conductivity.

The sensitivity analysis also showed the need to represent the rainfall with the highest number of available rainfall stations within the catchment. At the moment, SWAT models the spatial rainfall over the catchment by assigning rainfall data from the nearest raingauge to the centroid of each sub-basin. For the highly spatially variable rainfall that occurs over Wadi catchments, a better spatial rainfall interpolation technique is required within SWAT, or the improved functionality of rainfall radar data.

Following the sensitivity analysis, AVSWAT was set-up for the Wadi Ham catchment using the full range of soil and vegetation types and sub-basin configuration. A range of performance statistics were chosen to assess model performance because of their ability to evaluate different features of the calibrated model in terms of its (1) agreement between the average simulated and observed catchment runoff volume, (2) overall agreement of the shape of the hydrograph and (3) agreement of the peaks with respect to timing, rate and volume of the stream flow. For the simulated ephemeral streamflow at the Bithna Station during the calibration period between 1981 and 1982, the DRMS, PBIAS, NSE and PEM were 1.10 m^3/s, 27.12%, 0.78 and 0.80 respectively. During the validation period between 1983 and 1988, the performance statistics for DRMS, PBIAS, NSE and PEM were 0.93 m^3/s, -27.30%, 0.57 and 0.70 respectively. These performance statistics are acceptable results for such limited data conditions and for the model to be used for management purposes. Because the only quantitative time series data with which to validate the model were the observed streamflow data in Bithna, the internal components or processes of the SWAT simulation were compared with available information from the catchment, region or similar studies elsewhere in the region in order to further increase confidence in the model. The rates of simulated reservoir sedimentation, plant growth, irrigation abstraction and groundwater recharge via the transmission losses mechanism all showed very plausible behaviour. However, the analysis of the simulated behaviour of the reservoir of the recharge dam in the study demonstrated that SWAT was not able to correctly simulate the recharge from the bottom of the reservoir as evidenced by water being present in the simulated reservoir for the entire year as against weeks typically in reality. This was attributed to an inappropriate maximum effective hydraulic conductivity defined by the model.

Having established that SWAT could acceptably simulate the components of the hydrology of the Wadi Ham catchment, management scenarios have been simulated in SWAT to demonstrate its potential as a water resources management tool in arid catchments for assessing the consequences of potential management responses. Scenarios of two contrasting management responses were tested within the catchment, which have either been suggested for Wadi Ham catchment or for other Wadi catchments in the region. The first scenario related to the construction of an additional dam upstream within the catchment in order to assess how it would reduce the rates of sedimentation in the main dam reservoir. The second scenario examined how recharge volumes could be enhanced through the construction of a discharge point into the main stream channel for the treated wastewater from the principal town in the catchment. Both scenarios were conducted successfully. The results showed that the new constructed dam reduced the main dam reservoir sedimentation by 56% in 1987 and 29% in 1988 which will lead to higher storage capacity and higher reservoir bottom infiltration rate for the main dam. The second scenario illustrated that treated wastewater can provide a constant groundwater recharge resource within the catchment, even with the minimum discharge rate of 0.25 m^3/s which can be used mainly for downstream irrigation purposes.

Finally, this successful implementation of calibration, validation and scenario simulation in Wadi Ham represents the first use of the SWAT model in a truly arid climate. This research has therefore established the feasibility of using SWAT as a tool for integrated catchment modelling in arid region data-poor Wadi catchments and to support improved water resources management in this water stressed environment.

9.2 Recommendations

On the basis of the results from the application of SWAT in an arid environment, a number of recommendations for future work can be made, including:

- Since this successful application of SWAT is the first use of SWAT under arid conditions and in the Arabian Gulf region, it is recommended that SWAT is applied in further catchments for better evaluation of SWAT performance under arid catchment conditions, preferably with better datasets if possible.

- Because of the uncertain nature of the soils of the Wadi Ham catchment and the high sensitivity of the SWAT outputs to the soil properties, a further study to investigate the effect of spatial soil distribution on SWAT simulation results should be performed. This study could be conducted in a catchment with existing soil data, or with a soil map derived from ground-truthed remote sensing data or by conducting a sensitivity analysis of the spatial distribution of different soil types developed from DEM data.

- Although the simulated crop growth of the natural vegetation and annual crops were acceptable, weaknesses were observed. It is therefore recommended that further work is carried out to better parameterise selected key plants including the natural range plants and the crops (in particular perennial crops such as date palm) under arid catchment conditions. This important contribution will allow SWAT to be used to conduct management scenarios related to changes in land use or crop management in arid catchments.

- Recharge dams are an important and effective facility in many arid catchments especially in the Arabian Peninsula. SWAT demonstrated weaknesses in both being able to represent the range of hydraulic outlets in the dam and the rate of seepage to the underlying aquifer. It is therefore recommended that the reservoir component in SWAT is modified to allow it to better simulate the management of dam outflows and the recharge from the recharge dam reservoir.

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