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Saline Intrusion and Agricultural Water Resource Management, Sultanate of Oman

Number of Volumes: 2

Volume 1

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Year of Submission: 2000

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DURHAM UNIVERSITY

19 SEP 2001

ABSTRACT

Saline intrusion is symptomatic of the water management challenges facing many countries in the arid zone. On coastal aquifers, it results from the over development of limited groundwater resources leading to sea water intrusion. The challenge is to reduce groundwater abstraction to sustainable levels through the adoption of a management strategy.

In developing a management strategy it is necessary to understand the relationship between abstraction and water quality. This study investigated this relationship within the catchments of Wadis Taww and Ma'awil in the Batinah region of the Sultanate of Oman. Over 1994-99 it monitored abstraction, water quality and crops on farms within the catchments. The study also included an investigation of irrigation management on a group of case study farms.

The results confirmed the spatial relationship between rates of decline of abstraction and water quality. They show that abstraction is declining by more than ten percent per year within four kilometres of the coast, due to the loss of cropped area. The rate of decline decreases with distance from the coast and with better irrigation water quality.

The irrigation study confirmed the potential for improved methods and management. It shows that uniformity of application is low on more than 30 percent of sprinkler and bubbler systems and field efficiency less than 50 percent for surface irrigation. The potential improvements include more systematic scheduling of irrigation rates and frequency.

The current trends and the benefit of non-intervention and management intervention, demand and supply, were evaluated using a groundwater flow model. Non-intervention leads to a progressive decline in water use and continued saline intrusion to the year 2041 and beyond. It also shows that high levels of demand management, in excess of a 50 percent abstraction reduction, would be required to significantly reduce the extent of saline intrusion. The development of a supply option, the reuse of treated wastewater for irrigation, reduced the extent of saline by nearly 2 kilometres compared to the non-intervention and demand management cases.

DECLARATION

I certify that none of the material offered for assessment for this award, including my dissertation has previously been submitted by me for an academic award of this or any other University. If material has been generated through joint work, my independent contribution has been identified. In all other cases, material from the work of others has been acknowledged and quotations and paraphrases suitably indicated.

Signature of Candidate.....

Date: 28/09/00

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Most all I thank my wife, Val, for her patience, and material and moral support throughout the seven long years of study, and my seven year old daughter Allie, who has never known a father who wasn't studying for a Ph.D.

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LIST OF ABBREVIATIONS

AWC	Available waterholding capacity
CAC	Command ānd control
CU	Coefficient of uniformity
dSm^{-1}	deciSiemen per metre
EC	Electrical conductivity
ECav	Weighted average annual electrical conductivity per farm
ECe	Soil water extract electrical conductivity
ECw	Irrigation water electrical conductivity
ETc	Crop evapotranspiration
ETo	Reference evapotranspiration
EU	Irrigation efficiency
GIR	Gross irrigation requirements
ha	Hectare
l	Litre
ID	Irrigation depth
ITCZ	Inter tropical convergence zone
Lf	Leaching fraction
LR	Leaching requirements
Kc	Crop coefficient
kPa	kiloPascal
m	Metre
MBI	Market based incentives
NWIP	National Well Inventory Project
Qmax	Water meter maximum flow
Qmin	Water meter minimum flow
Qn	Water meter nominal flow
RO	Rial Omani (RO = $US 2.6)
TDEM	Time Domain Electromagnetic
TDR	Time Domain Reflectometry
μScm^{-1}	MicroSiemen per centimetre

LIST OF ACRONYMS

CCEP	Council for Conservation of Environment and Pollution
CCEWR	Council for Conservation of Environment and Water Resources
FAO	Food and Agriculture Organisation
MAF	Ministry of Agriculture and Fisheries
ME	Ministry of Environment
MEW	Ministry of Electricity and Water
MEWR	Ministry of Electricity and Water Resources
MM	Muscat Municipality
MOC	Ministry of Communications
MOI	Ministry of Information
MPM	Ministry of Petroleum and Fisheries
MRME	Ministry of Regional Municipalities and Environment
MWR	Ministry of Water Resources
NGO	Non Government Organisation
PAWR	Public Authority for Water Resources
UN	United Nations
UNESCO	United Nations Education, Science and Communications Organisation
WRC	Water Resources Council
WMP	Water Metering Project

GLOSSARY OF ARABIC WORDS

aflaj	plural of *falaj*
athar	unit of time for water allocation approximately half an hour
dawaran	rotation of water distribution in the falaj
falaj	system of water extraction and distribution by gravity
gayl	circular basin for the irrigation of tree crops
gelba	square or rectangular basin for irrigation of fodder and vegetable crops
haqq al shafa	customary right of access to water
harim	forbidden, a zone of exclusion around a well or falaj
jebal	mountain
khabir	expert for supervision of water use and distribution at community level
muhab	free to all
mann	bundle of alfalfa of typically 3-4 kg
rhutab	fresh dates
shamal	northerly wind
suq	market place
tamar	form of dried dates
tana	sale of dates on the palm
wakil	local adminstrator nominated by the community
wadi	dry stream or riverbed which carries spate flow
wilayat	administrative boundary
zagira	animal draft well

Note: all local place names in the text and figures have been anglicized and are listed without the definite article (*al*) which would be applied in Arabic.

CHAPTER ONE

INTRODUCTION

1.1. INTRODUCTION

This thesis is a study of agricultural water resources management within a part of the Batinah region of the Sultanate of Oman in the Middle East, Figure 1.1. In particular it is the study of the relationships between saline intrusion, abstraction and water management within the catchments of Wadis Taww and Ma'awil on the southern Batinah.

This chapter presents a brief background to the issues and water management problems being encountered on the southern Batinah that motivated the study. It presents a summary of the three research objectives and associated analyses, along with an outline of the adopted study methods. The chapter concludes with an outline of the thesis structure.

1.2. BACKGROUND

The Sultanate of Oman is located along the southeastern corner of the Arabian Peninsula, bordering the Arabian Sea and neighbouring the Republic of Yemen, Kingdom of Saudi Arabia and the United Arab Emirates, Figure 1.1. The arid climatic conditions of Oman provide limited opportunities for agriculture with less than 62,000 ha of irrigated area (MAF, 1996) which represents less than 1% of the potential cultivable land (MAF, 1992). Historically agricultural development was limited both by water availability and also lack of technology to exploit and pump groundwater. From the 1960s onwards Oman has experienced a period of unprecedented development, including expansion of the agricultural sector, supported with political reforms and funded from new found oil wealth.

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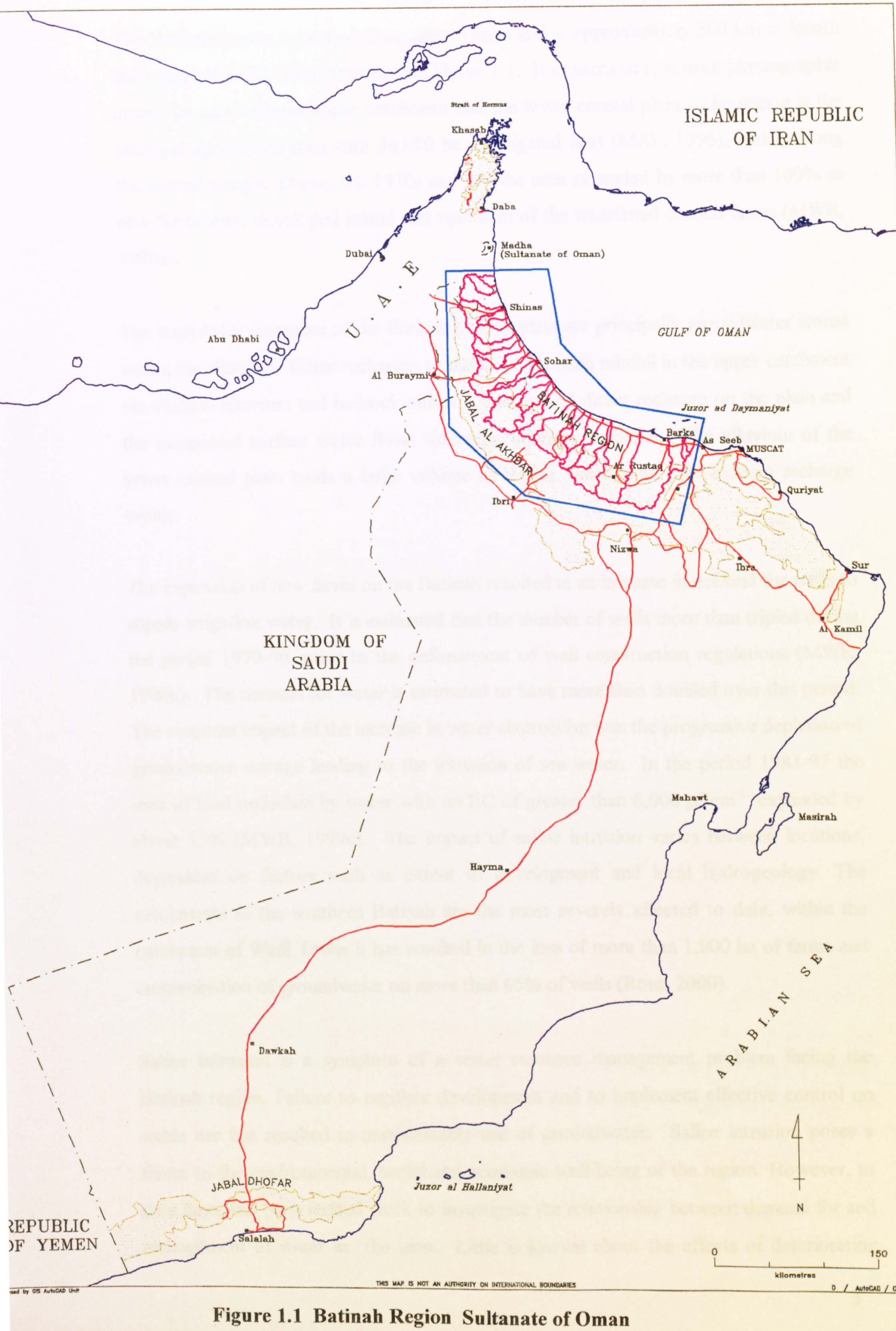


Figure 1.1 Batinah Region Sultanate of Oman

The Batinah region is located in northern Oman and is approximately 300 km in length and ranges in width from 20 to 70 km, Figure 1.1. It consists of two main physiographic areas, the mountainous upper catchment and the lower coastal plain. The region is the principal agricultural area with 36,000 ha of irrigated land (MAF, 1996), mainly along the coastal margin. During the 1970s and 80s the area expanded by more than 100% as new farms were developed inland and upstream of the traditional coastal farms (MWR, 1996a).

The freshwater resources of the Batinah coastal plain are principally groundwater stored within the alluvium. Water recharges to the alluvium from rainfall in the upper catchment via shallow alluvium and bedrock inflows, plus limited direct recharge on the plain and the occasional surface water flows following infrequent rainfall. The alluvium of the lower coastal plain holds a large volume of stored water from pre-modern recharge events.

The expansion of new farms on the Batinah resulted in an increase in demand for wells to supply irrigation water. It is estimated that the number of wells more than tripled during the period 1970-90, prior to the enforcement of well construction regulations (MWR, 1996a). The demand for water is estimated to have more than doubled over this period. The resultant impact of the increase in water abstraction was the progressive depletion of groundwater storage leading to the intrusion of sea water. In the period 1983-97 the area of land underlain by water with an EC of greater than 6,000 μScm^{-1} expanded by about 15% (MWR, 1999c). The impact of saline intrusion varies between locations, dependent on factors such as extent of development and local hydrogeology. The catchments of the southern Batinah are the most severely affected to date, within the catchment of Wadi Tawy it has resulted in the loss of more than 1,000 ha of farms and contamination of groundwater on more than 65% of wells (Rout, 2000).

Saline intrusion is a symptom of a water resource management problem facing the Batinah region. Failure to regulate development and to implement effective control on water use has resulted in unsustainable use of groundwater. Saline intrusion poses a threat to the environmental, social and economic well-being of the region. However, to date there has been limited work to investigate the relationship between demand for and management of water in the area. Little is known about the affects of deteriorating

water quality on abstraction and irrigation management on farms in the Batinah and what impacts these will have on future water resources management. A better understanding of these trends and impacts will provide a basis on which to predict the long-term impact of saline intrusion and the potential to limit or reduce the extent of intrusion.

1.3. STUDY OBJECTIVES

The study and research programme investigated three objectives related to saline intrusion, irrigation management and water management on the South Batinah of the Sultanate of Oman, including:

1) Water Use & Salinity; the relationship between changes in water abstraction and groundwater quality, most notably on farms nearer the coast.

2) Irrigation Management; investigated the efficiency of current irrigation management methods and the potential for improvements in irrigation scheduling.

3) Water Management; the impact of changes in water abstraction on demand and supply management options to reduce the rate of saline intrusion.

The programme comprised documentary study and field research elements and spanned the period Oct. 1993 to Sept. 2000. Virtually all of the programme was carried out in the Sultanate of Oman, apart from three visits to the University of Durham.

1.4. THESIS STRUCTURE

The thesis is presented in the following chapters:

- Chapter 2 Arid Zone and Oman; a review of the principles of water resources management in the arid zone and summary of their development and current status in the Sultanate of Oman.

- Chapter 3 Wadis Taww and Ma'awil; definition of the study area within the catchments of Wadis Taww and Ma'awil and description of the physical and human resources within the catchments.

- Chapter 4 Agricultural Development and Water Management; description of the development of agriculture within the study area and the impact of this development on the water resources as well as the management options implemented or proposed to date.

- Chapter 5 Research Programme; presentation of the study hypotheses, research objectives, research methods and implementation programme.

- Chapter 6 Results; presentation of the results of the programme including trends in abstraction, water quality, crop type and areas, and irrigation methods on samples of farms within the study area.

- Chapter 7 Analysis; the investigation of relationships testing the study hypotheses, including the relationship between changes in water quality and abstraction, at well and farm levels both spatial and temporal. The comparison of water balances for irrigation plots for fodder crops and for sprinkler and flood irrigation. Evaluation of the impact of current trends in water abstraction and demand management options on water management within the study area.

- Chapter 8; Conclusions and Discussion; development of the conclusions of the programme and compliance of study hypotheses and the implications of these to water resource management on the South Batinah.

- Appendices; The thesis is supported and supplemented with an extensive series of appendices providing technical details as well as data and research results.

CHAPTER TWO
WATER RESOURCE MANAGEMENT - ARID ZONE & OMAN

2.1. INTRODUCTION

The arid zone is a grouping of areas and regions defined by climate. While countries within the region are socially, economically and politically diverse they have in common, low annual precipitation. Based on the UNESCO (1977) definition of the arid zone, the region encompasses a significant proportion of the Middle East and North Africa, Figure 2.1. Though definitions of arid and hyperarid vary between sources depending on interpretation of climatic parameters, virtually all classify the Sultanate of Oman as arid.

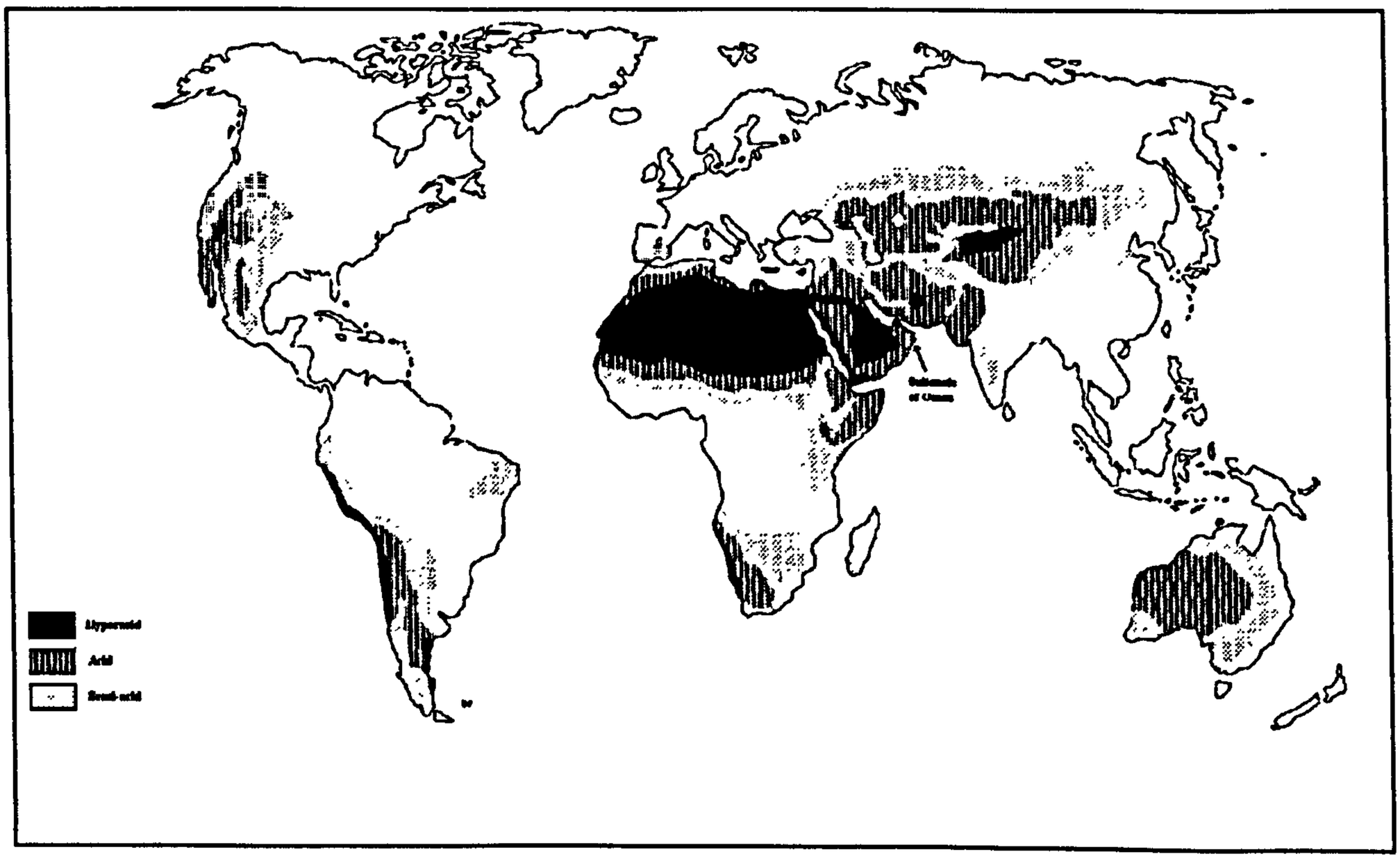


Figure 2.1 Arid Zones (UNESCO, 1977)

Water resource management in the arid zone is characterised by low water availability and, in many countries, increasing demand, due to development and population growth. Most countries within the zone are classified as "water scarce" having less than the equivalent of 1,000 cubic metres of renewable water per person per year (Engelman, 1993). In a number of countries, particularly in the Arabian Peninsula, water demand now exceeds renewable resources. The shortfall in supply is being overcome by various options including utilisation of non-renewable groundwater, desalination and food imports (virtual water imports).

This chapter outlines the main characteristics of water resource management in the arid zone including the hydrological cycle, management strategies and the move to integrated management. As the main focus of the research programme is the impact of saline intrusion on water demand, it presents the theory and principles of demand management in the agricultural sector along with examples of application in arid zone countries.

The chapter concludes with a discussion of the development of water resource management in Oman over the past 30 years. This has included the establishment of government institutions and legislation regulating the access to, and use of water. Over this period a number of projects and programmes have been initiated in an attempt to limit the expansion in demand for water resources and to encourage more efficient water use.

2.2. THE ARID ZONE

2.2.1. Arid Zone Hydrological Cycle

The hydrological system in the arid zone is described as "*intermittent and incomplete in both time and space*" (Agnew and Anderson, 1992). It is characterised by irregular inputs from precipitation and regular outputs to evapotranspiration and direct abstraction, Figure 2.2. Precipitation is scarce, irregular and highly variable both temporally and spatially.

Surface runoff and flow occur during infrequent storms or from aquifer leakage. Infiltration to the aquifer is influenced by the low antecedent moisture levels and surficial material. Flash floods occur during storms, with the loss of surface flow to the sea or to the desert. In some countries, notably on the Arabian Peninsula, man-made dams and structures are used for retention of water, flood control and enhancement of local recharge.

Water loss from the hydrological system results from surface evaporation, evapotranspiration from natural vegetation and direct abstraction from the aquifer. In

many areas direct pumping from the aquifer is the main source of water for agriculture, industry and domestic use.

Management in arid zones includes the modification of infrequent surface flow and the regulation of groundwater abstraction, Figure 2.3. The structure and characteristics of aquifers are often of concern in regulating groundwater use. The impact of the sea and brackish water on water quality are also important considerations.

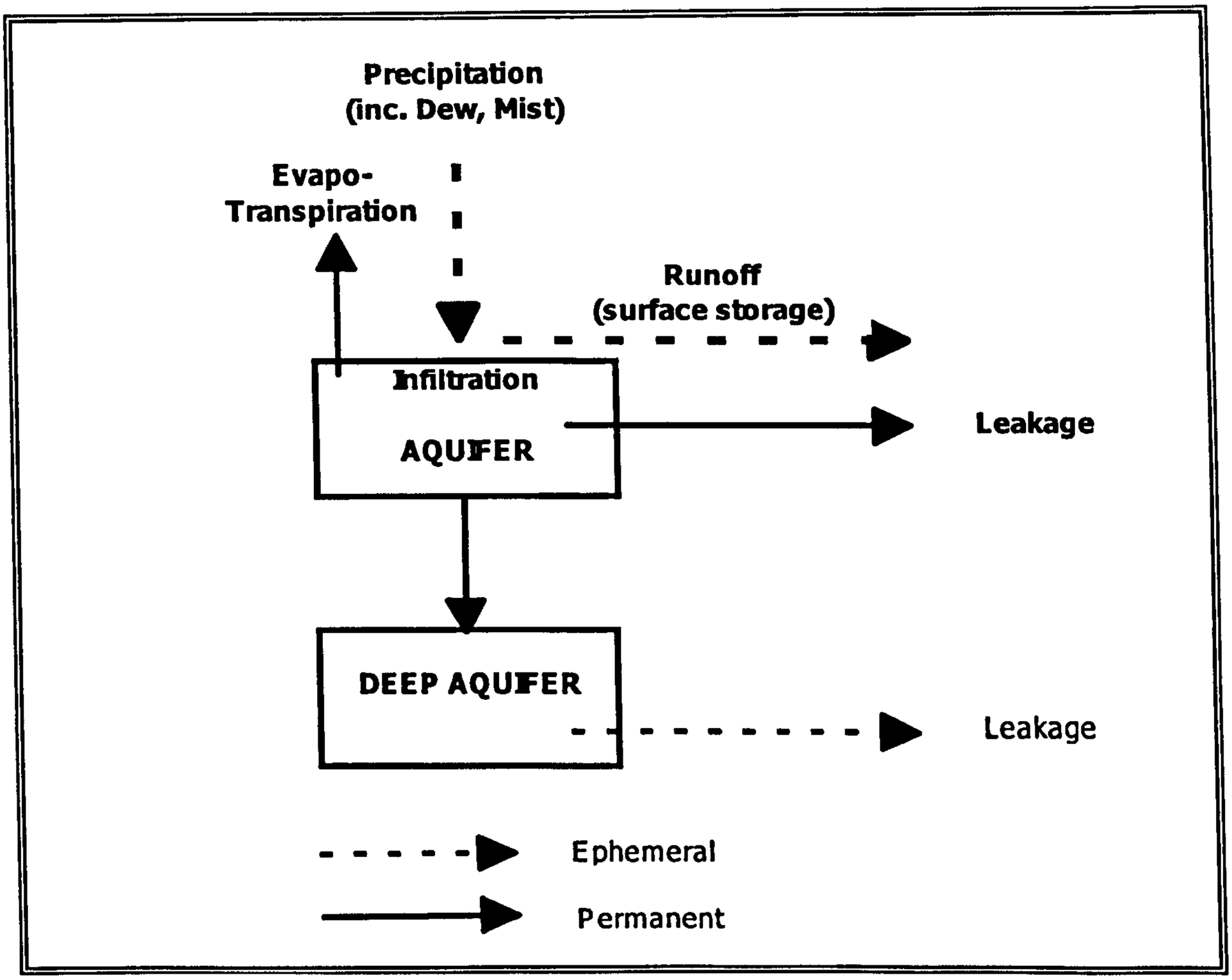


Figure 2.2 The Hydrological System (source: Agnew & Anderson, 1992)

In many areas groundwater is the predominant source of water for consumption and can broadly be classified as renewable or non-renewable. Renewable resources are those receiving recharge during current rainfall events. Non-renewable resources, commonly called "fossil water", are those that have accumulated during pre-modern recharge events and are in some cases many hundreds of thousands of years old.

In some arid zones non-renewable ground water resources play an important role in water management. In the Kingdom of Saudi Arabia for example, it is estimated that 75% of the annual water consumption is from non-renewable resources (Al-Ibrahim,

1990). While in Libya the development of the "Great Man Made River" project is based on the exploitation of non-renewable resources (Agnew et al, 1992). These resources are often classified as a "strategic resource" to be developed under specific economic, social and/or political conditions or for use as an emergency supply. The quantity, location and quality of these resources are important criteria in determining their utilisation.

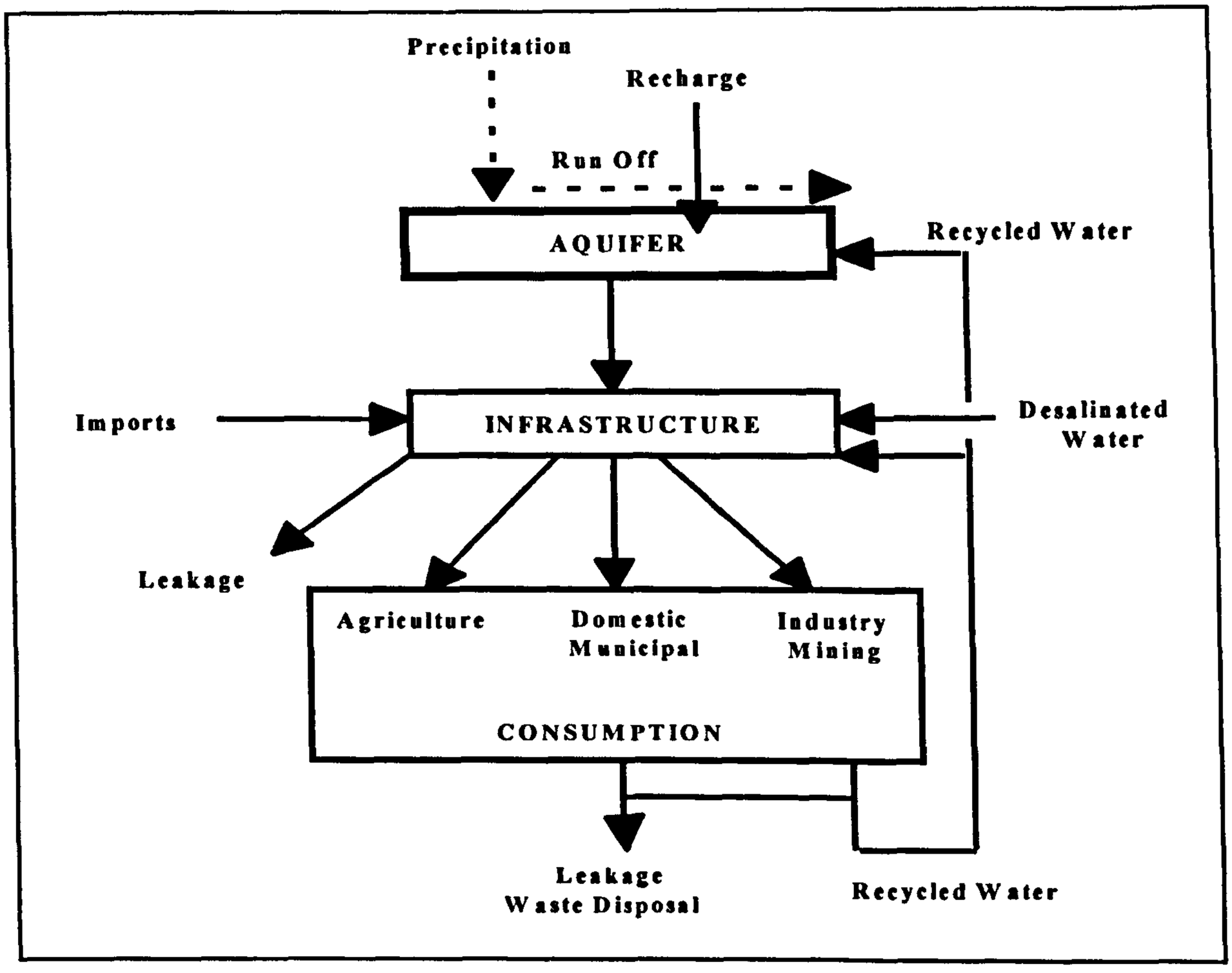


Figure 2.3 Arid Zone Water Management

In some countries alternative water sources are being developed by desalination of sea and brackish water and the direct import of water from other regions. Since the early 1970's in the oil-rich Gulf States of the Arabian Peninsula there has been an increase in the number and total production capacity of desalination plants. In the Kingdom of Saudi Arabia, 1980-1985, annual desalination capacity increased from 63 to 400 Mm^3 (Al-Ibrahim, 1990). The relatively high capital and operating costs usually require state financial support and subsidies and are normally limited to the supply of drinking water.

Agriculture is the major water consumer in virtually all arid zone countries due to the dependence on irrigation and relatively high crop water requirements. The irrigated area

in many of these countries has expanded over the past 20 years. This has been in response to national development programmes with objectives to increase agricultural production and employment as well as to enhance "food security". The expansion has been made possible by improvements in groundwater exploration and exploitation, such as the drilling of new wells and the installation of modern pumping systems.

Domestic water demand is predicted to increase due both to population growth and increases in per capita consumption as a result of improved living standards, as well as to the likely increase in demand for water resources by developing industries.

2.2.2. Open and Closed Water Basins

The river or water basin is defined as "*a geographical area determined by the watershed limits of a system of water, including surface and underground water, flowing into a common terminus*" (World Bank, 1993). Water basins are important from a management perspective, as discrete hydrological units with water sources and water sinks. As illustrated in Figure 2.2, sources include precipitation and in some cases water imports from desalination or other basins (basin transfers). Water losses occur through leakage to the sea, deterioration of water quality to a point where it is no longer useable and evaporation and evapotranspiration. Water recycled either by recharge to groundwater or by reuse of waste water is not lost from the basin. The recycling of water within a basin is an important component of water use and overall water use efficiency.

An open basin is one in which fresh water flows out to a salt sink, either to the sea or to a zone of unusable water (Seckler, 1996). Supply can be increased through the exploitation of water which would otherwise be lost from the basin. A basin is closed when there is no usable water leaving the water basin or water is not usable due to deterioration of quality.

As demand for water within a water basin increases it progressively moves from open to closed. The recycling of water down the basin can result in a deterioration in water quality due to salts and other pollutants. Water is no longer usable when its quality has deteriorated to a point where it is no longer suitable for any use within the basin. A

The effective efficiency within a water basin is a function of the total beneficial evaporation over the total initial freshwater supply. While local efficiency for a particular water use, for example irrigation, may be low, water which recharges back to the aquifer or river can be recovered by downstream users and therefore reused.

As a water basin closes the global effective efficiency increases. While local efficiency of water use may be less than 50%, with the reuse of water down the basin, effective efficiency could be greater than 85% due to water reuse (Seckler, 1996). Within a closed basin effective efficiency can be improved through the reduction in non-beneficial evaporation and reduction in water loss to the sink i.e. reduction in water pollution.

In many parts of the arid zone and in particular the Middle East, water basins are already closed or are progressively becoming closed, due to limited water resources and increasing water demand for domestic, agricultural and industrial consumption. Within the Sultanate of Oman a number of water catchments are effectively closed basins, including catchments on the southern Al Batinah and Salalah coastal plains.

2.1.2. Saline Intrusion into Coastal Aquifers

In coastal aquifers the quality of groundwater can be affected by the intrusion of saline water from the sea. There is a large body of information describing investigations and the processes of saline intrusion. In many regions of the world coastal aquifers have been heavily developed, resulting in the intrusion of seawater. One of the better reported cases is in California (California Department for Water Resources, 1976), where treated wastewater is recharged to create a hydraulic barrier to saline intrusion. There are also numerous other reports on saline intrusion into coastal aquifers in the Middle East, including Libyia (Belaid, 1995), Egypt (Amer, 1995) and United Arab Emirates (Shata, 1995).

A variety of aquifer types may exist at the coast including unconfined, confined, phreatic or multilayer. The interface between freshwater and seawater is dependent on the aquifer type its geometry and hydraulic properties, as well as the rate of freshwater recharge and seawater density (Walton, 1970). Typically it is wedge shaped, with the

denser seawater beneath the lighter freshwater, and the toe of the wedge inland of the tip. The shape and depth of the interface is described by the Ghyben-Herzberg relation (Sherif et al, 1990). Under steady state conditions a stationary interface is maintained, its shape and position being determined by the freshwater potential and gradient (Essaid, 1990). In multilayered aquifers there may be vertical leakage into an overlying seawater zone, creating a zone of non static mixed water.

For undisturbed aquifers, that are not intensively pumped, the immiscible nature of freshwater and seawater may, in principle, create a sharp interface (Amer, 1995). However others describe the interface as a dispersion zone, due to the effects of diffusion and mechancial dispersion (Kohout, 1964). The flux of water is controlled by the hydraulic gradient, while the transport of salt ions is a function of the concentration gradient. Within this zone there is cyclic flow of seawater, from the sea, to the zone of mixing and back to the sea.

The movement of the interface is induced by changes in the recharge and/or discharge within the aquifer. Reductions in freshwater recharge and/or increased discharge cause the interface to move inland and results in saline intrusion. Conversely increases in recharge and/or decreases in discharge cause seaward movement of the interface. The rate of interface movement and the transient aquifer head response is dependent on the boundary conditions and aquifer properties on both sides of the interface (Essaid, 1990). The ease with which saltwater can move into, or out of, and aquifer system affects the rate of interface movement in response to changes in offshore freshwater discharge.

A variety of numerical models have been developed to better understand and predict the processes of groundwater flow and saline intrusion. These models include a range of three-dimensional finite difference and finite element models such as MODFLOW and SUTRA, both of which were developed by the United States Geological Survey (Essaid, 1990). Typically a modeling approach involves the modification of a standard finite difference or finite element code to incorporate additional parameters and equations to quantify density and mixing effects. The applicability of a particular approach is dependent on hydrogeological and data constraints.

2.3. WATER RESOURCE MANAGEMENT

That water is "fundamental to life" is an often quoted truism. This is nowhere more self evident than in the harsh environment of the arid zone, where survival has historically been closely linked to the availability of water and access to it. Because water is critical not only for survival but also for national development, public authorities in most countries have assumed overall responsibility for the protection and management of this essential resource (World Bank, 1993).

The objectives of water resource management vary between climatic regions and countries. The policies and strategies to achieve these objectives are dependent not only on resource availability and water quality, but also on economic, political and social factors. In the arid zone the distorted hydrological cycle, with low levels of inputs and regular and, in many cases, increasing levels of output, present unique problems to water management (Agnew & Anderson, 1992).

If sustainable and efficient water use is to be achieved in the long term, a number of strategies can be adopted to enhance long term water supply and/or regulate water demand. While water management policies vary widely between countries, they generally focus on three main issues:

i. Environmental: the availability, sustainability and quality of water resources to meet current and future demand.
ii. Economic: the cost of developing supplies to meet increasing demand and to optimise productivity and return per unit volume of water.
iii. Social: the impact of water availability and quality on public health and development.

The goal of national water management policy should be "to ensure the sustainability of the water environment for multiple uses as an integral part of a country's economic development process" (World Bank, 1993). Water resources should be managed in the context of a national strategy that reflects the nation's social, economic and environmental objectives. In cases where water supplies are limited, often there is conflict in the objectives, for example the goal of food self sufficiency may be incompatible with sustainable water use. Ideally the development and resource

management objectives should be well coordinated between the various organisations with institutional responsibilities, though the reality is often less than ideal.

In the arid zone the sustainability of the variable and limited water resources is often the key issue facing water resource planners. In some countries, particularly in the Gulf States of the Middle East, limited natural water resources have been augmented with desalinated water from brackish and/or sea water sources. For example, in Saudi Arabia desalinated water contributes 400 Mm^3 to the annual water supply and is scheduled to increase to 1,200 $Mm^3\ a^{-1}$ by the year 2010 (Al Ibrahim, 1990).

Potential shortfalls in water resources have been alleviated through the importing of food commodities, or "virtual water" (Allan, 1995). The importation of foods with a "virtual water" content effectively reduces the demand on local water resources. For example, one ton of wheat would require the equivalent of more than 2,500 m^3 of water if produced on the Arabian Peninsula (PDO, 1988). While there are a number of economic and political constraints, such as the market cost and national security, food imports significantly contribute to the water balance of a number of countries in the arid zone.

In the Sultanate of Oman it is estimated that food imports account for the equivalent of more than 3,800 Mm^3y^{-1}, which is the equivalent of more than four times the annual renewable water resources (MOI, 1995). The recent lifting of import duty on imports of fodder crops is expected to further increase virtual water imports and reduce local water use.

As described by the World Bank (1994), there are two phases included in the planning and formulation of water management strategies. The first phase is the assessment of water resources and their management including water sources, water use (current and projected), institutional organisation, legal framework and human resource development. From this assessment, key issues in the management of water are identified and ranked according to importance in supporting development and key water related policies.

The second phase of formulation is developing and evaluating policy and strategy options. These options may include water supply, water demand, water quality, human resources development and issues related to institutional organisation, economic, environment, public health and international affairs. Evaluation of options and issues is based on environmental, economic and social criteria, with the selection and prioritisation of options to meet national, regional and local water management objectives.

2.3.1. Integrated Management

In recent years there has been a greater awareness of and interest in the concept of integrated water resource management and the development of integrated resource plans. Integrated management is the concept of coordinating policies and strategies on water, land, environmental, social and political issues.

As described by Mitchell (1990), there are three ways to consider integrated management:

i. Hydrologic - interaction between surface and groundwater quality and quantity.
ii. Water system - interaction between water, land and environment.
iii. Inter-relationships between water, social and economic development that determine the extent of water as an opportunity and constraint for development.

The latter option (iii) is perhaps the most relevant to water management in the arid zone, as water is closely linked to social and economic survival and the development of rural and urban communities. In this situation availability of water is a major constraint to the development and prosperity of these communities.

Integrated management requires the commitment and coordination of water users and administrators to achieve common goals in terms of not only resource management but also social and economic development. This coordination in some instances is being promoted through the establishment of water user associations, although associations of

water users is not a new concept, particularly with the development of surface water schemes (Byrnes, 1992), in recent times the participation of water users has been seen as an essential component of sustainable resource planning and management. The World Bank has been active in promoting the concept and assists with the formulation of the legal framework for their formation (Salman, 1997).

In Oman the falaj is an example of a long established local water user association, as it exemplifies a group of water users who have cooperated for the development and management of a water distribution system.

2.3.2. Management Strategies

Management strategies are medium to long-term action programmes to support the achievement of development goals and to implement water related policies (World Bank, 1994). Strategies include the ways and means of achieving the national, regional and local goals.

Management strategies can be broadly classified into supply and demand mechanisms. Supply strategies focus on the various alternative options for improving water availability including natural and artificial water sources. Natural sources relate to the development and enhancement of groundwater and surface water including recharge dams and wellfields. Artificial sources include desalination, waste water recycling and water imports from other regions.

As the main focus of the thesis research programme is the study of demand management strategies in the agricultural sector, this aspect is presented in detail in the following sections. These are presented as the general principles of demand management and give an overview of the various actions.

2.3.3. Demand Management

Water resource demand management is defined by the World Bank (1993) as "*the use of price, quantitative restrictions and other devices to limit the demand for water*".

Demand management can be classified according to two broad strategies of action, command and control mechanisms (CAC) and market based incentives (MBI) (Schiffler, 1994). These strategies are not mutually exclusive and in many cases a combination of both are applied simultaneously. The selection and application of strategies is dependent on environmental, economic, social and political objectives. Strategies adopted also vary between water sources, use and users.

2.3.3.1. Command and Control Strategies (CAC)

Command and control are strategies that regulate demand for water through administrative decisions, without regard for the costs incurred by the user. These strategies include a wide range of options from specific restrictions on water abstraction to more general conservation measures. Examples of CAC strategies include the following:

* Ban on drilling of new wells.
* Ban on deepening of existing wells.
* Limits on seasonal and/or annual abstraction.
* Limits on water uses such as restriction on high water demand crops.
* Public awareness campaigns to encourage water conservation.
* Extension programmes to encourage improved irrigation management.

2.3.3.2. Market Based Incentives (MBI)

Market based incentives do not prescribe what a user may do, but give incentives for certain behaviour by making resources more expensive. The ultimate decision regarding the use of the resource is made by the user. MBIs are based on the assumption that market forces will lead to the more efficient and more productive use of limited water resources. Examples of MBIs include:

* Tariffs on the abstraction of groundwater.
* Markets for groundwater abstraction rights.

Tariffs for abstraction can be based on a number of criteria related to quantity consumed, water quality, source and water use. There are a number of options for the types of tariff including flat rate, linear and progressive charges. Potentially the most effective for

demand management are the application of linear or progressive charges, as both are related to the volume of water abstracted. While the linear charge is constant per unit volume, progressive charges increase in successive blocks with total abstraction and therefore create an even greater incentive to save water.

In some cases an abstraction allowance may be exempt from charges, for instance for domestic or livestock consumption. Charges may differentiate between location or groundwater sources, with higher rates in areas or aquifers endangered by over-abstraction. The quality of water sources may be also be a criterion for differentiating tariffs between locations.

Water markets can work on the basis of voluntary trading of water rights between buyers and sellers. The price of the water right is determined by supply and demand. The creation of a groundwater market is dependent on two preconditions: that water rights are clearly defined and that these rights are enforced. A water right in this context is a "right to use" rather than a right of ownership of the resource, which in many cases rests with the state.

The components of a well defined water right may include the following:

* Quantity: the amount of water that can be abstracted per unit time or for the lifetime of the right.
* Time: period for which the right is valid.
* Location: aquifer from which water may be abstracted.
* Quality: usually determined by location.

To be effective in protecting the groundwater resources the total allocation of water rights should not exceed the sustainable long-term yield of the aquifer. The enforcement of rights requires monitoring of abstraction by metering and punitive measures such as fines or withdrawal of rights for non-compliance.

In theory, water markets should ultimately lead to a higher level of water productivity. In a free market and over time, water rights would tend to gravitate to those users that could use them most efficiently, as they will be able to bid the highest price. In some

cases this may lead to the transfer of water rights between sectors, in particular from the agricultural to the domestic and industrial sectors.

2.3.4. The Agricultural Sector

The regulation of water demand in the agricultural sector is one the greatest challenges facing water resource management today. It is estimated worldwide that agriculture accounts for more than 70% of the total annual water consumption (Engelman, 1993). In many arid zone countries, agricultural use, predominantly irrigation, accounts for more than 90% of annual water demand. There is increasing awareness in many areas of the need to reduce the abstraction of groundwater for irrigation to protect the aquifers and meet increasing demand in the domestic and industrial sectors.

Historically a wide variety of approaches have been taken to regulate water demand in the agricultural sector. In many cases agricultural development has occurred without regulation or restrictions on water resources. The need for regulation is often in response to limitations on water availability and/or competing water demands by the domestic and industrial sectors. There appears to be no consistent approach to the issue of regulating water demand by the agricultural sector, but rather strategies have evolved to resolve specific problems. This is to a large degree still an evolving problem, which involves not only resource management, but also economic, social and political issues. In many arid zone countries, the agricultural sector has been, and still in many cases is regarded as an essential industry for reasons of employment and food security.

The relatively low productivity and returns per unit of water in the agricultural sector compared to industry would encourage the transfer of water between sectors in a free market approach. For example in Jordan it is estimated that the productivity for industry is 40 times greater than that of agriculture (Shiffler et al, 1994).

A variety of CAC and MBI strategies have been adopted worldwide for the regulation of water demand in the agricultural sector. In the selection of strategies there is often a distinction between surface water and groundwater sources. Irrigation schemes based on the development and distribution of surface water frequently include water allocation

and tariffs for partial or full cost recovery. The approach to the regulation of groundwater appears to be less consistent, possibly due to the greater difficulties of clearly defining water rights and the enforcement of regulations. Because the main focus of the field research in this thesis is related to the demand management of groundwater resources, the discussion is limited to this and related issues.

Command and control strategies are widely adopted in the agricultural sector to limit the demand for groundwater. The regulation of demand for groundwater appear to be based more on political and social criteria rather than economics or productivity.

In some countries in recent years there has been greater interest in the adoption of MBI strategies due to increased demand for water resources, not only for irrigation but also for domestic and industrial consumption. This interest stems in part from recognition of the potential to increase water supplies through improved water use efficiencies and the potential to transfer water from the agricultural to the domestic and industrial sectors.

2.3.5. International and Middle East Experience

As indicated above a variety of strategies have been adopted to regulate water demand in the agricultural sector, listed below is a brief summary of the strategies adopted internationally and more particularly in the Middle East.

2.3.5.1. Water Allocations

Limits on water abstraction are used in a number of countries to regulate annual and/or seasonal, water demand from groundwater aquifers. In Western Australia for example, upper abstraction rates are allocated on an annual basis with limits based on demand criteria of cropped area and available water resources (WA, 1992). The well owner is required to install a water meter and annually to submit a hydrological report with details of total abstraction and water quality.

Similar allocation systems are also reported in a number of southern states of the United States of America, including Arizona, New Mexico and Colorado (Fenemore, 1994).

In Jordan an upper limit of abstraction was established in 1984 for new wells used to supply agricultural and industrial users. But it is reported that monitoring of abstraction and enforcement of these limits was only being initiated from 1994 onwards (Schiffler et al, 1994).

2.3.5.2. Water Markets

Water markets have been used as a mechanism for the transfer of water rights between users in some countries. Probably the most notable examples exist in the south-western states of the USA. In many cases the transfer is between sectors, most commonly from agriculture to adjacent municipal water supply.

2.3.5.3. Water Tariffs

There are few examples of the imposition of tariffs on groundwater abstraction by the agricultural sector. In Jordan "a special tariff" for abstraction from private wells used for agriculture and industry was declared as part of the National Environment Strategy (Schiffler et al, 1994). The tariff was introduced in January 1994 and amounted to the equivalent of $US 0.15 m^{-3}. But as of 1994, it was only applied to industrial water users.

In Israel tariffs for water use by the agricultural sector have been enforced for a number of years. A progressive tariff was established in 1972 with the objective of attaining improvements in efficiency of water allocation (Yaron, 1979). The tariff was in three stages:

i) A relatively low tariff (price A) was charged for 85% of the historical approved water quota.

ii) A higher tariff (price B) was charged for the remaining 15% of the water quota.

iii) A very high tariff (price C) was charged for any water use above 100% of the water quota.

2.3.5.4. Improved Irrigation Management

The adoption of improved irrigation methods and management is often set as an objective to improving water use efficiency and water productivity. This is in response to the market based incentives listed above which provide a financial incentive for more efficient and productive water use, or more commonly in response to incentives and subsidies for the adoption of improved irrigation methods and management.

The promotion of improved irrigation management is often seen by water administrators as a more acceptable option to farmers than regulation of water use. In the case of subsidies for conversion from traditional flood systems to drip and sprinklers, it is promoted as benevolent support to the agricultural sector. In the case of Oman, a "modern irrigation programme" was established in 1990 on the basis of up to 75% subsidy for the system capital cost (MAF, 1992).

Significant reductions in water demand have been reported following the introduction of improved irrigation methods and management. The conversion of farms from traditional flood systems to drip irrigation in the Jordan Valley in the 1970s, reduced water demand from 12,000 to 6,000 $m^3 ha^{-1}$ and increased yields by three to four times (Eldar, 1987).

Similar reductions in water demand are reported in Israel, where average water consumption decreased from 8,700 m^3 ha^{-1} in the 1950's to 5,700 m^3 ha^{-1} in the late 1980's (Van Tuijl, 1993). This reduction was largely attributed to the adoption of improved irrigation methods and management.

While the adoption of improved irrigation management can lead to the reduction of water consumption per unit area, it may not necessarily reduce total water consumption within a water basin. In some instances it has led to an expansion in the irrigated area and an overall increase in water demand. Within a closed basin improved water use efficiency may not significantly increase global water availability. Therefore within these basins if 'real' savings in water demand are to be achieved, the adoption of improved irrigation management must be accompanied by the imposition of conditions limiting the expansion of irrigated areas.

2.3.5.5. Crop Selection

In the arid zone with high evaporative losses in the hot summer months, water demand can be significantly reduced by switching from perennial to winter seasonal crops. For example, in Oman annual water demand for winter vegetables is typically 1,500 to 2,000 $m^3\ ha^{-1}$ compared to more than 17,000 $m^3\ ha^{-1}$ for tree crops. Vegetables also have the added advantage of higher yields per unit area and per unit volume of water use.

2.4. WATER RESOURCE MANAGEMENT IN OMAN

The water management problems and challenges being experienced on the Batinah Coastal Plain including the study area, are to a large extent a legacy of the past and present limits on water resource management in Oman. The uncontrolled expansion of new wells and unregulated pumping is the primary cause of the deterioration in water levels and saline intrusion on the lower Plain. This section presents a summary of the background to water management in Oman and the development of water related institutions and management strategies adopted since the mid 1970's.

2.4.1. Shariah and Customary Water Law

Prior to the mid 1970's water use and management was principally regulated by tribal and local leaders. This control was largely based on the interpretation of Islamic Shariah and local customary laws. The former is a compilation of judgements based on the Holy Koran, the Haditha, and judgement of Islamic schools as well as consensus of Islamic jurists. Within Oman there are four main Islamic schools, of which the Ibadite is predominant. Oman is in fact is the only Islamic state where this is the case. It is speculated that customary water laws are of pre-Islamic origin but with advent of Islam were adapted and modified to comply with Shariah principles (Bhacker, 1992).

The *wakil* (agent) or *khabir* (expert) supervised the use and distribution of water within each community. While today the regulation of water use from wells has been superseded by central government regulations, the *wakil* is still responsible for overseeing the distribution of water for irrigation in community owned aflaj (sing. falaj).

Distribution is based on the ownership of rights to water use, these rights are based on contributions to falaj construction and maintenance. Falaj water use rights are traded on a temporary or permanent basis. In the larger aflaj details of the ownership of rights are recorded in the "falaj book" (Wilkinson, 1977).

Although Islamic law differentiates between groundwater and surface water, similar principles in terms of access and use are applied to both (Bhacker, 1992). Groundwater is perceived as an underground flowing stream of water rather than an inscrutable body of water. The flowing/standing distinction is made in the context of ownership of water. Flowing water, whether groundwater or surface water, is regarded as "*mubah*" that is free to all men.

The legal status of water is altered by possession, which in the narrow sense means the holding of water in a receptacle. Other forms of possession, while not complying in theory may, in practice, according to the custom and interpretation of the relevant school, correspond to a right of ownership or exclusive use.

In Oman there was a distinction between ownership of a well and a falaj as a source of water. In general a well was owned in perpetuity by the person(s) who dug the well provided that they owned the land on which the well was constructed, or otherwise until the well was abandoned. In the case of water supplied from a falaj it is the property of those who contribute to its construction and maintenance. This might be a community of users or an individual family. Within the falaj, water is distributed via a system of rotation (*dawaran*) and water shares based on time, with the standard unit being an *athar*, which approximates to half an hour of irrigation (Wilkinson, 1977).

Under the Ibadi Islamic doctrine, irrigation rights from wells or aflaj could be traded independently from the sale of land. The right to use water was based on three criteria:

i) Free for all for drinking, the customary right of "thirst" (*haqq al shafa*).

ii) Reserved for the exclusive use of the owner(s) for irrigation.

iii) Unlimited as to the total quantity that could be drawn by the well owner.

Shariah law provided for protection zones around wells and aflaj with the establishment of the "*harim*" which provided for a zone of exclusion (Caponera, 1973). In these areas

a minimum distance had to be respected between the existing well or falaj and a new well, to protect the groundwater yield.

Shariah law is the foundation on which modern legislation is based in Oman and therefore remains an important component of water resource management. The rights of well owners and rights of water use defined within Shariah law, form the foundation for regulations on well permitting and discharge from wells under current legislation.

2.4.2. Post 1970 - Water Resource Management

2.4.2.1. Institutional Development

Since the mid-1970s there has been a progressive development of government institutions with responsibilities for the assessment and management of water resources in the Sultanate of Oman. During the period 1975-96 these responsibilities have been transferred and shared between various organisations, Figure 2.4.

Formal state control of water resources was established in 1975 with the formation of the Water Resources Council (WRC). The Council included representatives from the Ministries with an interest in water, such as the Ministry of Agriculture and Fisheries (MAF), the Ministry of Petroleum and Minerals (MPM) and the Ministry of Communications (MOC). Its primary role was advisory, including the co-ordination of proposals for water related developments by Ministries and the preparation of a National Plan for the water sector. The Council was disbanded in 1985 and responsibilities transferred firstly to the Council for Conservation of Environment and Water Resources and subsequently to the Ministry of Environment and Water Resources (MEWR).

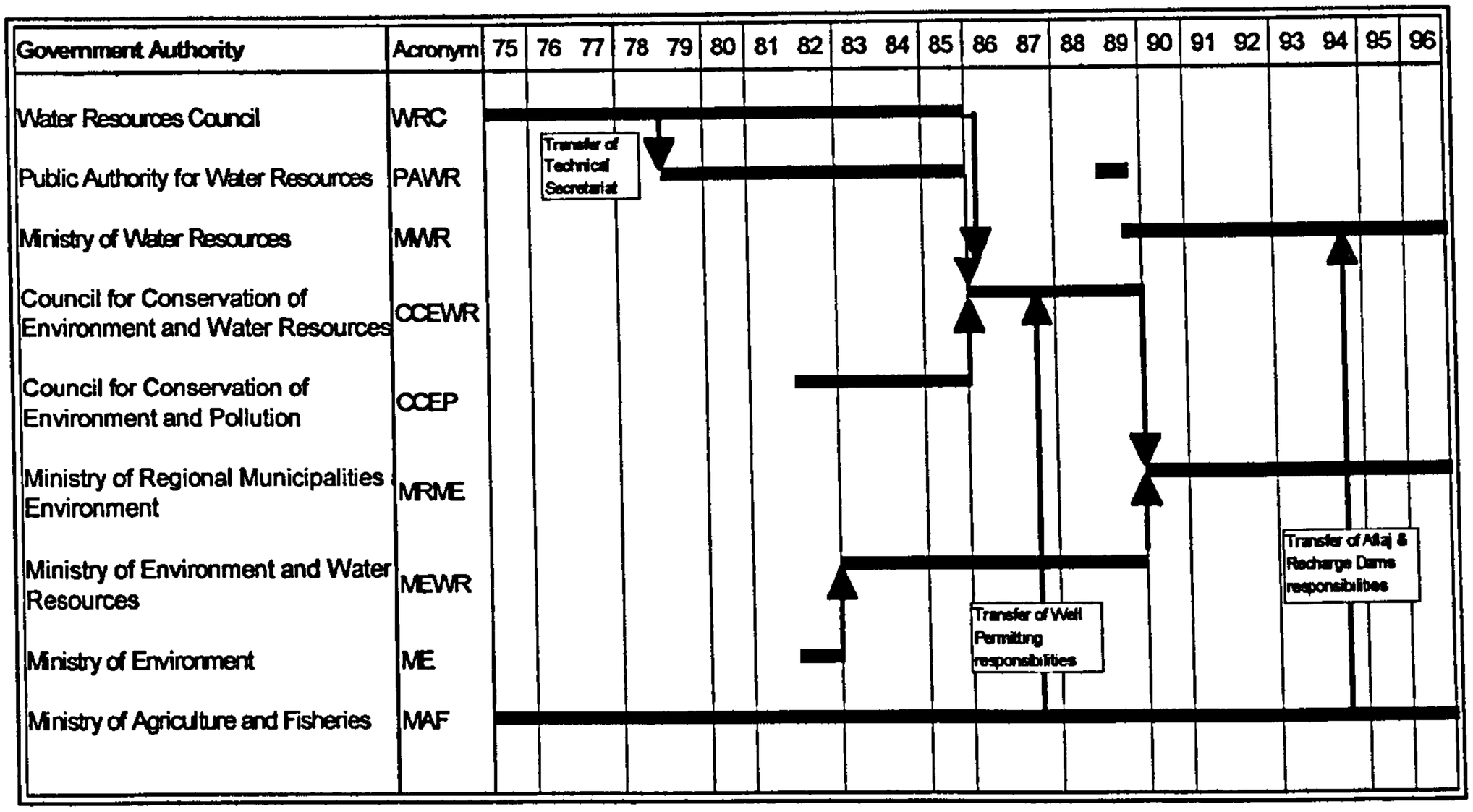


Figure 2.4 Development of Water Related Institutions - Sultanate of Oman

The Public Authority for Water Resources (PAWR) was established by Royal Decree in 1979 and assumed the technical responsibilities of WRC, including undertaking studies and maintaining a centre for water resources data and information. These responsibilities were transferred to the Council for Conservation of the Environment and Water Resources (CCEWR) in 1985. In 1986 specific responsibilities for aflaj, irrigation and the construction and maintenance of recharge dams and structures were assigned to the Ministry of Agriculture and Fisheries (MAF). PAWR was briefly reformed in 1989 prior to the formation of the Ministry of Water Resources (MWR) by Royal Decree in the same year (Royal Decree, 1989).

The Ministry of Water Resources is the principal organisation responsible for water resource assessment, planning and management in Oman. In 1994 these responsibilities were expanded to include the construction and maintenance of falaj and recharge dams (Royal Decree, 1994). MWR currently comprises three technical directorates; management, assessment and regional affairs, together with two administrative directorates. The Batinah is one of the eight national administrative regions. The regional office at Rustaq for the southern Batinah overseas monitoring activities within the catchments of the study area.

While MWR is the lead organisation for water resources, responsibilities for some aspects of water management are shared with other organisations, including:

* The Ministry of Electricity and Water (MEW): supply and management of drinking water.
* MAF; irrigation management in the agricultural sector.
* Ministry of Regional Municipalities and Environment (MRME): water pollution regulations and enforcement.
* Muscat Municipality (MM): waste water treatment and disposal.

2.4.2.2. Development of Legislation

In the Sultanate of Oman laws are issued as Royal Decrees by His Majesty The Sultan. Ministerial Decisions are issued by the empowered Minister according to responsibilities defined within the Royal Decree(s).

A number of Royal Decrees and Ministerial Decisions have been issued since 1975 for the protection and management of water resources. The most significant was the declaration that the "water reservoir" is a "national wealth" (Royal Decree, 1988). The decree authorised government agencies to protect and conserve underground water and ensure the sustainable development of existing water resources. The responsibility for the management of water was largely vested in the Ministry of Water Resources.

In April 2000 the responsibilities of MWR were further clarified and strengthened with the issuing of Royal Decree 29/2000, for the "Protection of Water Resources in the Sultanate of Oman" (Royal Decree, 2000). The Decree further defined water as a "national wealth" to include all water resources, with the exception of sea water, from whatever source, including surface and ground water resources. It also provided for the issuance of additional legislation for the protection of water resources from pollution and depletion.

A permit system for drilling new wells and deepening existing wells was established in 1983 by MAF and later transferred to MWR. The purpose of the legislation was to limit the expansion of new wells and demand from existing wells. Regulations on well drilling were extended by subsequent MWR Ministerial Decisions in 1992 and 1995 (MD

13/95). The current system requires a permit for the construction of new wells and deepening and maintenance of existing wells. It bans the granting of permits for new wells for agricultural use in areas declared to be in water deficit, which includes the Batinah region (inclusive of the study area). Permits are granted for replacement or deepening of existing wells, in cases where there is deterioration of well yield or water quality, for existing agricultural use. The impact of the these regulations on the number of wells and water demand within the study area is further discussed in Chapter Four.

A national programme was established in 1990 by MWR for the registration of all existing wells. A total of more than 167,000 wells were registered by July, 1991 (MWR, 1995b), though the subsequent National Well Inventory indicated that there were less than 130,000 wells.

2.4.2.3. Management Activities

Since the mid-1970s there has been a growing awareness of the need to adopt strategies to limit and regulate the demand for water and to improve the efficiency of use. In 1977 Wilkinson warned of the dangers of uncontrolled expansion of boreholes on the Batinah Coastal Plain. PAWR annual reports of the early 1980's indicated that over-abstraction in some areas was resulting in declining water levels and saline intrusion and proposed the introduction of a water allocation programme.

A number of programmes and activities have been initiated by various government organisations and NGO's since the mid 1980's to limit the expansion of demand for groundwater and to improve irrigation efficiency. In addition to the well permitting and registration regulation mentioned above, other projects and programmes have included evaluation of water metering as a mechanism for regulating well discharge and a modern irrigation programme.

Water metering is one of the conservation policies currently being evaluated by MWR. While meters are widely used in Oman to monitor water consumption for tariffs in the domestic and industrial sectors, there has been little research into their use in the agricultural sector. In 1994 the MWR initiated a series of projects to install water meters on wells on farms in the southern Batinah. Under the first phase of the project,

114 meters were installed on 27 farms within the catchments of Wadis Manumah, A'Taww and Al Ma'awil. The second phase of the project included the installation of an additional 307 meters on 119 farms within the same catchments. The objectives of the project included the monitoring of groundwater abstraction and the identification of the potential for water conservation through improved irrigation efficiency and better crop selection.

MAF with the technical support of the Food and Agriculture Organisation (FAO) initiated a "modern irrigation programme" in 1990 (MAF, 1992). Under the programme MAF subsidised the conversion of farms from traditional flood to pressure irrigation systems, including drippers, bubblers and field sprinklers. In 1990-94 more than 800 farms on the Batinah were converted. The objectives of the programme included improvement in irrigation efficiency and higher farm productivity.

2.4.2.4. Future Management

A broad strategy for the future of water resource management in Oman was identified in the national conference on development "Oman Vision 2020" in Muscat, 1995. The water sector report states that the "*future vision for water resources in the Sultanate of Oman focuses on reducing current deficits and striking a balance in major underground storages in different parts of the country*" (MWR, 1995b). Based on a planning horizon to the year 2020 it goes on to list the main objectives for the sector as:

i) Striking a balance between water usages and renewable resources and to safeguard water resources against depletion and pollution.
ii) Provision of drinking water for the citizens and finding ways and means for using effluent treated water.
iii) Provision of water for industrial, commercial and agricultural use within the limits of available resources to realize sustainable development.

The Vision lists a number of policies and mechanisms to achieve these objectives including promotion of improved irrigation methods and management and the introduction of a water quota system. The 'Vision' was adopted as a strategic planning

document by all participating organisations i.e. MWR, MAF, MEW and MRME, and forms the foundation of the 5-year plans for all Ministries to the year 2020.

The Ministry of Water Resources is currently formulating a "National Water Resources Master Plan" (NWRMP), which will ultimately form a water sector plan. It is based on a water basin approach with classification of 27 major water basins nationally. The study area falls within the "Barka" water basin, which includes five surface water catchments of the southern Batinah region (Binnies, 2000).

As a starting point, for NWRMP water balances, current and future, are being compiled to define areas of water deficit and surplus. The plan will evaluate the resource, economic and social issues and constraints to resolving sustainable water use. Given the high proportion of water consumed by the agricultural sector, it is anticipated that many of the strategies proposed in the Plan will be based on reduction of water demand in this sector including improved water use efficiency, crop selection and limits on water demand.

The NWRMP is scheduled for completion in the year 2000, and if adopted by the government of Oman, will form the planning blueprint for water resource management to 2020 and beyond.

CHAPTER THREE
WADIS TAWW & MA'AWIL

3.1. INTRODUCTION

The study area is a zone located within the lower catchments of Wadis Taww and Ma'awil, at the southern end of the Batinah Region, Figures 3.1 and 3.2. The catchments are two of the most severely affected on the Batinah by the impact of sea water intrusion (MWR, 1999c). While the research programme focuses on water management on a sample of study farms within this zone, the availability, quality and demand for water within it is influenced by physical and human factors within the catchment as a whole. Therefore this chapter presents a description of the physical and human resources within the catchments that influence water resources and their use.

3.2. CLIMATE

The annual migration of the Inter Tropical Convergence Zone (ITCZ) is the major influence on weather patterns in northern Oman (Stanger, 1987). The northerly migration of the ITCZ during the summer months is responsible for the generally calm clear conditions experienced in northern Oman. The southward migration during the winter months can be responsible for northerly weather fronts reaching the region along with the occurrence of the northeasterly "*shamal*" wind pattern.

The climate of the Batinah is characterised as hot, with a mean annual temperature at the coast of around 28°C, and high humidity during the summer months. Annual rainfall is generally low with less than 100 mm at the coast increasing inland with altitude to more than 200 mm (MWR, 1994b). While rainfall events are infrequent they tend to be more widespread during the winter months and more localised during the summer. The occasional cyclonic front may bring widespread high intensity rainfall events, though these are relatively rare.

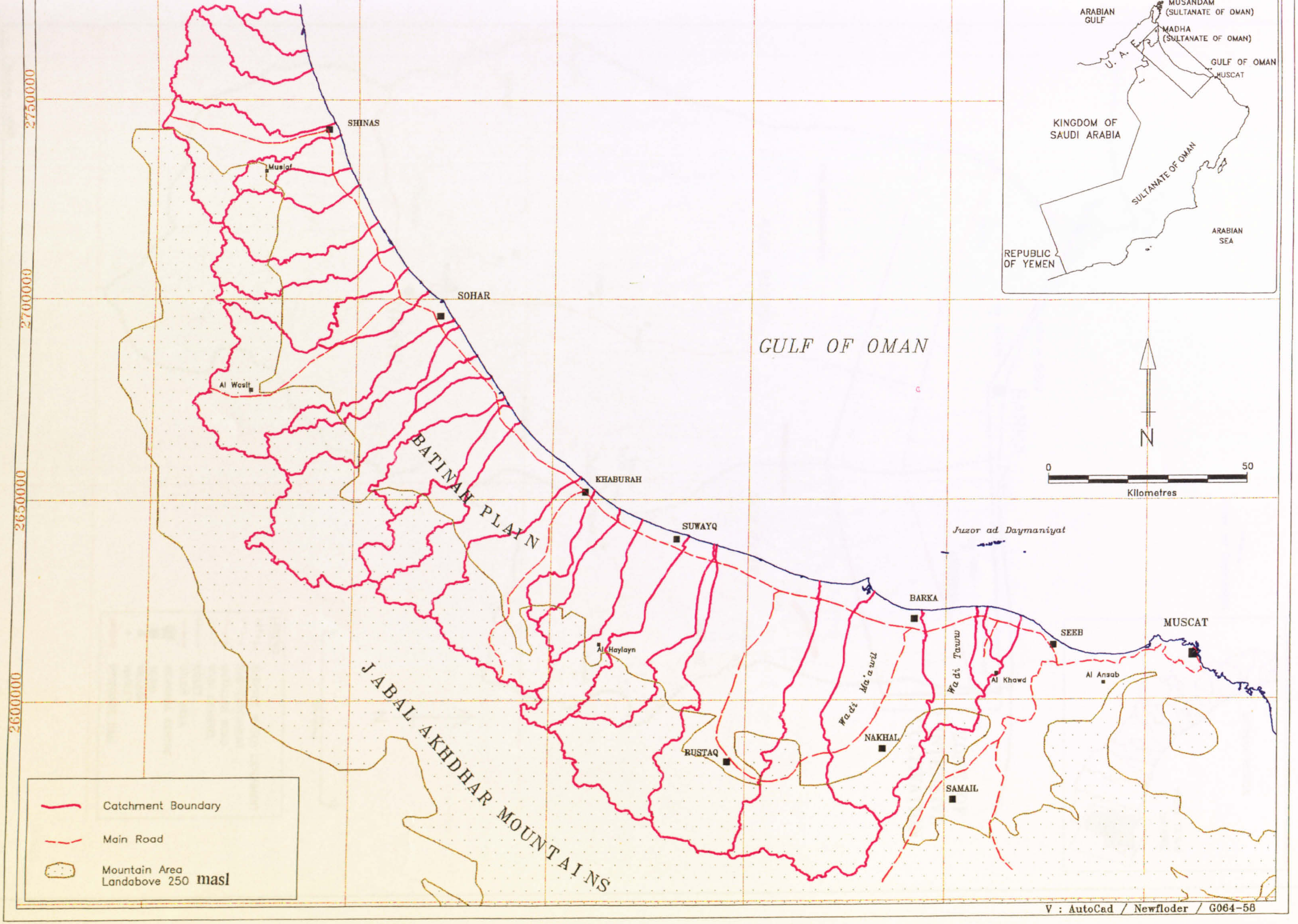


Figure 3.1 Batinah Region

575000

600000

Juzer ad Daymaniyat

BATINAH REGION

WADIS TA'WW & MA'AWIL

Hifri al Batha

BARKA

Haradi

An Naman

Ukdah

Abu Nukhayl

Hayy Asim

Rumays

ZONE OF INTENSIVE CULTIVATION

2625000

WADI MA'AWIL

WADI TA'WW

Aflaj

Halban

Taww (II)

Wasit

Sheria

Lajal

Hibra

Jaarah

Taww (I)

Buwah

Khatum

Khubrah

2500000

Afi

Sulawah

Muslimat

Tawiyah

NAKHL

N

0 10

kilometres

LEGEND

SURFACE WATER CATCHMENT

SUB-CATCHMENT

METALLED ROAD

WADI CHANNEL

COAST

STUDY AREA

REGIONAL CENTRE

TOWN

VILLAGE

HAMLET

RECHARGE DAM

2375000

Source : MWR

V : AutoCAD / Newfolder / G164-57

Figure 3.2 Wadis Taww and Ma'awil

3.2.1. Sources of Data

For the description of the climate within the catchments data was compiled from two meteorological stations and sixteen rain gauges within or near the study area. These included the following:

i) Rumais Research Station: the station was established in 1989 and is located on the MAF Research Station at Rumais within the lower catchment of Wadi Taww.

ii) Muladdah Station: the station is located at Muladdah, approximately 20 km west of Wadi Ma'awil. It is owned and operated by MWR.

iii) Rain Gauges: there are nine rain gauges located within the catchments and seven in adjacent catchments, installed and monitored by MWR. These are located in both the lower and upper catchments of the wadis. Monthly records for five stations are available from 1974 onwards and for the balance of gauges from 1984.

Apart from rainfall, the longest set of climate data (air temperature, wind speed, relative humidity and daylight hours) is that from the MWR Muladdah meteorological station, Figure 3.4. The available data covers the 11-year period 1983-94. The station is located approximately five km from the coast at an attitude of 18 metres (MWR, 1994b). While it is not located within the study area, it is at a similar latitude, altitude and environment to that experienced on the study farms. A shorter and rather incomplete climate data set exists for the MAF station at Rumais, with records available for 1989-91.

The objective in defining the climate of the catchments is to present a description of the parameters that influence availability of water either directly to the irrigated area or via recharge to groundwater. It is also to present a summary of the climate parameters that influence the calculation of reference evapotranspiration. The following descriptions are a summary and in some cases a collation of the above-mentioned data.

3.2.2. Rainfall

Based on the analysis of data from the rain-gauges within and around the catchments, mean annual rainfall ranges from less than 75 mm at the coast to more than 200 mm in the mountainous upper catchment, Figure 3.4 (MWR, 1995c).

Rainfall records within the study area are available from two gauges, one located near Barka and the other near Rumais. The readings for the latter gauge span a period of 18 years, from 1974-91. Average annual rainfall over this period was nearly 60 mm but ranged from zero to more than 190 mm, Figure 3.3. The total annual rainfall only exceeded 100 mm in 3 years out of the 18 years and was less than 20 mm in six years.

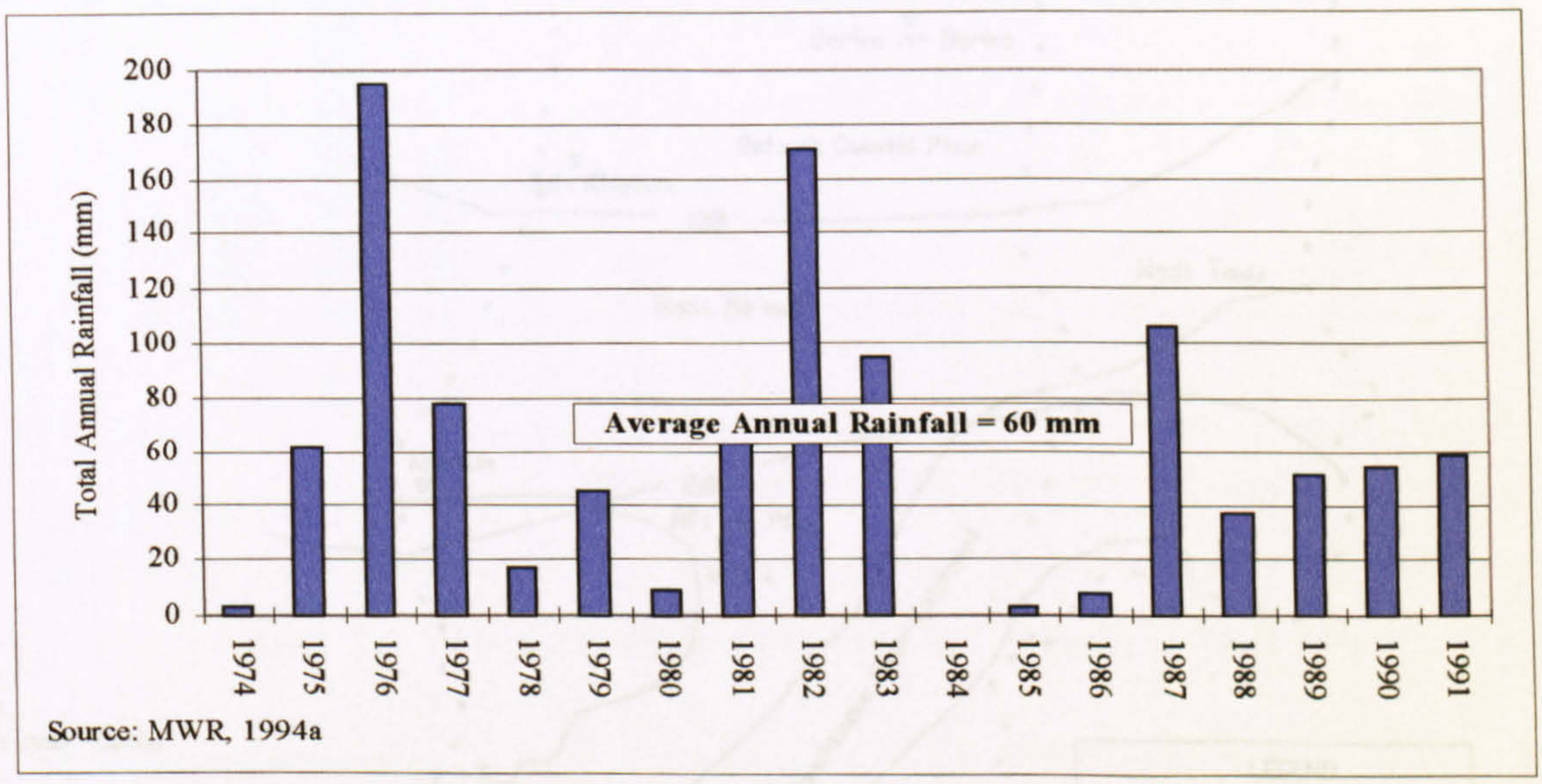
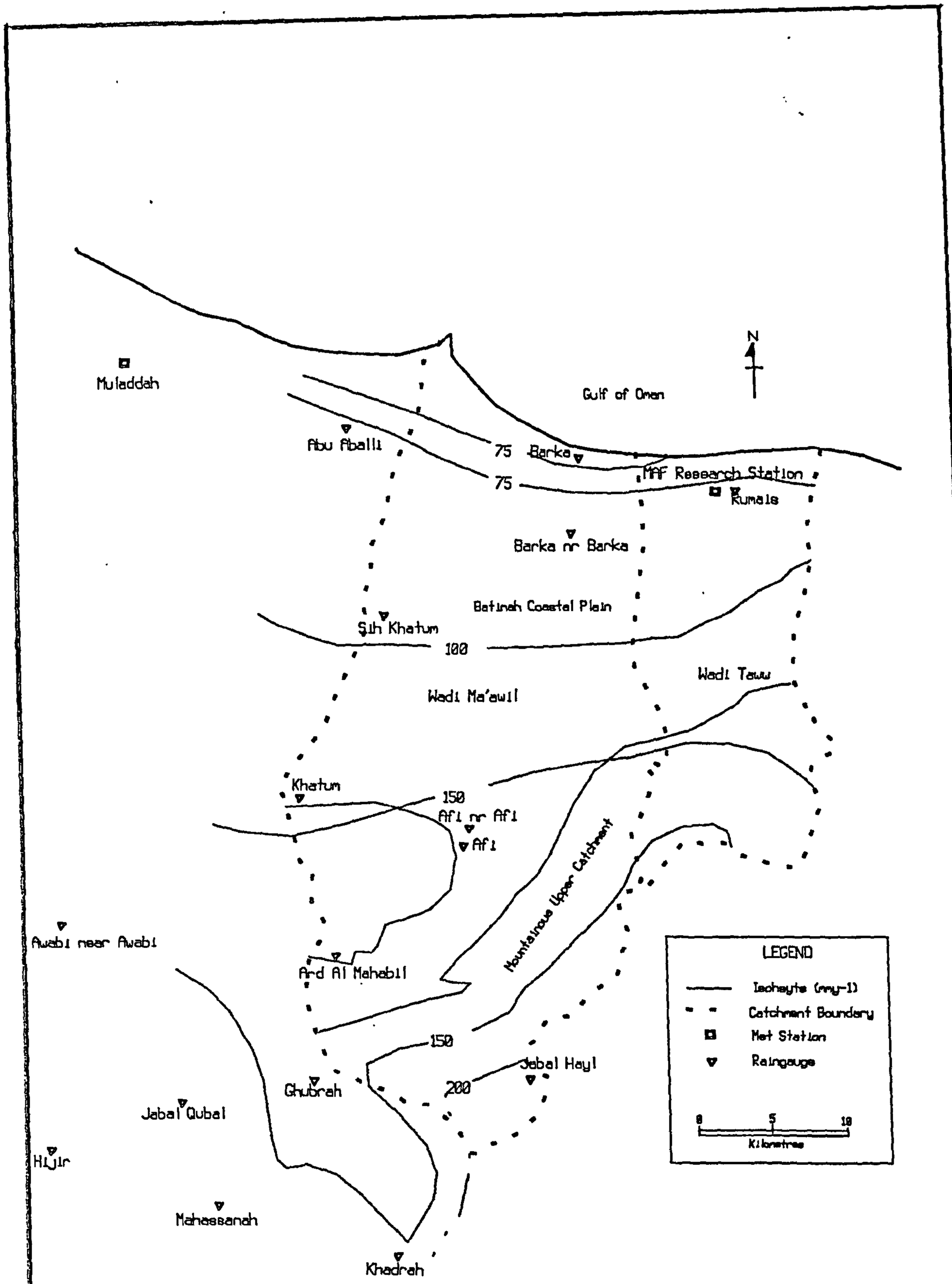


Figure 3.3 Annual Rainfall for rain gauge near Rumais

As indicated in Figure 3.5, monthly rainfall on average is highest in February (23 mm) and lowest during the summer months from June to September (less than 5 mm). The maximum monthly rainfall over the period 1974-91, of 82.4 mm, was recorded in February 1976.

Under the high evaporative conditions experienced within the study area it is predicted that much of the rainfall is lost to surface evaporation, particularly low intensity events. Annual potential evapotranspiration is estimated to be nearly 2,000 mm (Section 3.2.6), more than 30 times greater than average annual rainfall. While rainfall on the lower plain may occasionally contribute to soil water and possibly groundwater recharge, it is a relatively small and infrequent contribution to annual irrigation requirements.



Source: MWR, 1994a

Figure 3.4 Isoheyts for Wadis Taww and Ma'awil

On irrigated areas local rainfall can cause the inward lateral movement of soil salts from the perimeter to the soil wetted zone. The resultant increase in soil salinity within the root zone has been a cause of the defoliation of tree crops particularly lime trees on the Batinah coast during and following rainfall events (MAF, 1991). On this basis local irrigation engineers advise that irrigation should be continued during low intensity rainfall events to maintain the outward movement of soil water and salts from the root zone.

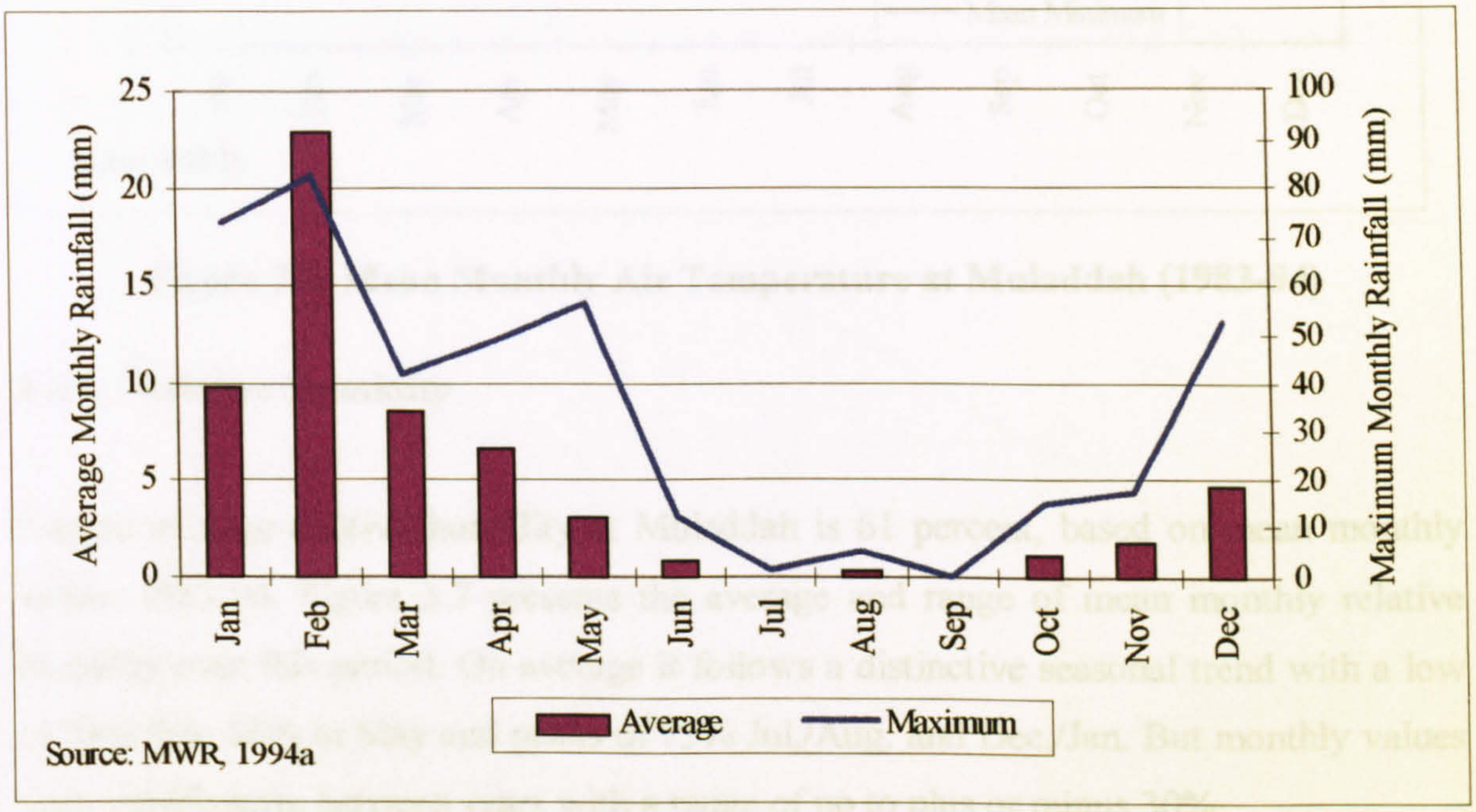


Figure 3.5 Mean Monthly Rainfall near Rumais - Wadi Taww

3.2.3. Temperature

Monthly variations in air temperature (mean, maximum and minimum) at Muladdah, 1983-94, are presented in Figure 3.6. Mean monthly temperature ranged from nearly 35°C in June to 19°C in January, while mean maximum and mean minimum ranged from 25 to 41°C and 14 to 29°C respectively. Individual daily temperatures can exceed more than 45°C during May and June.

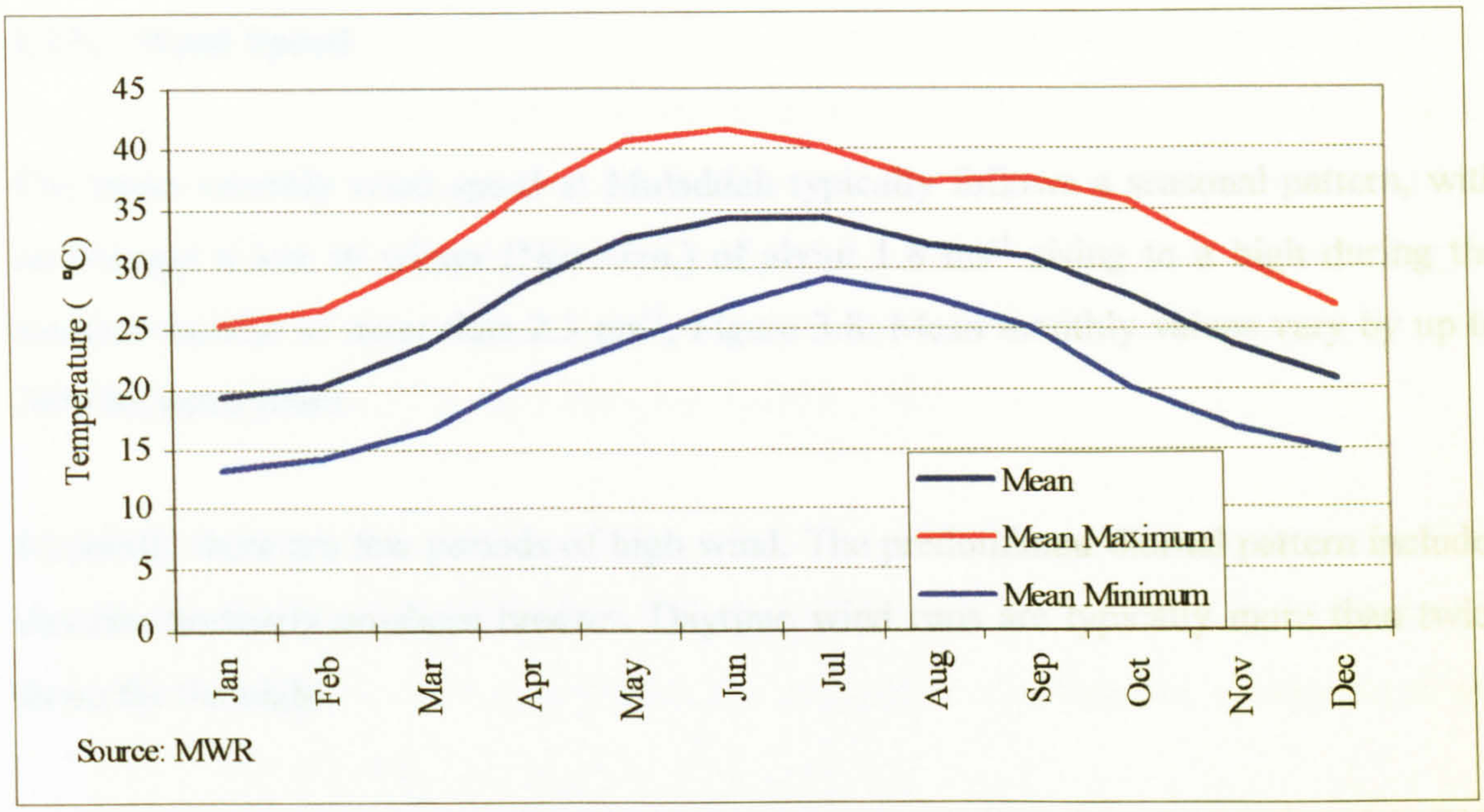


Figure 3.6 Mean Monthly Air Temperature at Muladdah (1983-94)

3.2.4. Relative Humidity

Annual average relative humidity at Muladdah is 61 percent, based on mean monthly values 1983-94. Figure 3.7 presents the average and range of mean monthly relative humidity over this period. On average it follows a distinctive seasonal trend with a low of less than 50% in May and peaks of 75% Jul./Aug. and Dec./Jan. But monthly values vary significantly between years with a range of up to plus or minus 30%.

Figure 3.7 Mean Monthly Relative Humidity at Muladdah (1983-94)

3.2.5. Wind Speed

The mean monthly wind speed at Muladdah typically follows a seasonal pattern, with on average a low in winter (Nov.-Jan.) of about 1.8 ms^{-1} rising to a high during the summer months of more than 2.3 ms^{-1}, Figure 3.8. Mean monthly values vary by up to 24% between years.

Generally there are few periods of high wind. The predominant diurnal pattern includes daytime northerly on-shore breezes. Daytime wind runs are typically more than twice those for the night.

Figure 3.8 Mean Monthly Wind Speed at Muladdah (1983-94)

3.2.6. Reference Evapotranspiration

Reference evapotranspiration (ETo) is defined as "*the rate of evapotranspiration from an extensive surface of 8-15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water*" (Doorenbos, 1984, pg. 1). A number of empirical formulae have been developed for the calculation of ETo based on climatic parameters. The availability of climate data is often the primary consideration in the selection of a formulae.

In Oman the Blaney-Criddle formula was used in studies in the 1970's and 80's as the

basis for estimates of ETo, due in part to the limits on availability of climate data. More recent studies have adopted the Penman-Monteith formula (MAF, 1992) in part due to the availability of more extensive climatic data and the recommendation of FAO (FAO, 1990). A review of formulae and comparison with irrigation research in Oman by the MWR indicated a close correlation between Penman-Monteith estimates of ETo and crop water requirements for Rhodes grass (MWR, 1993).

Based on the above reviews and recommendations, the Penman-Monteith method has been adopted in this study for the calculation of ETo. It forms the foundation for the estimates of crop water requirements for evaluation of irrigation management and calculation of water use.

While the Muladdah station has the longest data set (1983-94) it is approximately 20 km to the west of the study area. The Rumais station is located within the study area, but only data for two years (1989-90) have been published to date (MAF, 1991). On the basis of the longer data set and similarity of location to the study area, data from the Muladdah station was used for the calculation of mean monthly and annual ETo. All units of ETo presented in this study are expressed in equivalent depth in millimetres (mm) of water; annually (mmy^{-1}), monthly ($mmmth^{-1}$) and daily (mmd^{-1}).

Appendix A presents the monthly and annual ETo for Muladdah over the period 1983-94. Mean annual ETo at Muladdah over the period 1983-94 is 1999 mm. However, over this period it varied between years from 1877 to 2083 mmy^{-1}.

As illustrated in Figure 3.9, mean daily ETo (based on mean monthly climatic data) is almost 8 mmd^{-1} in May-Jun. and drops to 3 mmd^{-1} in Dec.-Nov. However peak values ranged between 7 to more than 8 mmd^{-1} (mean maximum and minimum). There is smaller variation in minimum ETo values with a range from approximately 2.7 to 3.4 mmd^{-1} (Appendix A).

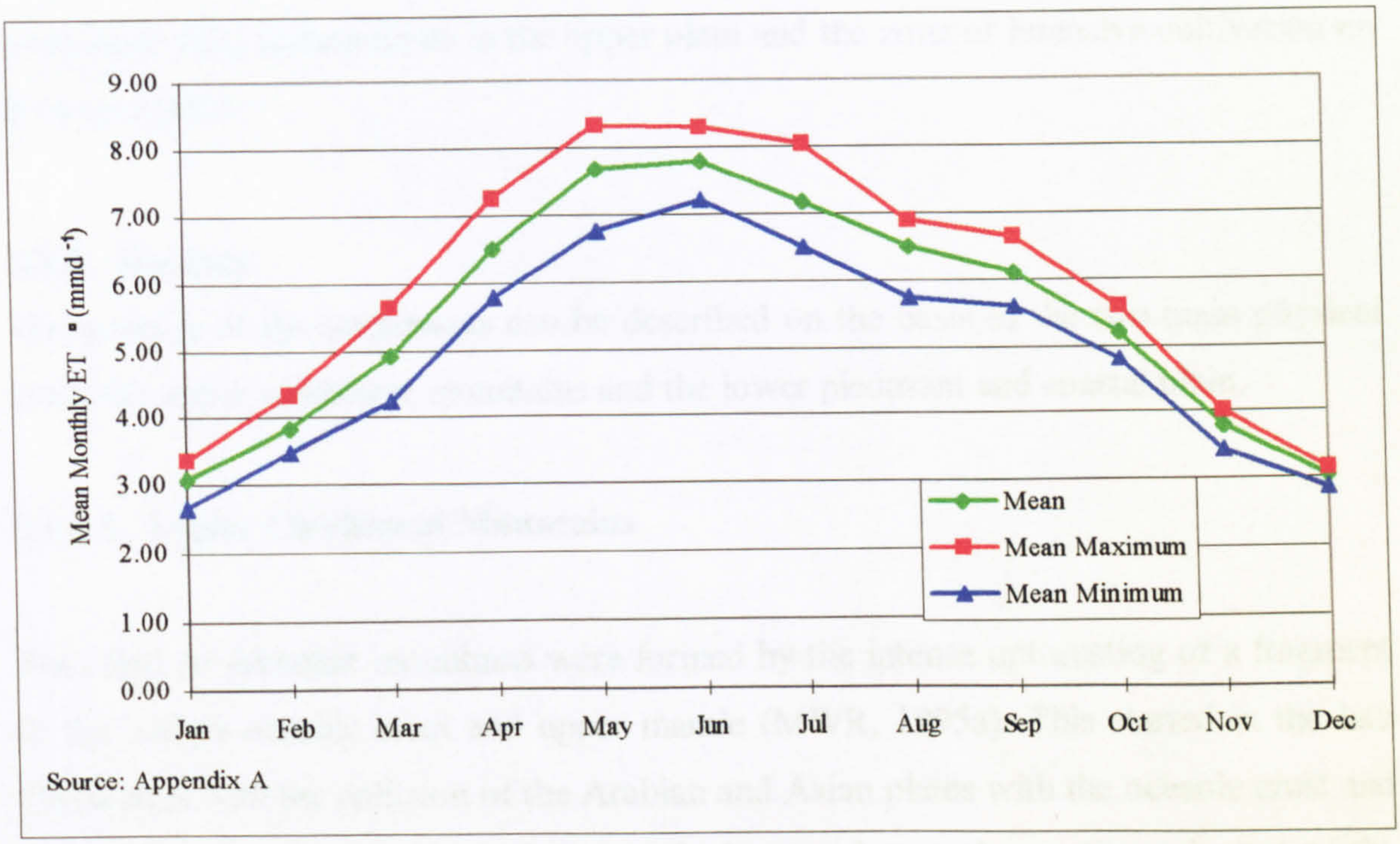


Figure 3.9 Mean Monthly ETo (mmd^{-1}) at Muladdah 1983-94

3.3. HYDROLOGY AND HYDROGEOLOGY

The availability and quality of water for irrigation of farms within the study area is mainly dependent on the recharge and through-flow of groundwater from the upper catchments. This section presents an overview of the key hydrology and hydrogeology features of the catchments.

3.3.1. Topography

The catchments rise from sea level at the Gulf of Oman to more than 2500 mamsl in the Jabal Al Akdhar mountains or "green mountains" (of the Western Al Hajar chain of northern Oman). Three distinct land forms are recognised: a mountainous upper catchment, piedmont and lower coastal plain. The upper catchment is dissected by deeply incised valleys (wadis) which discharge to the alluviums of the piedmont and coastal plain.

Figure 3.10 is reproduced from a 1996 Landsat image of the catchments. It illustrates the main topographical features including the mountains of the upper catchment and the coastal plain. Irrigated and natural vegetation is represented in green, indicating the

location of falaj communities in the upper plain and the zone of intensive cultivation on the lower plain.

3.3.2. Geology

The geology of the catchments can be described on the basis of the two main physical units, the upper catchment mountains and the lower piedmont and coastal plain.

3.3.2.1. Upper Catchment Mountains

The Jabal Al Akhdhar mountains were formed by the intense upthrusting of a fragment of the Tethys oceanic crust and upper mantle (MWR, 1995a). This started in the late Cretaceous with the collision of the Arabian and Asian plates with the oceanic crust and part of the mantle of the latter being pushed upward over the continental crust of the Oman Margin.

The simplified geology of the catchments presented in Figure 3.11, is derived from geological maps of the region. As described by MWR the "*upper catchment bedrock consists allochthonous units of the Samail* (Ophiolite*) and Hawasinah* (Hawasinah) *Nappes and Autochthonous units A and B* (Huqf and Hajar Super Group respectively*). The Autochthonous unit A (pre-Permian) is represented by the Mistal Formation consisting predominantly of siltstones and greywackes. The autochthonous unit B (Permian and Cretaceous) is represented mainly by carbonates of the Akdhar Group to the Aruma Group"* (MWR, 1994b pg. 16)

The report goes on to say "*The Samail Nappe Ophiolite is composed of crustal and mantle sequences. The crustal sequence consists of gabbroic and basaltic units which have been affected by tectonic movements. The mantle sequence is composed of coarse grained peridotites, characterised by intense fracturing and weathering. Both the basalts and peridotites have significant secondary porosity. The Hawasinah Nappe is composed of limestone dominated by sediments of the Hamrat Dura Group, Al Aridh Group and Umar Group (Permian to Cretaceous). Secondary porosity is present in the carbonates due to folding and weathering along joint and bedding plates".*

Source: MWR

Figure 3.10 Landsat Image (1996) of Wadis Taww and Ma'awil

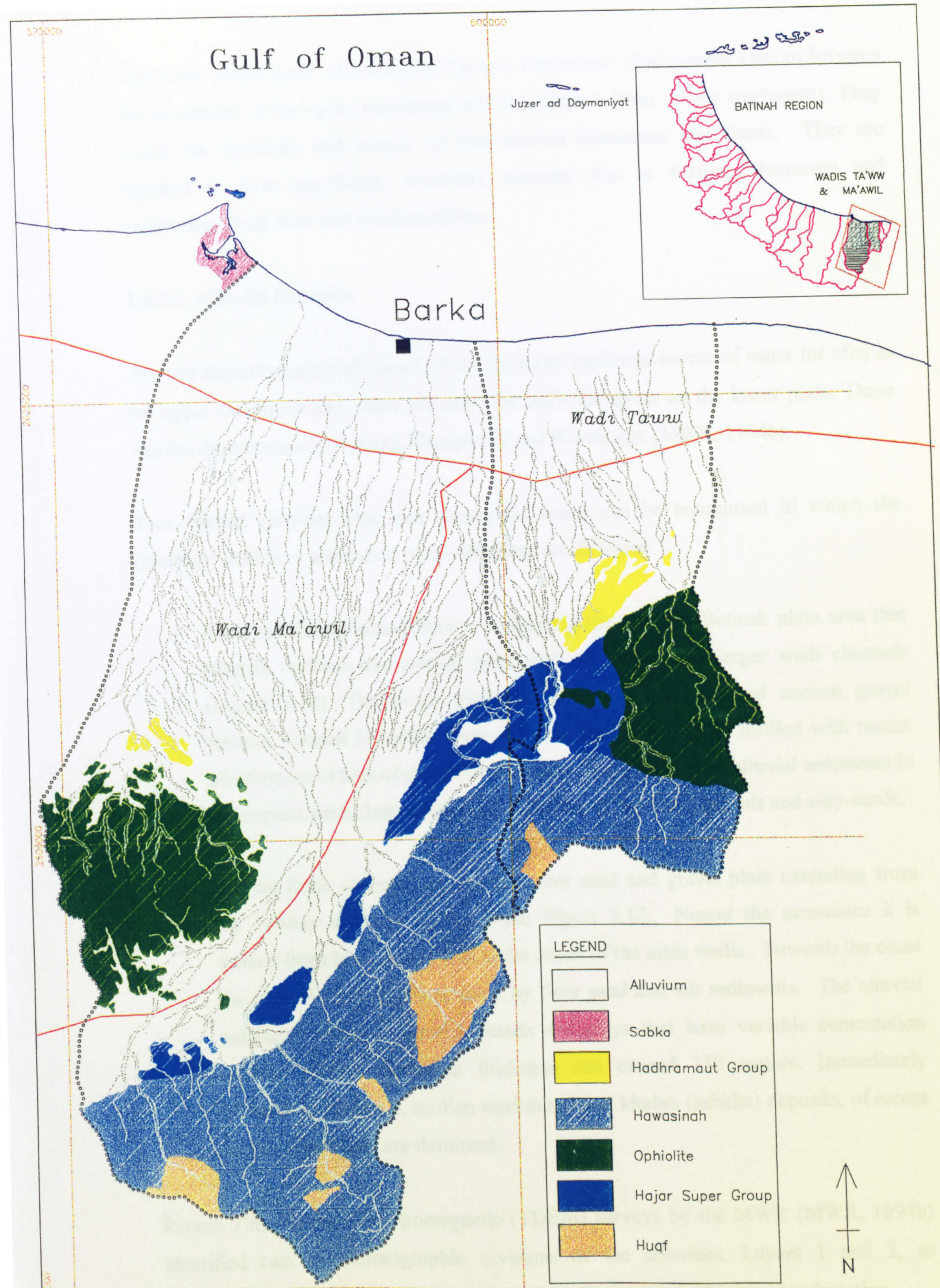


Figure 3.11 Simplifed Geology Wadis Taww and Ma'awil

There are small areas of outcrop of Tertiary Limestone (Hadhramaut Group) between the mountains of the upper catchment and the Batinah Plain (lower catchment). They overly the Ophiolite and consist of inter-layered limestones and cherts. They are reported to have significant secondary porosity due to folding, fracturing and weathering along joint and bedding planes.

3.3.2.2. Alluvial Deposits

Alluvial deposits have traditionally been the most important source of water for aflaj in the upper catchment and, more recently, for wells for farms on the lower plain. These alluvial deposits are of Tertiary, Quaternary and Recent age (MWR, 1994b).

Two distinct physiographic and geological zones can be recognised in which the lithology, thickness and extent of the alluvium are different:

i) Piedmont/Intermontane Zone - comprising the elevated Batinah plain area that extends between the coastal plain and mountains and larger wadi channels (Figure 3.12). The lower piedmont areas are composed of ancient gravel terraces, incised by active wadi channels and subsequently infilled with recent alluvium up to tens of metres in thickness. The uncemented alluvial sediments in the current wadi channels typically consists of boulders, gravels and silty-sands.

ii) Coastal Zone - comprising an extensive sand and gravel plain extending from the Tertiary outcrops to the coast, Figure 3.12. Nearer the mountains it is formed from large gravel fans at the outlet of the main wadis. Towards the coast the plain flattens and is covered by finer sand and silt sediments. The alluvial sediments comprise gravels, sands and clays that have variable cementation (MWR, 1995c). Sediment thickness can exceed 350 metres. Immediately adjacent to the coast, aeolian sand dunes and khabra (sabkha) deposits, of recent to sub-recent age, are dominant.

Recent Time Domain Electromagnetic (TDEM) surveys by the MWR (MWR, 1994b) identified two hydrostratigraphic divisions of the alluvium, Layers 1 and 2, as represented in Figure 3.13. Layer 1 comprises of sub-recent alluvium, has low clay

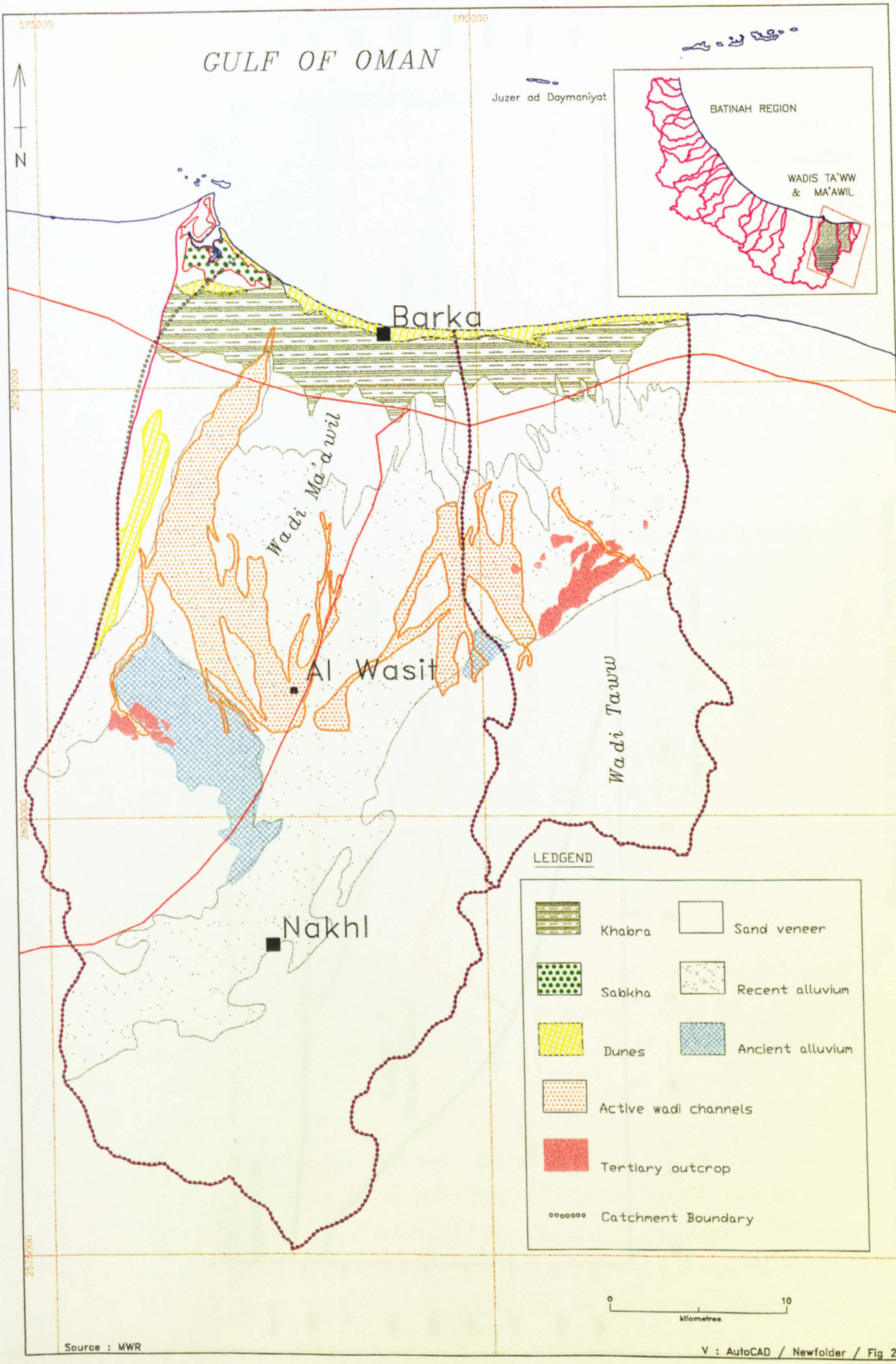
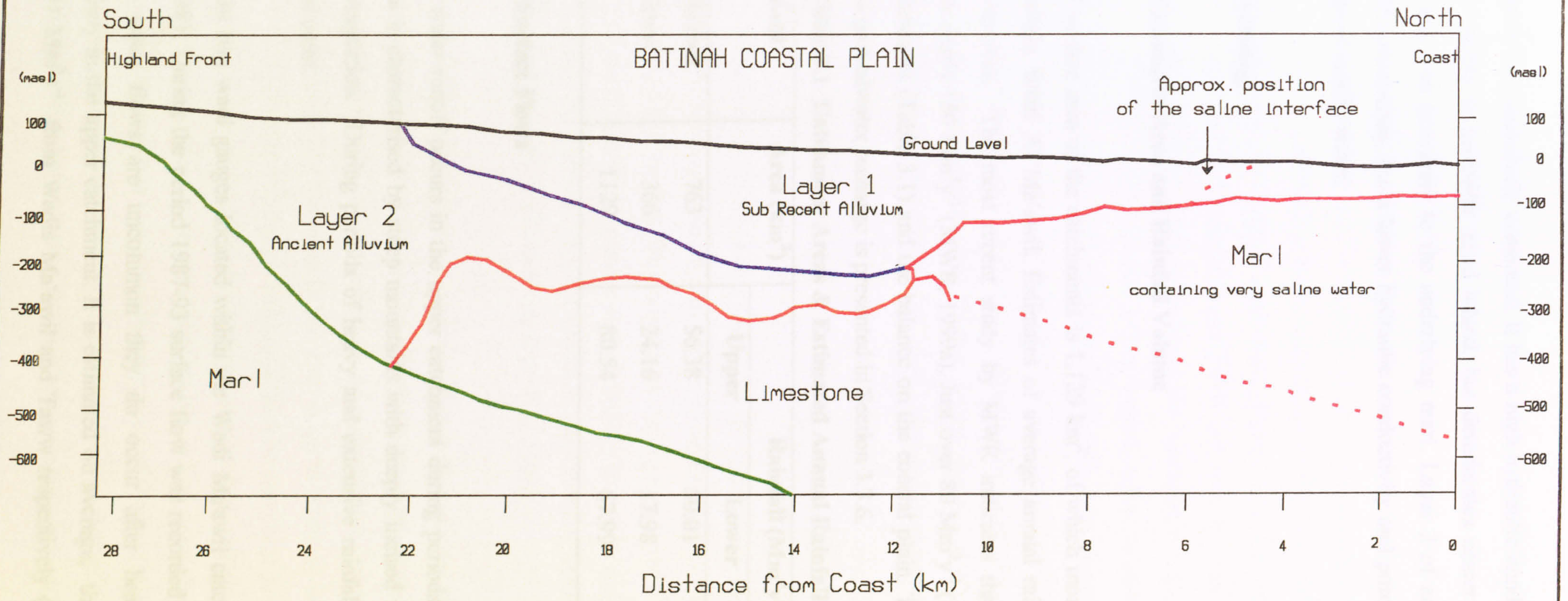


Figure 3.12 Alluvial Plains Taww and Ma'awil



Source: MWR, 1995c

Figure 3.13 Alluvial Plain Cross Section

content and is not extensively cemented. It has a high hydraulic conductivity (20 md^{-1}) and water quality is generally good inland, but deteriorates nearer to the sea water interface and with proximity to the underlying marl. Layer 2 of ancient alluvium is closer to the mountains, has a lower hydraulic conductivity and porosity but generally contains good quality water.

3.3.3. Hydrology

3.3.3.1. Catchment Area and Rainfall Volume

The total surface area of the catchments is 1,129 km^2, of which more than 70% of the area is within Wadi Al Ma'awil. Estimates of average annual rainfall volume vary between sources. The most recent study by MWR indicates that total rainfall on average is nearly 150 Mm^3y^{-1} (MWR, 1999a). Just over 80 Mm^3y^{-1} (53%) occurs in the upper catchment (Table 3.1) and the balance on the coastal plain. The contribution of rainfall to groundwater recharge is presented in Section 3.3.6.

Table 3.1 Catchment Areas & Estimated Annual Rainfall Volume

Catchment	Area (km^2)	Rainfall (Mm^3y^{-1})		
		Upper	Lower	Total
Wadi Ma'awil	763	56.38	50.01	106.39
Wadi Taww	366	24.16	17.98	42.14
Total	1129	80.54	67.99	148.53

3.3.3.2. Surface Flows

Surface water runoff occurs in the upper catchment during periods of intense rainfall. The area is characterised by steep mountains with deeply incised valleys (wadis) and sparse vegetation. During periods of heavy and extensive rainfall surface flow may reach the coast.

There are two wadi gauges located within the Wadi Ma'awil catchment with records since 1983. During the period 1987-93 surface flow was recorded eight times. While surface water flows are uncommon they do occur after heavy rainfall events, particularly in the upper catchment. It is estimated on average, that 6.8 Mm^3y^{-1} (4.41 and 2.41 Mm^3y^{-1} from Wadis Ma'awil and Taww respectively (Figure 3.14)) flows

from the upper catchment annually onto the lower plain (MWR, 1999a). The water contributes approximately 2.2 Mm^3y^{-1} to groundwater recharge.

A relatively small volume of surface flow discharges from the lower catchment to the sea, estimated to be on average 1.1 Mm^3y^{-1}, virtually all from Wadi Ma'awil (Figure 3.15). Three recharge dams have been constructed in the catchments since 1991 to capture surface runoff in the upper coast zone (Figure 3.2). Two dams, Ma'awil and Halban, are located in Wadis Ma'awil and Taww respectively. The third dam, Taww, straddles the surface water boundary between the catchments. This latter dam would appear to contradict the classification of the surface water boundaries. More recent studies by MWR have listed a sub-catchment between the two catchments referred to as Ajal (MWR, 1999a). For the purpose of this study the original surface water boundaries of Wadis Taww and Ma'awil have been retained. The three dams have a combined reservoir volume of 19 Mm^3 (MWR, 1999b). During the period 1991-97 the dams are estimated to have contributed a total of 47 Mm^3 to groundwater recharge (MWR, 1997).

3.3.4. Groundwater Occurrence

In the upper catchment groundwater occurs in the Quaternary and Recent alluvium deposits in active wadi channels. It also occurs in the fractures of the Autochthonous B formations giving rise to high flow springs at the highland front. Aflaj in the upper catchments are fed from these sources. It is speculated that there may also be significant water storage in the Samail Nappe Ophiolites and Tertiary limestones, though few boreholes have been drilled into these areas (MWR, 1995c).

The most significant groundwater resources occur in the coastal aquifer, underlying the coastal plain. This aquifer provides virtually all (apart from several small desalination units for potable supply) of the water for agricultural and domestic demand on the lower Coastal Plain. The alluvium in this area is up to 350m in depth as discussed in Section 3.3.2.2). Recent drilling investigations indicate that there is a trough-like feature in the centre of the plain with significant water storage volume (see Figure 3.13). Though the extent, storage volume and quality has not yet been fully quantified, tentative estimates indicate it contains in excess of 1,000 Mm^3 (MWR, 1995c). This is a significant resource which could contribute to supporting domestic water uses not only on the South Batinah but also as a strategic resource for use in the municipality of the

Greater Muscat area to the east.

Water recharges to the alluvium of the Coastal Plain via direct recharge from rainfall and surface water inflows, and as through flows from the upper and adjacent catchments within the alluvium and bedrock. Groundwater through flows are estimated to be in the order of 40 Mm^3y^{-1}, of which 32 Mm^3 are from bedrock and the balance from alluvium (MWR, 1999a). Figure 3.14 shows the distribution of groundwater inflows from the upper to lower catchment for Wadis Taww and Ma'awil.

The trends in groundwater levels have been monitored since the mid 1970s. They indicate that there has been a progressive decline in the water level particularly, on the lower coastal plain. Figure 3.14 presents hydrographs for three monitoring wells located within the study area, approximately 10 km from the coast. These wells are located within the zone of recent agricultural development. Over the period 1974-94 water levels declined from several metres above sea level to, to more than four metres below.

Due to the impact of over-abstraction of the aquifer on the adjacent to the coast (as discussed in Chapter 4), there is also inflow of sea water. Total inflows of sea water are estimated to be in the order of 38 Mm^3y^{-1} (Figure 3.15), with 18.5 and 19.1 Mm^3y^{-1} entering Wadis Ma'awil and Taww respectively.

Figure 3.16 presents groundwater contours for the coastal plain interpreted from monitoring wells within the catchments for 1974 and 1994. It has been suggested that the 1974 water levels represented the situation when recharge was at least equivalent to average annual demand (MWR, 1994b). As indicated in 1974, water levels were above sea level and therefore provided a positive hydraulic gradient toward the coast. The 1994 water levels indicate a decline in water levels over the 20 years, 1974-94. While there has been a general decline in water levels in the lower catchment, there are also several distinct "holes" where levels are more than five metres below sea level. More recent evaluation of groundwater levels indicates the groundwater levels have continued to decline and in part of the study area are now more than seven metres below sea level (MWR, 1999a).

The impact on water users of these changes within the lower catchment may be expressed in terms of both water quantity and quality. It has resulted in reduced well

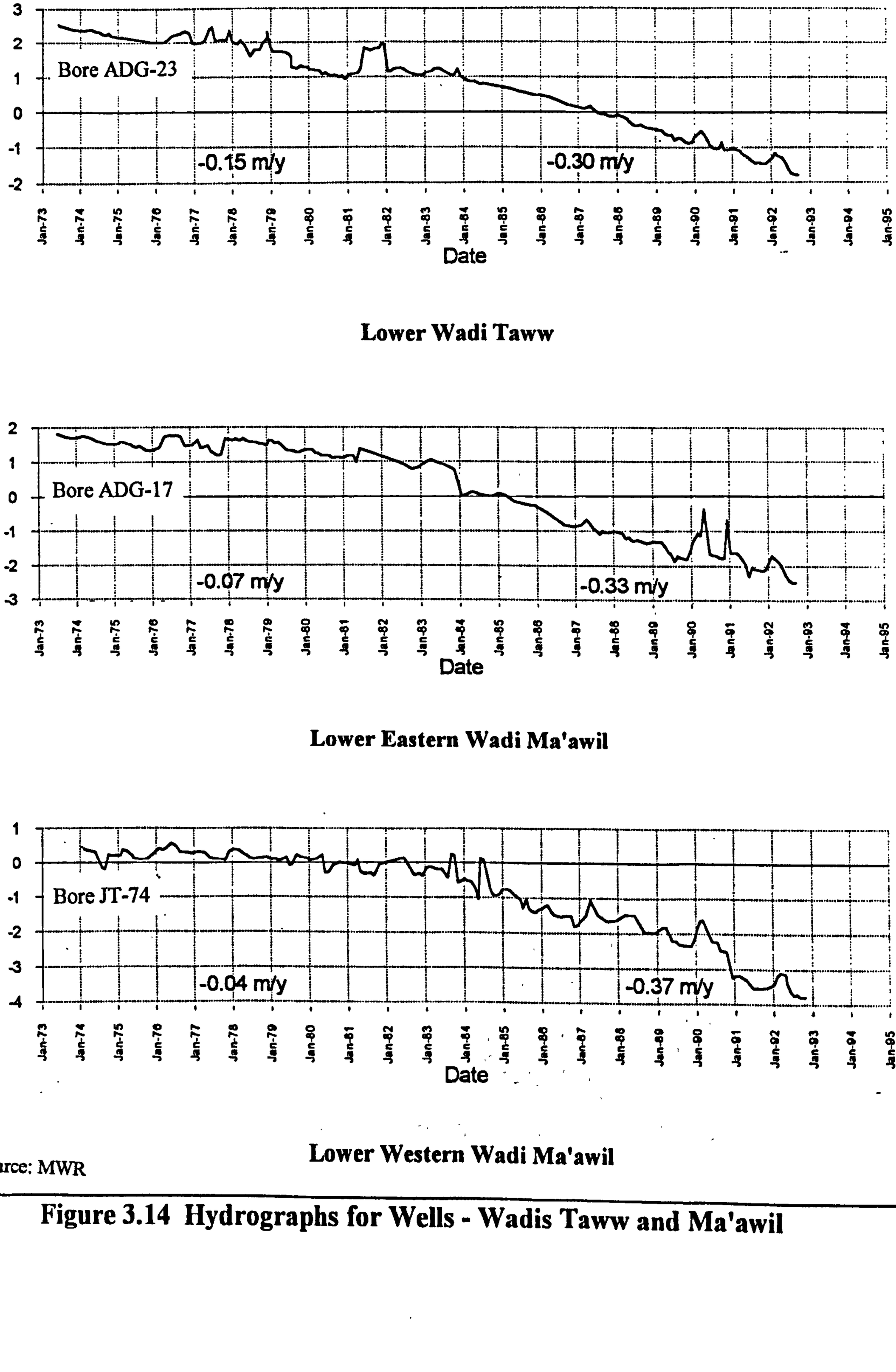
yields, particularly in shallow hand dug wells near the coast which in some cases have less than a metre of static water. It has also created the hydraulic gradient for the intrusion of sea water into the aquifer. The resultant deterioration of water quality and impact is discussed in Section 3.3.5. This depression in groundwater levels is a function of the increase in water abstraction for the irrigation of new farms developed since the mid 1970's. The history of development of farms in the catchments is further discussed in Chapter Four.

3.3.5. Groundwater Quality

In the upper catchment water quality is generally good, which is attributed to the close proximity of the recharge source (MWR, 1994b). In the upper portion of the coastal aquifer water quality is also good, with electrical conductivity less than a 1,000 μScm^{-1}.

On the lower Coastal Plain water quality deteriorates with proximity to the coast. As discussed above, over-exploitation of groundwater since the mid 1970's has resulted in saline intrusion into the aquifer. There has also been an increase in water salinity further inland, possibly due to the percolation of leachates from irrigation.

Groundwater quality on the Batinah Coastal Plain has been monitored by the MWR and its predecessor organisations since the early 1980's. The results are presented periodically in "Salinity Reports", which highlight the changes in water quality and particularly the expansion of areas of water with electrical conductivity greater than 2,000 μScm^{-1}. In the period 1983-97 this area expanded by 44 % while the area with more than 6,000 μScm^{-1} increased by more than 30%. As indicated in Figure 3.17 there has been a general deterioration of water quality within 10 km of the coast over this period. This is having a major impact on agricultural and domestic water supply for farms and villages adjacent to the coast (further discussed in Chapter Four).



Source: MWR

Figure 3.14 Hydrographs for Wells - Wadis Taww and Ma'awil

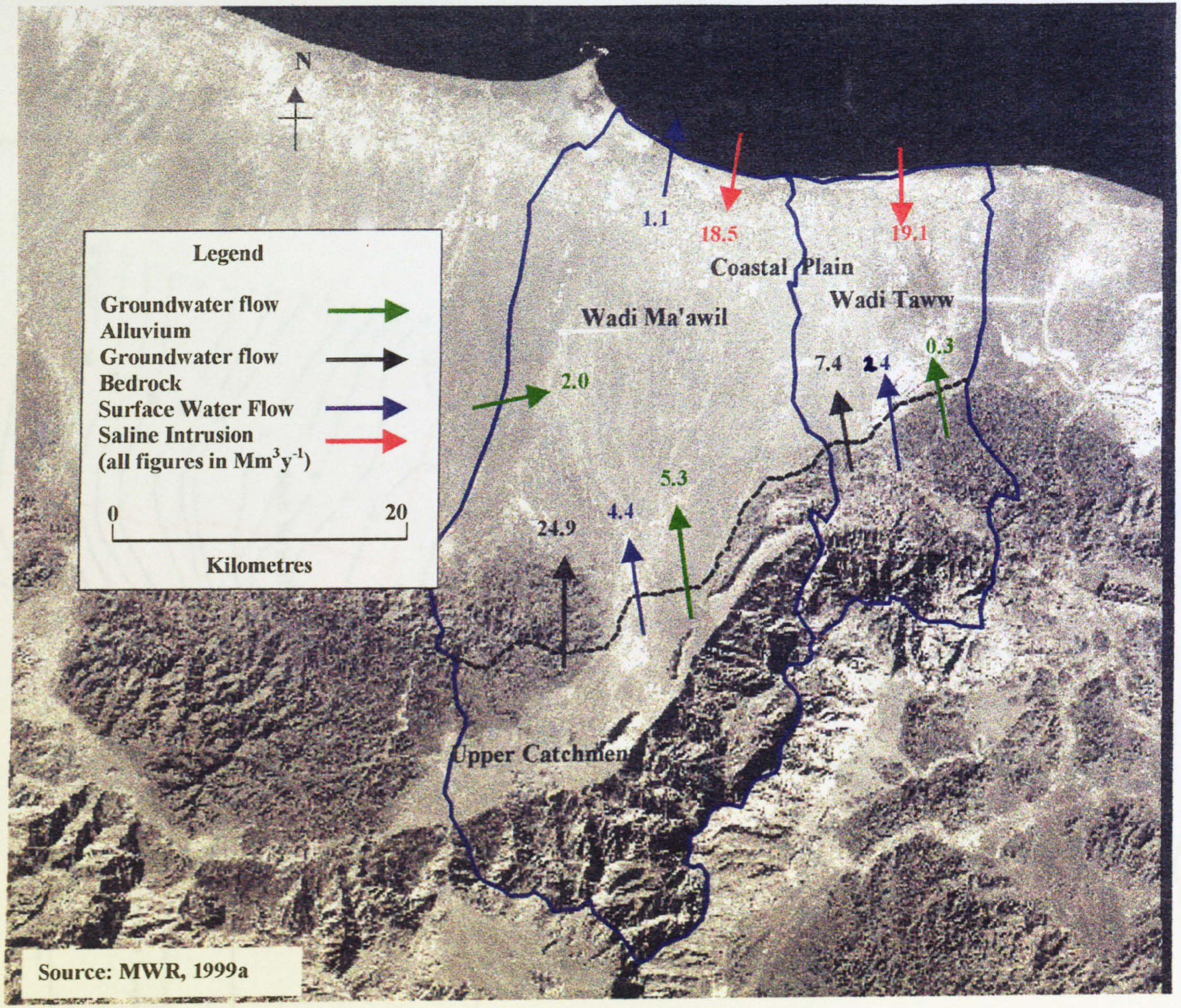
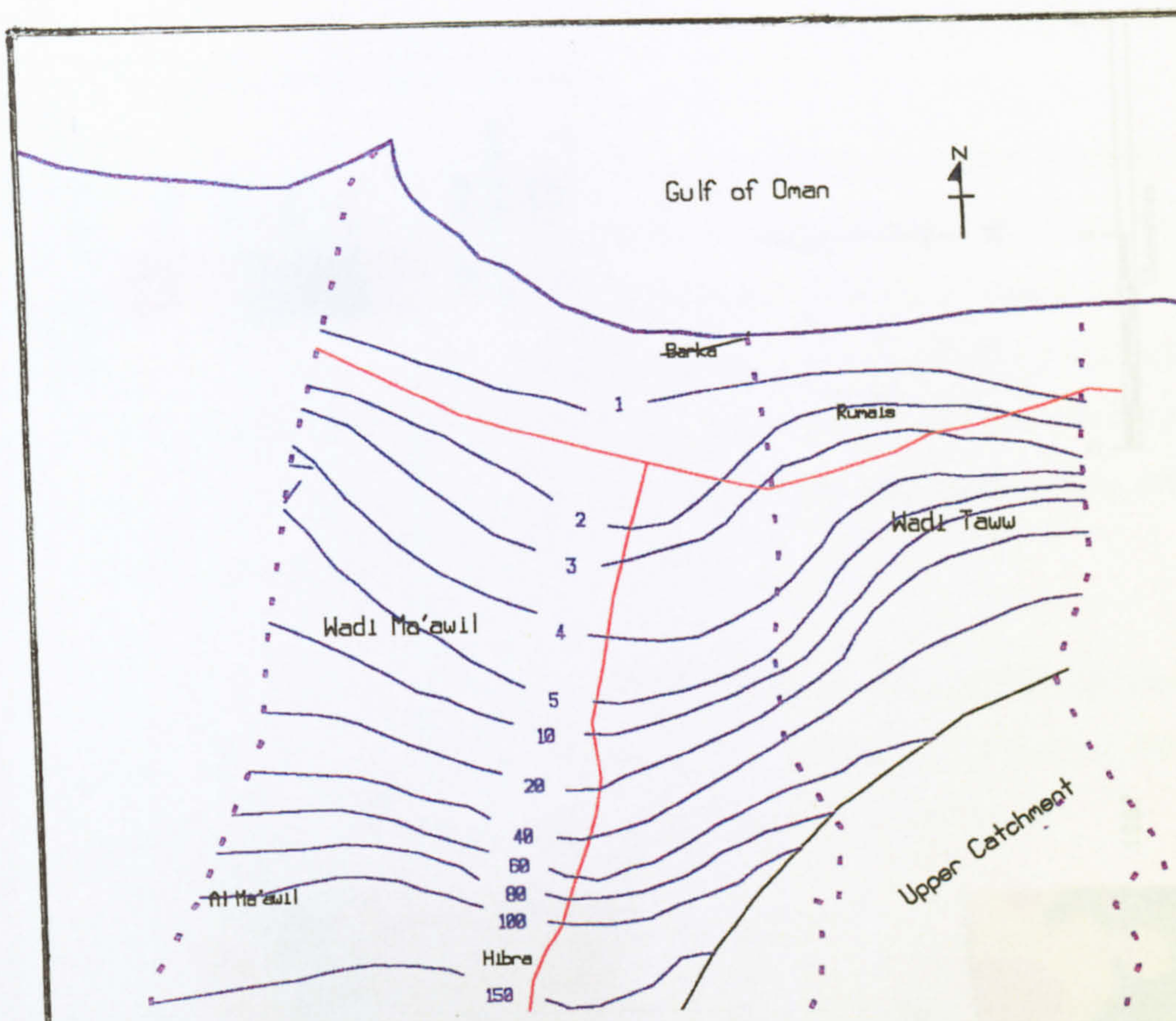
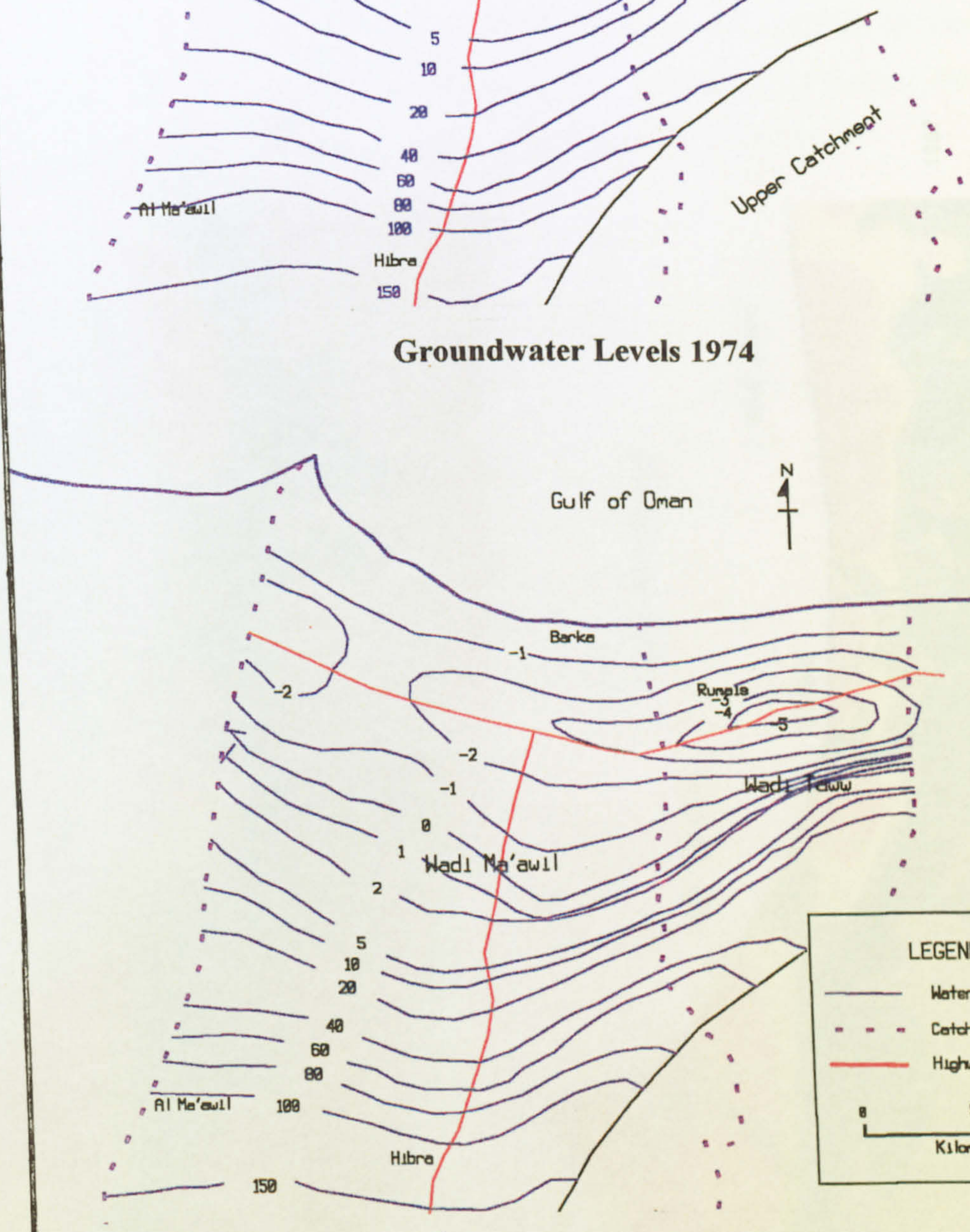


Figure 3.15 Surface and Ground Water Flows to Coastal Plain



Groundwater Levels 1974

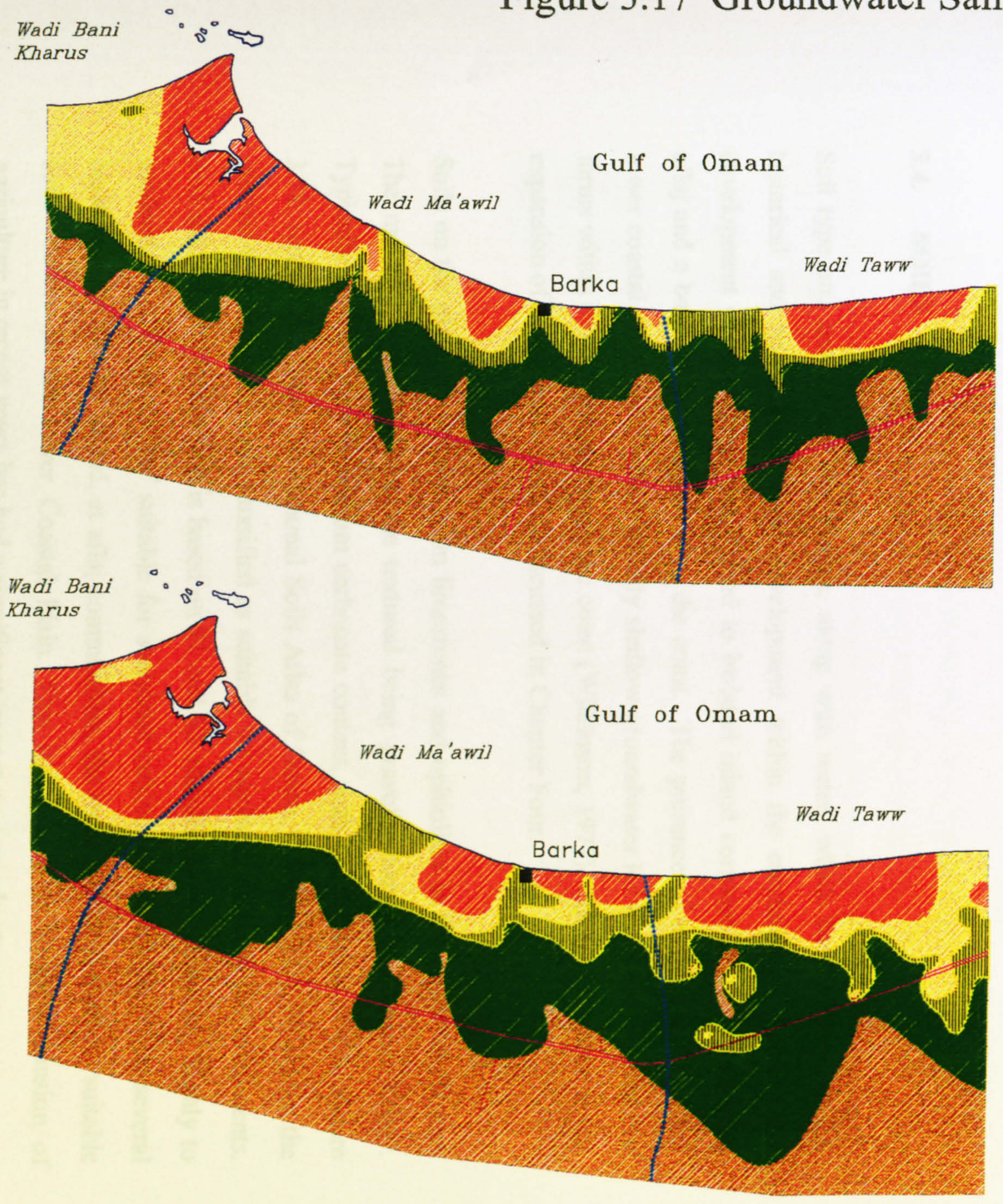


Groundwater Levels 1994

Source: MWR 1995c

Figure 3.16 Groundwater Levels on Coastal Plain 1974-94

Figure 3.17 Groundwater Salinity 1983 - 1997



EC VALUES (μScm^{-1})

16000
10000
6000
2000
0

TOWN
CATCHMENT
ROAD
COAST

N

5 0 5
kilometres

This Map Is Produced by Data Base – AutoCad

Source MWR : (1999)

V :/ AutoCAD / New Folder / Salinity

3.3.6. Groundwater Recharge

The most current estimate for recharge within the catchments is that compiled by MWR for the National Water Resources Master Plan (MWR, 1999a). For the purposes of this study, discussion is confined to recharge to the Coastal Plain, as this is most relevant to the impact on water resources within the study area. Total recharge to the aquifer on the Coastal Plain is estimated at 49 Mm^3y^{-1}, of which 10 Mm^3 is from rainfall and surface water inflows. The balance is from groundwater through-flows within alluvium and bedrock (Section 3.3.4).

Groundwater recharge is further discussed in Chapter Four, within the context of the water balance within the study area, and in Chapter Seven as part of the analysis of current and future trends in water demand and demand management.

3.4. SOILS

Soil type and quality are key factors, along with water, which have influenced the historical and recent agricultural development within the catchments. Historically development of agriculture was limited to isolated inland communities irrigated from aflaj and a band of farms adjacent to the coast. The presence of suitable soils on the lower coastal plain along with relatively shallow groundwater led to the development of farms within a five km band along the coast (Wilkinson, 1977). The recent trends in the expansion of new farms is further discussed in Chapter Four.

Soils on the plain are derived from limestones and ophiolites in the upper catchment. The majority of soils are coarse textured being gravelly, sandy and coarse loamy. Typically they are high in calcium carbonate content, with pH in excess of 8.0. Figure 3.18, reproduced from the National Soils Atlas of Oman, (MAF, 1990), illustrates the general distribution of soils classified as suitable for agriculture within the catchments. Soil suitability classification is based on S1 and S2 classification, defined as "highly to moderate" and "marginally" suitable for sustained cultivation. While there are several isolated areas located inland, at aflaj communities, the most extensive area of "suitable soils" occurs on the lower Coastal Plain. This is the area in which expansion of agriculture in recent years has had a significant impact on groundwater resources.

A detailed soil survey was completed by MAF of the lower catchment on the South Batinah in 1992 (MAF, 1992). The survey was based on classification of soil types at the farm level with detailed analysis of soil and water parameters. While the mapping methodology was somewhat unconventional being based on property rather than soil type boundary, the survey nevertheless provides the most detailed interpretation of soils on the lower Plain.

The survey identified six main soil groups, with the Torrifluvents (60%) and Torriothents (20%) being the most common, Table 3.2.

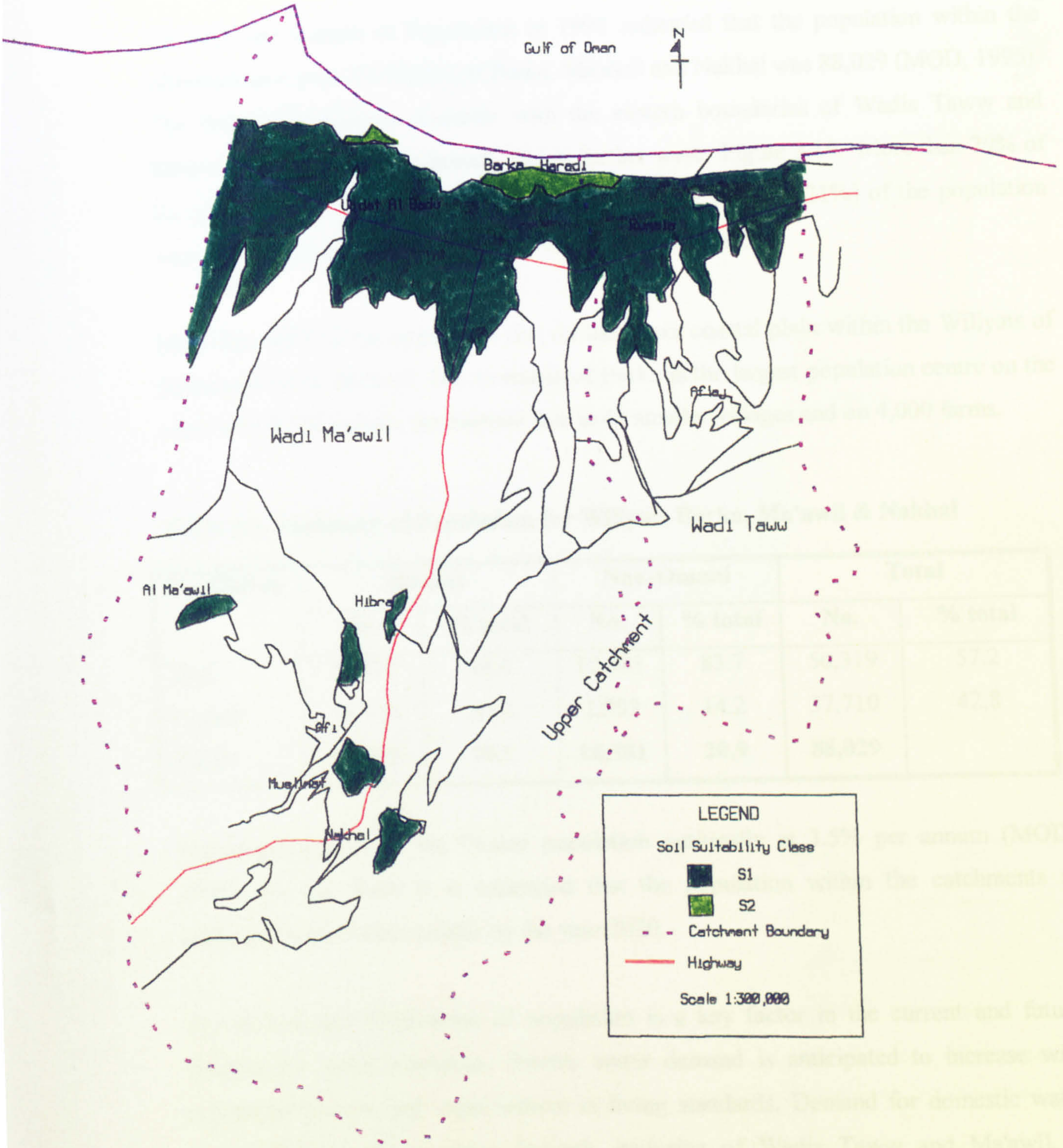
Available waterholding capacity (AWC) of soils within the study area range from less than 60 up to 150 mm m^{-1}. Generally AWC decreases with distance from the coast along with the increase in sand and gravel content.

Permeability of the soils is moderate to moderately rapid typically within the range 5-15 cmh^{-1}. No drainage problems where identified during the MAF survey. Field observations confirm this point with no obvious or reported drainage problem on farms even with excessively high irrigation rates.

Soil salinity on 50% of the surveyed area was less than 4 dSm^{-1}, while on more than 30% of sites it was more than 8 dSm^{-1} and nearly 15% were classified as extremely saline (more than 64 dSm^{-1}). While the distribution of high salinity soil was not published, it is anticipated that it correlates well with the distribution of groundwater salinity.

Table 3.2 Summary of Soil Groups

Soil Group	Area (%)
Salorthids	8.2
Gypsiorthids	1.0
Calciorthids	0.9
Torripsamments	8.4
Torrifluvents	61.4
Torriorthents	20.2



Source: MAF, 1990

Figure 3.18 Soil Suitability

3.5. HUMAN RESOURCES

3.5.1. Population

The National Census of Population in 1993 indicated that the population within the administrative areas (Wiliyats) of Barka, Ma'awil and Nakhal was 88,029 (MOD, 1995). The Wilayat boundaries coincide with the eastern boundaries of Wadis Taww and Ma'awil and extend approximately 10 km further west, Figure 3.19. More than 79% of the population were Omani nationals, Table 3.3. The balance (21%) of the population were non-Omani's, predominately expatriate farm workers.

More than 80% of the population live on the lower coastal plain within the Wiliyats of Barka and lower Ma'awil. The township of Barka is the largest population centre on the coast with 8,552 people, the balance live in 43 smaller villages and on 4,000 farms.

Table 3.3 Summary of Population for Wiliyats Barka, Ma'awil & Nakhal

Population	Omani		Non-Omani		Total	
	No.	% total	No.	% total	No.	% total
Male	34,531	49.6	15,381	83.7	50,319	57.2
Female	35,117	50.4	2,593	14.2	37,710	42.8
Total	**69,648**	**79.1**	**18,381**	**20.9**	**88,029**	

Population growth of the Omani population nationally is 3.5% per annum (MOD, 1995). On this basis it is estimated that the population within the catchments is predicted to more than double by the year 2020.

The growth and distribution of population is a key factor in the current and future demand for water resources. Potable water demand is anticipated to increase with population growth and improvement in living standards. Demand for domestic water consumption in the southern Batinah, inclusive of Wadis Taww and Ma'awil, is predicted to double by the year 2020 (Mott, 1991). Domestic consumption is a relatively small proportion of total demand, at less than three percent (MWR, 1996b&c), but is greatest in the population centres on the lower coastal plain, within the area most affected by deteriorating water quality over the past 20 years. As an alternative to ground water supplies it has been

575000

600000

Gulf of Oman

Juzer ad Daymaniyat

BATINAH REGION

WADIS TA'WW & MA'AWIL

Barka

Wiliyat Barka

Al Wasit

Khatum

Wiliyat Ma'awil

Wiliyat Nakhl

Nakhl

Al Ghubrah

Hadsh

2625000

2600000

2575000

Legend

- Wiliyat Barka
- Wiliyat Ma'awil
- Wiliyat Nakhl
- Catchment boundary

N

0 10

kilometres

Produced by GIS AutoCAD Unit

V / AutoCAD /NewFloder / Willyat

Figure 3.19 Wiliyat Boundaries & Population Centre

proposed to construct a desalination unit near Barka to meet future domestic water demand (Observer, 1996).

Expatriate workers are an important component of water resource management within the catchments. It is estimated that approximately 20% of the expatriate workforce in the South Batinah region are employed in the agricultural sector (MOI, 1993). A survey of 50 farms in the region in 1992 indicated that all the permanent labourers on the farms were expatriates (MAF, 1992). The survey supported the general observation of the predominance of the expatriate workforce in the agricultural sector nationally. These labourers were of various nationalities including Bangladeshi (63%), Pakistani (15%), Indian (13%) and Egyptian (9%). On 80% of the surveyed farms, the labourer is responsible for daily farm management including irrigation. The association with and impact of expatriate labour on agricultural water management is further discussed in Chapter 4.

3.5.2. Government Administrative Units and Institutions

Most government institutions are organised on regional and wilayat boundaries. Wilayat boundaries are essentially historical tribal and village boundaries, which in themselves are also related to the geographical boundaries. There are a number of government ministries and organisations that have direct or indirect responsibilities related to development and water resource management on the southern Batinah and specifically in the Wiliyats of Barka, Ma'awil and Nakhal. The following sections present a brief outline of administrative institutions represented in the catchments.

3.5.2.1. Wali Office

The Wali is the government's local representative within each wilayat. There are three wali offices within the two catchments for the above mentioned wilayats. The Wali is appointed by the Diwan of the Royal Court and in the interests of impartiality is usually selected from an external tribe. One of the principal roles of the Wali is to arbitrate in local disputes, in non-criminal cases his discretionary power is influential in the settlement of these disputes including issues related to land and water. As a government notary his duties also include verification of applications for land, well permits and maintenance or extension of aflaj.

3.5.2.2. Ministry of Water Resources (MWR)

The MWR is represented within the catchments by the Regional Office located at Rustaq to the south of the catchments and a local office at Barka. The Regional Office is responsible for well permitting, aflaj maintenance and extension and water and climate monitoring. All applications for new wells and deepening or maintenance of existing well are directed through the Rustaq office. It is also responsible for the routine monitoring of groundwater levels and quality on the lower coastal plain, the results of which are periodically published in the "Salinity Reports" of the South Batinah.

The Barka office is responsible for the establishment, maintenance and monitoring of studies within catchments of the South Batinah. Facilities at the office include a Water Meter Test Station, for the volumetric calibration of water meters. The office have been associated with the evaluation of current water use patterns on farms in the region and performance of a variety of water meter makes and types.

In the period 1992-93 MWR maintained an office in Barka to support the inventory of wells within the wadis. A'Taww catchment was a pilot area for the evaluation and development of methodologies for the National Well Inventory Project, which was subsequently extended to the remainder of the country and completed in 1995.

3.5.2.3. Ministry of Agriculture and Fisheries (MAF)

Ministry of Agriculture and Fisheries direct support services within the catchments includes an Extension Centre located at Barka and a Research Centre at Rumais. The Extension Centre is responsible for technical support services to the farmers in the South Batinah region, inclusive of the Wiliyats of Barka, Al Ma'awil and Nakhal. The Centre was established in the early 1980's, and is currently staffed with five extension workers.

The Rumais Research Centre is one of four national centres, others being located in the Dakhliyah (Interior) and two in Dhofar. The Centre supports a number of research activities associated with crop and livestock production. It comprises several farms, within the Rumais area. A Training Centre was established in 1996 as a facility for

providing training programmes for both MAF research and extension staff.

3.5.2.4. Ministry of Housing (MOH)

The Ministry of Housing is an important organisation in terms of land allocation and development. It is responsible for the distribution of "new" land for rural development. The terms and conditions of land allocation and purchase has influenced the expansion of agriculture within the catchments. As discussed in the Chapter 4, MOH land distribution policy is a key factor in the expansion of new farms within the catchments.

3.5.2.5. Public Authority for Marketing Agricultural Produce (PAMAP)

PAMAP is a government authority established in the 1980's with responsibilities for the marketing of agricultural produce. The objectives of PAMAP include the support of produce prices to farmers, stability of crop production and produce supply to wholesalers. Within the catchment it maintains an office and distribution centre at Rumais for the purchase and marketing of produce. The Authority has a government subsidy of more than RO 4 million annually. It is currently being privatised which is anticipated to lead to the closure of the Rumais centre. PAMAP policy on crop produce influenced the cropping patterns, with price support and market protection, particularly of seasonal vegetable crops. These mechanisms encourage the production of specified crops, such as tomatoes, cucumber, carrots and water melons for the local market.

3.5.2.6. Oman Bank for Agriculture and Fisheries (OBAF)

OBAF is a government credit agency for the agricultural and fisheries sector. Financial support is offered to farmers through a variety of "soft" loans, for the purchase of equipment and structures. OBAF is represented in the South Batinah region with an office at Barka. The most direct impact of the OBAF on water use has been via support for the MAF modern irrigation programme, with financial support for the farmer share of the programme.

CHAPTER FOUR

AGRICULTURAL DEVELOPMENT AND WATER MANAGEMENT

4.1. INTRODUCTION

As described in Chapter Three, there has been a significant decline in water levels and deterioration of groundwater quality in the lower catchments of Wadis Taww and Ma'awil in the period 1970-95. This deterioration can be primarily attributed to the impact of an increase in the number of farms and the size of the irrigated area and the resultant increase in pumping of groundwater. This Chapter describes the status of farming in the lower catchment in the early 1970s, the development of new farms during the period 1970-95 and the consequent impact on water resources. It outlines water management strategies that have been either adopted or studied with the objective of limiting these impacts. The current rates of abstraction of groundwater are unsustainable and, unless measures are adopted to reduce water demand, will lead to further depletion of the aquifer and continued saline intrusion. The Chapter concludes with a discussion of the options to reduce and/or regulate demand for water in the future.

4.1.1. Sources of Information

A number of regional and national surveys and reports on agriculture and water resources have been completed since the early 1970s. These provide a useful source of information on agricultural development in the lower catchment of Wadis Taww and Ma'awil and include the following:

- Water Resources Survey of Northern Oman in 1973, which included the southern Batinah region, with sample surveys of farms (Gibb, 1976).
- A survey of all wells and agricultural properties in the National Well Inventory Project of Wadis Taww and Ma'awil in 1992-93 by the Ministry of Water Resources (MWR, 1996b and MWR, 1996c).
- South Batinah Integrated Study (MAF, 1992) in 1992 surveyed soils, crops and water quality within all farms in the catchments and included a farming systems survey.
- Study of a New Organisation of Irrigation in Barka-Rumais Area, which examined the opportunities for the establishment of central irrigation system(s) and included a representative survey of farming households (BRGM, 1993).

- Research & Development Surveys in Northern Oman by the University of Durham, which provides useful details of agriculture, land and water use on the Batinah coastal plain. Though the study area was located at Khaburah north of the catchments, it provides some useful indicators of traditional farming systems on the Batinah (Durham, 1982).

4.2. AGRICULTURAL EXPANSION

The South Batinah and in particular the lower catchments of Wadis Taww and Ma'awil have experienced an expansion in the number of farms and cultivated area since the early 1970s. This expansion was initiated following the ascension to power of His Majesty Sultan bin Qaboos Al Said, which ushered a new period of national reconciliation and development. Sultan Qaboos Al Said is largely credited with being the architect of the modernisation of Oman, often referred to as the "renaissance period", with the rapid development of the national economy and infrastructure.

The drive to expand agriculture has been part of a broad national strategy to develop all sectors of the economy, supported from oil revenue. In the agricultural sector this was supported and encouraged by the government with a land allocation programme, financial incentives and subsidies on inputs such as seeds, fertilisers and irrigation systems. The primary purpose of this expansion was the horizontal development of the sector, with an increase in cultivated area. The allocation of new lands, or "white lands" (land not previously developed) opened up an opportunity for citizens to establish farms outside the traditionally farmed areas along the lower coastal plains of the Batinah and Salalah.

The catchments of Wadis Taww and Ma'awil have experienced a large increase in the number of farms and the size of the irrigated area since the early 1970's. This expansion is the result of a combination of factors including proximity to the major population centre of the capital area of Muscat. It has also benefited from new infrastructure, particularly the Batinah highway, which has enabled quick access. The availability of land with soils suitable for development and the presence of shallow, good quality groundwater were also major factors in this development.

4.2.1. Traditional Farming

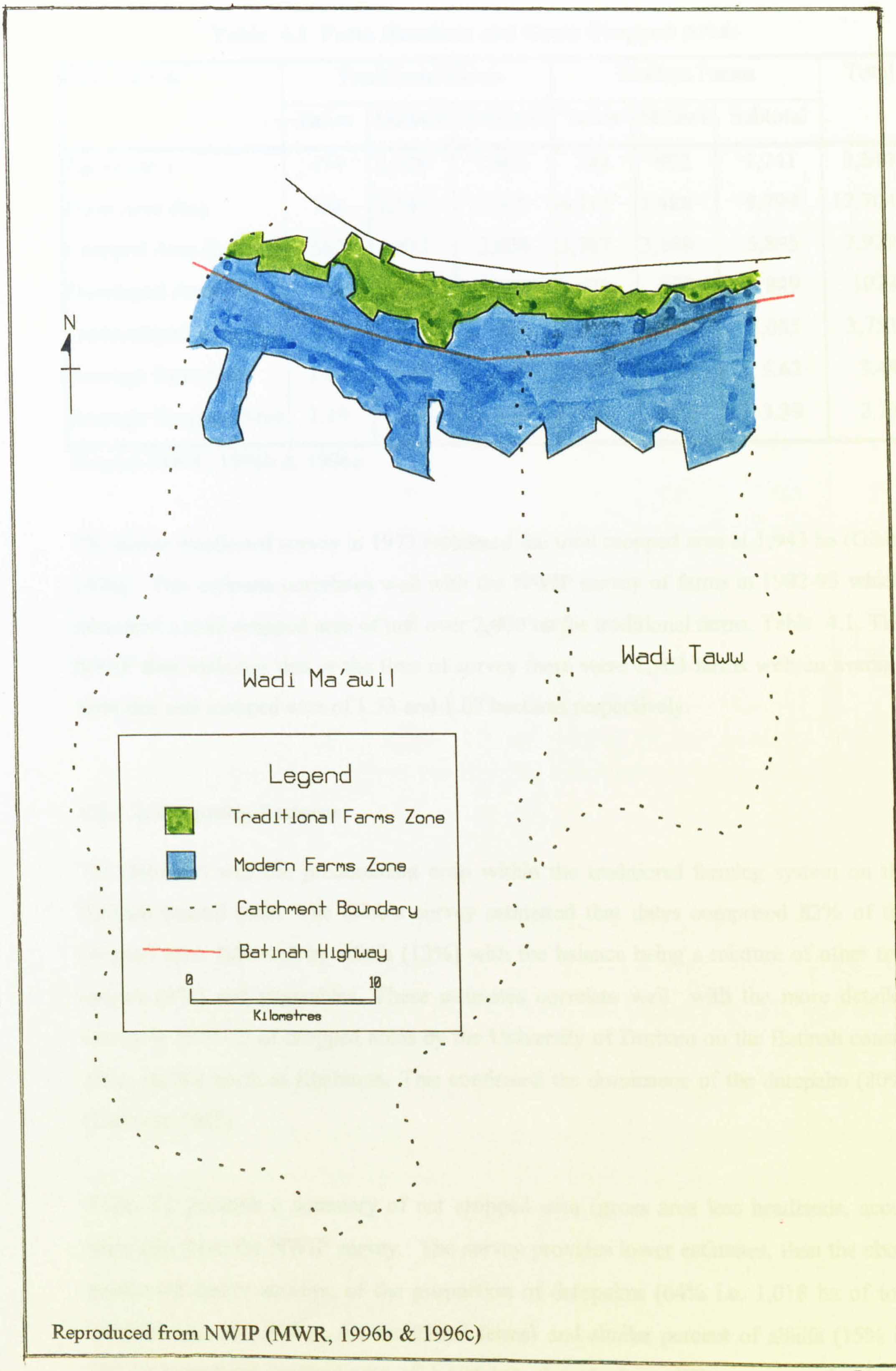
There is limited quantitative information and data on the type and extent of farming on the lower catchments of Wadis Taww and Ma'awil prior to 1970. The first detailed study of the area was initiated by the then Directorate General of Finance as part of a land and water survey of northern Oman in 1973 (Gibb, 1976). The purpose of the survey was to identify areas suitable for agricultural development. The results of this survey plus more recent surveys by MWR and MAF provide an indication of the extent and type of farming being practiced on the lower catchments at the start of the expansion of agriculture in the area.

For the purpose of this thesis traditional agriculture is defined as the farming system and associated structures and practices that existed prior to 1970. This date is taken as the milestone at which in Oman there was a fundamental change in development policy associated with the accession of Sultan Qaboos Al Said and oil wealth. While there was undoubtedly some limited development prior to 1970, development was actively promoted after this period through a number of government led initiatives.

To establish a baseline for comparison of agricultural development, the following sections present a summary of the farming systems that existed within the study area prior to 1970. This is based on a general description of farming and pumping systems, supplemented with information and data from other sources such as surveys and aerial photographs.

4.2.1.1. Farm Numbers and Location

The cultivated area of the lower catchments was described in the early 1970's as a "*discontinuous mosaic of small gardens in a narrow strip within 5 kilometres of the sea*" (Gibb,1976). Figure 4.1 is reproduced from the NWIP and shows the location and extent of traditional and modern farms. The traditional farms are located within a band, within five kilometres of the coast, with intermittent groups of farms stretched along the coast. The grouping of farms was probably primarily a function of proximity to shallow, good quality groundwater and suitable soils, particularly those inland of the saline sabakh soils adjacent to the coastal dunes.



Reproduced from NWIP (MWR, 1996b & 1996c)

Figure 4.1 Location of Traditional and Modern Farms

Table 4.1 Farm Numbers and Gross Cropped Areas

Farm Details	Traditional Farms			Modern Farms			Total
	Taww	Ma'awil	Subtotal	Taww	Ma'awil	Subtotal	
Farms (no.)	474	1,429	1,903	749	992	1,741	3,644
Farm Area (ha)	764	2,141	2,905	4,313	5,486	9,799	12,704
Cropped Area (ha)	562	1,472	2,034	2,707	3,188	5,895	7,929
Developed Area (ha)	46	129	175	479	370	849	1024
Undeveloped Area (ha)	156	540	696	1,127	1,928	3,055	3,751
Average Farm Size	1.61	1.50	1.53	5.76	5.53	5.63	3.49
Average Cropped Area	1.19	1.03	1.07	3.61	3.21	3.39	2.18

Source: MWR, 1996b & 1996c

The above mentioned survey in 1973 estimated the total cropped area at 1,943 ha (Gibb, 1976). This estimate correlates well with the NWIP survey of farms in 1992-93 which measured a total cropped area of just over 2,000 ha for traditional farms, Table 4.1. The NWIP data indicates that at the time of survey there were 1,903 farms with an average farm size and cropped area of 1.53 and 1.07 hectares respectively.

4.2.1.2. Cropping Patterns

The datepalm was the predominant crop within the traditional farming system on the Batinah coastal plain. The Gibb's survey estimated that dates comprised 82% of the cropped area, followed by alfalfa (13%) with the balance being a mixture of other tree species (4%) and vegetables. These estimates correlate well with the more detailed survey in 1973-75 of cropped areas by the University of Durham on the Batinah coastal plain, further north at Khaburah. This confirmed the dominance of the datepalm (80%) (Durham, 1982).

Table 4.2 presents a summary of net cropped area (gross area less headlands, access ways etc) from the NWIP survey. The survey provides lower estimates, than the above mentioned earlier surveys, of the proportion of datepalms (64% i.e. 1,018 ha of total cropped area of 1,594 ha for traditional farms) and similar percent of alfalfa (15% i.e. 247 ha over total cropped area of 1,594 ha), though these differences may be due to

survey methodologies or due to a general decline in area of datepalm in the period between the surveys.

Table 4.2 Summary of Net Cropped Areas

Net Cropped Areas (ha)	Traditional Farms			Modern Farms			Total
	Taww	Ma'awil	Subtotal	Taww	Ma'awil	Subtotal	
Dates	249	769	1,018	368	335	703	1,721
Limes	12	68	80	362	336	699	779
Bananas	1	19	20	14	32	46	65
Mango	5	44	49	187	199	386	435
Coconut	1	6	7	28	21	50	57
Other Trees	18	85	103	308	235	543	646
Alfalfa	63	184	247	176	289	465	712
Grasses	10	24	34	293	649	942	976
Cereals	3	0	3	33	3	37	39
Win Veg	1	28	29	270	175	445	474
Sum Veg	0	5	5	113	55	168	173
Tobacco			0	3		3	3
	363	1,231	1,594	2,156	2,331	4,487	6,081

Source: MWR, 1996b & 1996c

4.2.1.3. Wells & Pumps

On the Batinah coast, water for domestic and irrigation purposes was largely dependent on supplies from wells. Two distinct types of well construction are recognised, the traditional dug well (or *zagira* well), in which water was originally lifted by draft animal (ox or donkey). More recently these have been replaced by boreholes abstracting water by diesel or electric pumps. With animal draft the volume of water was limited and it is reported that the wells were largely used for supplementary irrigation of datepalms and/or winter cereal crops (Durham, 1982). Dug wells are typically square or rectangular in the upper sections, with each side 2-3 m long. Above the water bearing alluvium they are lined with cement blocks. Well depths vary with depth to water level, but most within the study area are less than 15 m total depth.

N

0 10

Kilometres

LEGEND

SUBZONE

ROAD

ZONE BOUNDARY

OPERATIONAL DUG WELL

OPERATIONAL BOREHOLE

DISUSED DUG WELL

DISUSED BOREHOLE

Source: MWR 1996b & 1996c

Figure 4.2 Distribution of Wells in Wadis Taww and Ma'awil

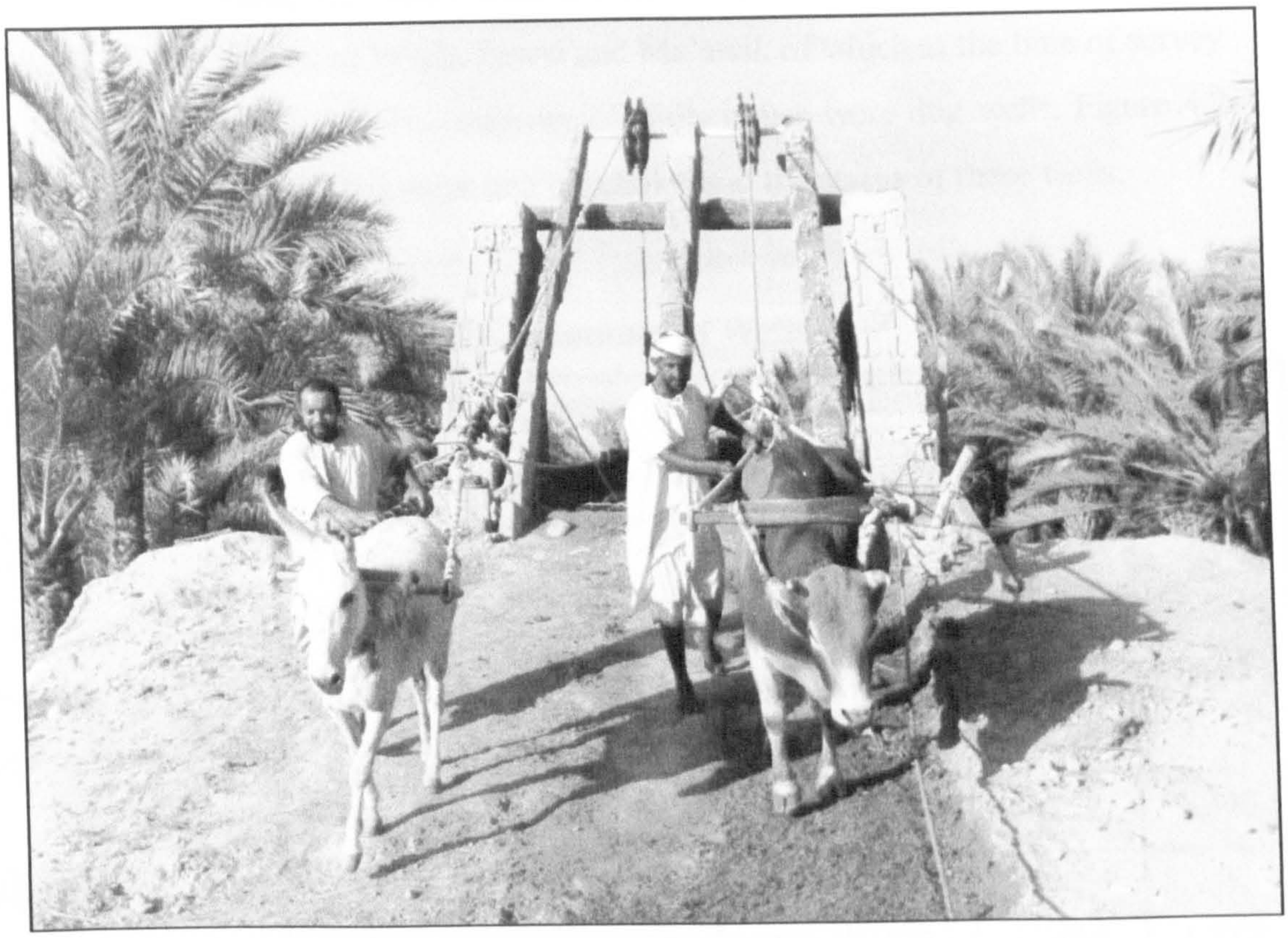


Figure 4.3 Zagaria Well

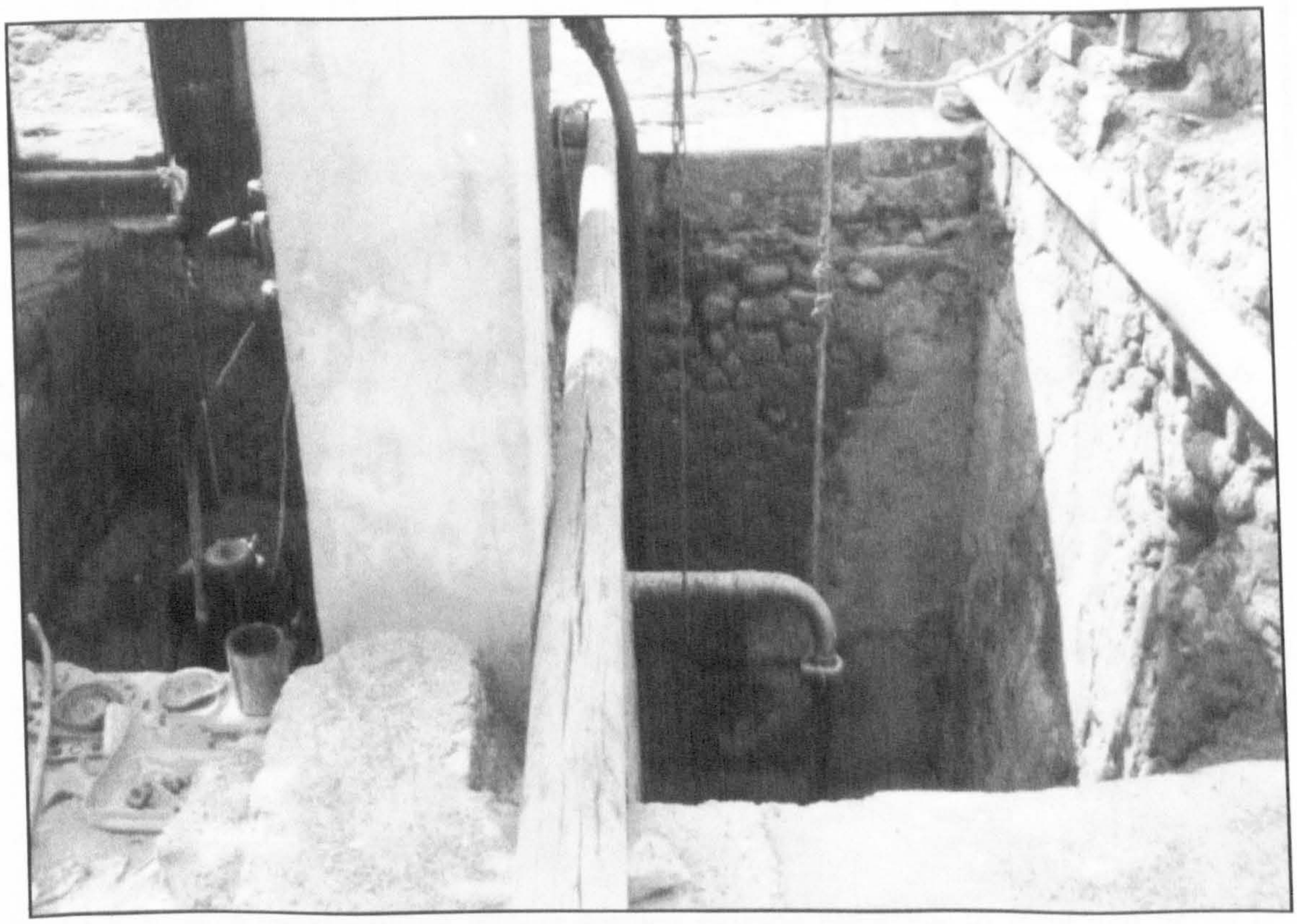


Figure 4.4 Dug Well

There are no early surveys of well numbers within the catchments. Based on the NWIP survey in 1992-93, (Table 4.3) there were a total of 2,852 wells (dug and boreholes), within the lower catchments of Wadis Taww and Ma'awil, of which at the time of survey 2,126 (75%) were operational. The majority of wells in use were dug wells. Figure 4.2 illustrates the distribution of dug wells and boreholes and the status of these wells.

Table 4.3 Summary of Wells

Wells (No.)	Traditional Farms			Modern Farms			Total
	Taww	Ma'awil	Subtotal	Taww	Ma'awil	Subtotal	
Operational							
• Dug wells	503	1,509	2,012	488	1,221	1,709	3,721
• Boreholes	5	107	112	735	778	1,513	1,625
• Other structures	0	2	2	0	0	0	2
Subtotal	508	1,618	2,126	1223	1,999	3,222	5,348
Non-Operational							
• Dug wells	215	443	658	111	343	454	1,112
• Boreholes	6	16	22	245	172	417	439
• Other structures	14	32	46	13	19	32	78
Subtotal	235	491	726	369	534	903	1,629
Total	743	2,109	2,852	1,592	1,533	4,125	6,977

4.2.1.4. Irrigation Methods

Irrigation methods adopted on traditional farms were variations of surface flooding. A number of types of basin irrigation were distinguished including:

- "*gayl*" a circular basin of about 3 m diameter for the irrigation of datepalms and other tree crops, Figure 4.5
- "*gelba*" usually of 20 to 30 m^2 for the irrigation of alfalfa and cereals, Figure 4.6.
- "furrow" a series of furrows within a *gelba* for vegetable crops, Figure 4.7.

Water distribution from the pump and/or surface storage reservoir to *gayl* and *gelba* is via open lined and unlined channels. Lined channels are typically constructed of a

concrete base, with solid cement block sides and plaster on the internal surface. They are relatively simple to make, constructed from locally manufactured materials, Figure 4.8. Other structures are also used, such as inverted siphons for crossing roadways and stilling chambers to reduce water velocities in the main distribution network.

Simple unlined channels, formed and roughly graded *in-situ* in the soil, form a secondary distribution network linking the main channels to the *gayl*(s) or *gelba*(s). Water is diverted by temporary earth bunds into the *gayl* or *gelba* (Figure 4.9).

The adoption of pressurised irrigation methods, such as bubbler, dripper and sprinklers, is relatively recent, from the early 1980s. Virtually all traditional farms did, and largely still do, utilize various forms of surface irrigation distribution and application methods as described above. While in recent times, some forms of improved distribution, such as use of pipes and valves have been adopted, traditional farms have largely not been eligible for government sponsored improvement programmes, as discussed in Section 4.4.1. The NWIP indicated that 1,530 ha (96% of the total of 1,591 ha) of the irrigated area of traditional farms was either "lined or unlined" flood methods, Table 4.4.

Table 4.4 Irrigation Methods

Irrigation Methods (ha)	Traditional Farms			Modern Farms			Total
	Taww	Ma'awil	Subtotal	Taww	Ma'awil	Subtotal	(ha)
Flood Lined	170	599	768	339	548	887	1,655
Flood Unlined	186	576	762	750	611	1,361	2,123
Drip	0	6	6	457	278	736	741
Sprinkler	0	4	4	200	190	389	394
Bubbler	1	34	35	333	184	517	552
Spray Gun	0	1	1	41	207	248	250
Pipe/Hose	3	10	13	25	78	103	115
Boom Irrigator	0	3	3	11	237	249	251
Tanker	0	0	0	0	0	0	0
	360	1,232	1,591	2,156	2,334	4,490	6,081

Source: MWR, 1996b & 1996c

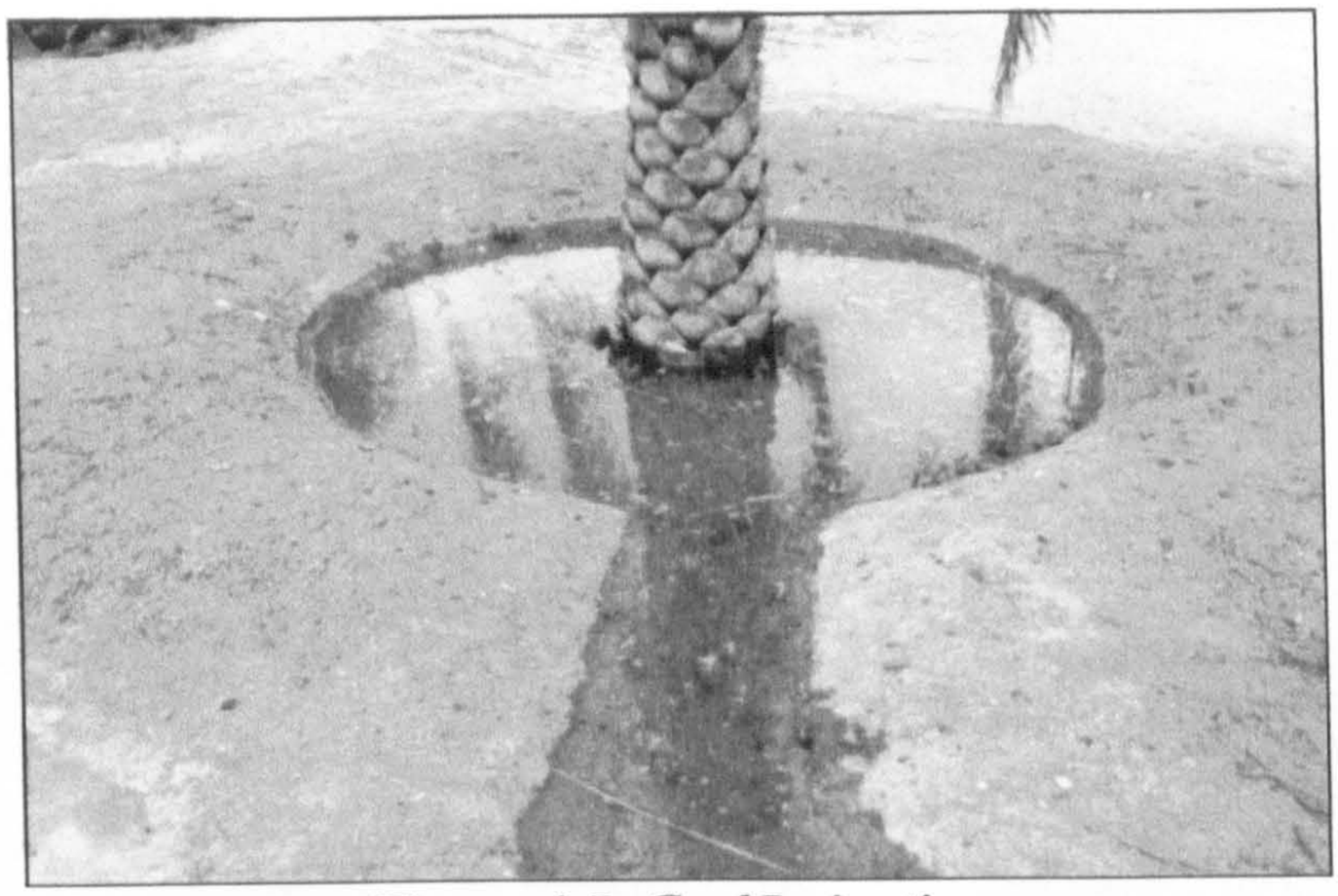


Figure 4.5 *Gayl* Irrigation

Figure 4.6 *Gelba* Irrigation

Figure 4.7 Furrow Irrigation

Figure 4.8 Lined Irrigation

Figure 4.9 Unlined Irrigation

4.2.1.5. Water Demand

Estimates of water demand for traditional farms on the lower catchments of Wadis Taww and Ma'awil vary between sources. In 1973 annual water demand was estimated at more than 18 Mm^3y^{-1} based on a cropped area of nearly 2,000 ha or the equivalent of 11,000 $m^3ha^{-1}y^{-1}$ (Gibb, 1976) . More recent estimates based on the NWIP survey have calculated a higher net water demand (i.e. water consumption due to evaporation and evapotranspiration) of 34 Mm^3y^{-1} (MWR, 1996b & 1996c). The difference between estimates is primarily due to differences in methodologies, with the former based on an average pumping rate and time approach and the latter on crop area and type survey, and irrigation water demands.

Irrespective of differences in estimates of water demand, groundwater levels were above sea level until the mid-1980s, as described in Chapter Three. It is estimated that water demand was equal to or less than annual groundwater recharge from rainfall (MWR, 1994b). Areas of sabkah adjacent to the coastal sand dunes also indicated that there was groundwater through-flow and water loss through surface evaporation.

4.2.1.6. Social & Economic Aspects

Surveys in the early and mid 1970's by Whitehead (Whitehead, 1972) and the University of Durham provide an insight into the social organisation and economics of farming on the Batinah (Durham, 1982).

The surveys indicate that on the majority of farms, the farm owner and his family were the main labour source. Whitehead reported that of the 35 farms surveyed in Masna'ah and Khaburah (north of the study area) all farms were run by the owner, exclusively with the assistance of family members on two thirds of the farms. Similar figures are reported for the more extensive University of Durham study in the Khaburah area, where 80% of farms were run by the owner or a close relative. Labour was employed on a permanent or casual basis on some farms to carry out specific tasks, in particular activities associated with date production, such as pruning, pollination, fruit thinning and harvesting. By the late 1970's it was noted that on farms in Khaburah local labour was being replaced by expatriates. This is attributed to the growth in higher paid off-farm

opportunities in other sectors, particularly the government sector.

Estimates of crop production, contributions to household food supply and returns on traditional farms varies between sources. Date production was a major contribution to household food supply, either as fresh fruit, *rhutab*, consumed during the season, or as dried dates, *tamar*, stored and consumed during the winter months. For dates sold off-farm, there were a variety of marketing mechanisms. They could be sold on the palm, *tana*, with the purchaser being responsible for harvest, or, in the case of the *Mebseli* variety (the main variety on the Batinah) preserved and sold for export (to India and Pakistan). Estimates of net returns based on 1975 prices, indicate they were in the order of around RO 34.7 ($US 90.2) per 100 palms (Durham, 1982) or the equivalent of RO 48 ($US 124.8) per hectare. Based on an average holding with 162 mature palms this could have contributed RO 56 ($US 145.6) per annum to household income.

In the period 1960-80 limes were a major export crop in Oman, produced mostly on the Batinah coast (Whitehead, 1982). Net returns for farms with an average of 38 trees per farm were estimated at RO 159.4 ($US 414.4), or the equivalent of more than RO 1,300 ($US 3,380) per hectare, based on a density of 260 trees per hectare. The export market for dried limes to Iran and Iraq collapsed during the war between the two countries in the 1980s and subsequently never recovered to previous market volumes or prices. Major lime diseases became established during the 1970s and contributed to the long term decline in crop yields.

The principal fodder crop, alfalfa was grown to provide feed to the farmers own livestock with surplus sold either on the farm standing or by the bundle (*mann*) either in the garden or in the village market (*suq*). Prices per *mann* (approximately 4 kg) varied between location and season. In 1974-75 the range was between RO 0.100-0.150 ($US 0.26 - 0.39) (Durham, 1982). Based on 11 cuts per year, net returns were estimated to be the equivalent of 270 RO ($US 702) per hectare.

4.2.2. Modern Farms

Since 1970 there has been an expansion of new farms within the lower catchments of Wadis Taww and Ma'awil resulting from government policies that have promoted

agricultural development through the allocation of land and was supported with both public and private investment. Public sector investment included a range of financial and technical support programmes. Throughout the 1980's and early 90's inputs, in the form of fertilisers, seed, pesticides, irrigation and pump systems and machinery, were available either free or at substantially subsidised prices. Financial support included the provision of soft loans and grants for farm development allocated via government authorities, principally the OBAF. Indirect financial support was offered in terms of guaranteed markets and subsidised commodity prices, via the Public Authority for Marketing of Agricultural Produce (PAMAP). Within guidelines PAMAP operated as a marketing authority, for the purchase and resale of agricultural produce at both the local and national levels.

For the purpose of definition the group of farms developed from the early 1970's onward are described as "modern", meaning more recently developed farms, as opposed the "traditional" farms that largely existed before the current era of national development. The modern farms though far from homogenous in many respects, are largely distinct from traditional farms, particularly in terms of location, size, cropping patterns and irrigation method. More importantly they resulted in a large increase in the demand on groundwater for irrigation purposes over the period 1970-95. The following sections present an outline of the location and main characteristics of the modern farms and their impact on demand for groundwater resources.

4.2.2.1. Farm Numbers and Location

As indicated in Table 4.1 the total number of modern farms was recorded as over 1,700 in 1993 (MWR, 1996b & 1996c). These farms are located inland and up catchment from the traditional farms, as illustrated in Figure 4.1, and form a more or less continuous belt of cultivated lands 5-15 kilometres from the coast. The number of new farms is slightly higher in Wadi Ma'awil (992) than Wadi Tawww (749), which is to be expected given the significantly greater area of the former wadi. Since the early 1990s, however, there has been a reduction in the allocation of land for new farms.

4.2.2.2. Property and Cropped Areas

The total area of modern farms in the study area is nearly 10,000 ha which is more than three times the area of traditional farms (2,905 ha), Table 4.1. At the time of the survey in 1993, approximately 60% of the total property area was cropped (5,895 ha), or nearly a tripling of the cropped area since 1973. The area of undeveloped land (that is land not previously cultivated) but which could be brought under production at a future date was nearly 30%. By comparison on traditional farms more than 90% of the total area was cultivated or in fallow.

Modern farms are larger than the older traditional farms, at an average of 5.63 ha per holding (compared to 1.53 ha for traditional farms). This difference is due in part to the recent land allocation programmes, based on a minimum holding size of 10 feddans (2.38 ha) and the fact that the farms are relatively new, within one generation of ownership, and therefore not yet been subdivided through inheritance.

4.2.2.3. Cropping Patterns

Overall there is a significant change in cropping patterns on modern farms from those practiced on the older traditional farms, Figure 4.10. In particular the proportions of datepalms (16%) and alfalfa (10%) are lower (compared to 64% and 15% respectively for traditional farms) with an increase in the overall percent of grass (22% compared to 3%) and trees crops, particularly mangoes and limes.

4.2.2.4. Wells & Pumps

There are more than 4,100 wells located within the modern farms of which 3,222 (78%) were operational at the time of the NWIP survey in 1992-93, Table 4.3. Non-operational wells (dug and boreholes) accounted for 12% of the total. These included wells abandoned and those drilled but in which a pump had not yet been installed. Boreholes comprised 47% of all wells, compared to 5% on traditional farms, Figure 4.11. This increase in the proportion of boreholes, is probably due to combination of factors, such as the greater depth to water level further inland and the availability of local contractors with drilling rigs.

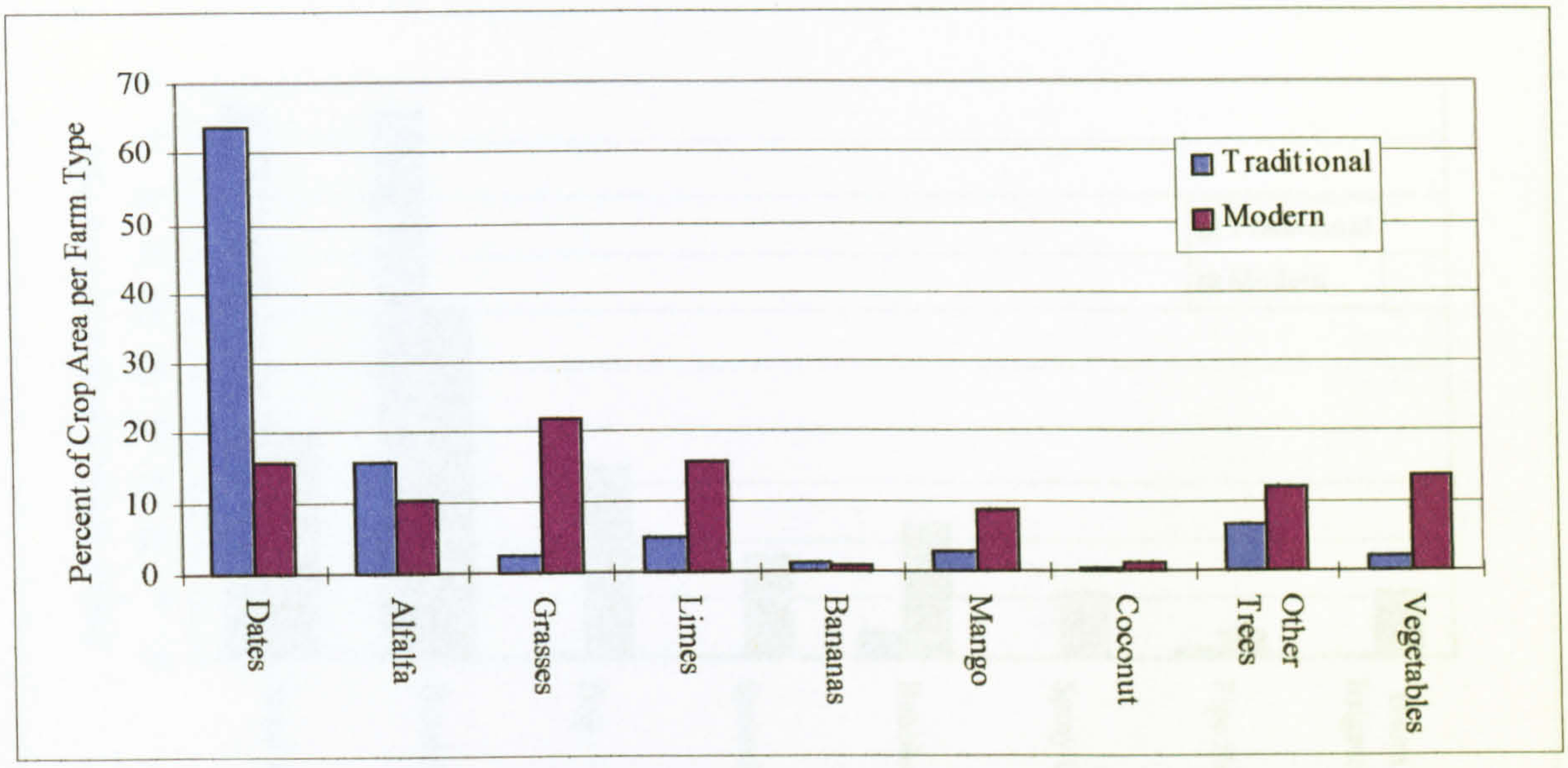


Figure 4.10 Changes in Cropping Patterns

Since the early 1990's and the declaration of well permit regulations (MWR, 1990), all well and prospective well owners require permits for the deepening existing wells and constructing new wells. The impact of the regulation has been to limit, to some extent, the expansion of new wells and the deepening of existing wells, as described in Section 4.4.1.3

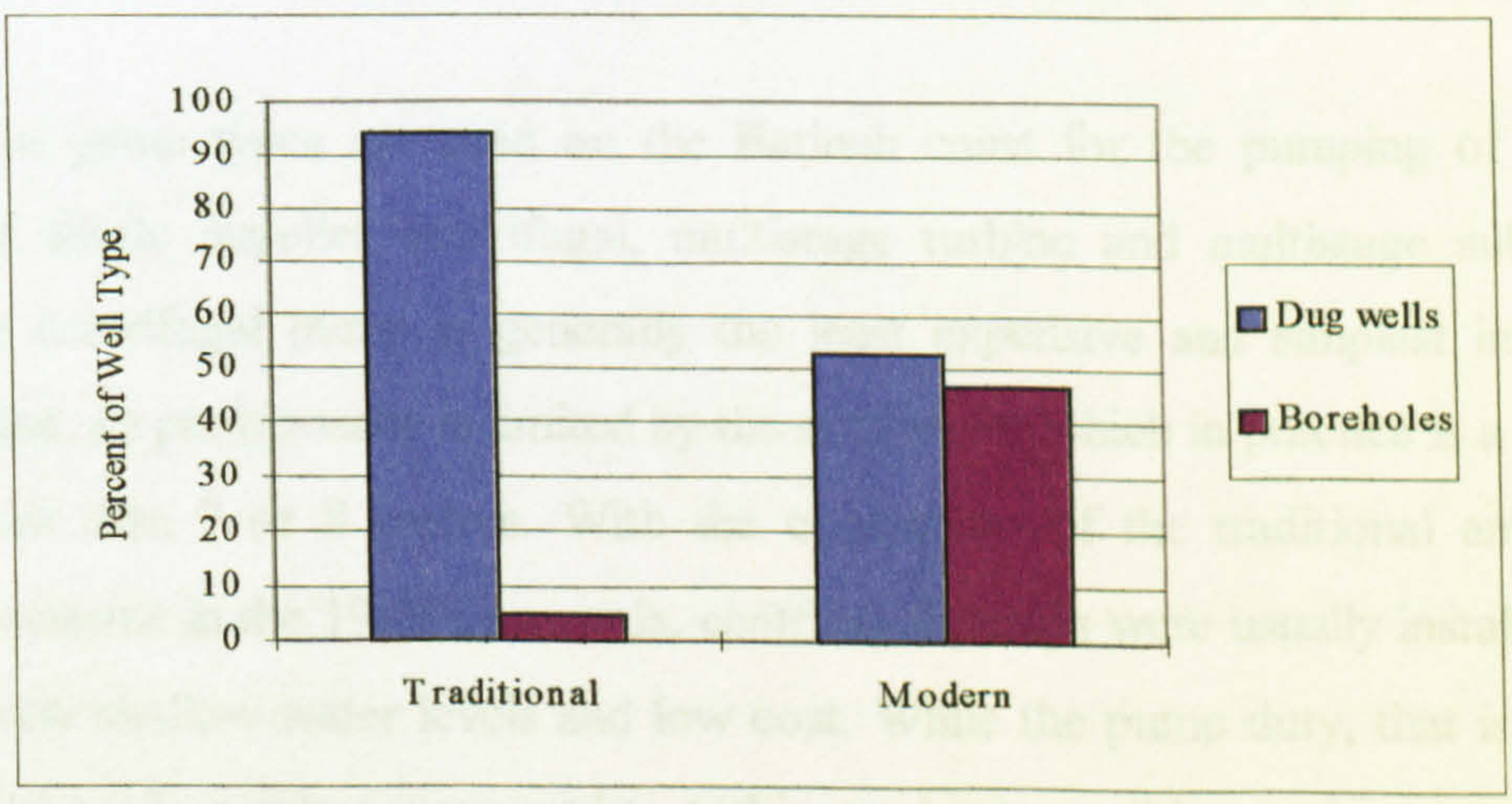


Figure 4.11 Comparison of Wells Types

4.2.2.5. Irrigation Methods

Pressure irrigation methods, such as drip, bubbler and sprinklers have been adopted on about 50% of the cropped area, compared to 4% on traditional farms, Figure 4.12. Many of these farms where part of the target group of farms greater than 5 feddans (2.1 ha) on the MAF Modern Irrigation Programme in the early 1990s (Section 4.4.1.2).

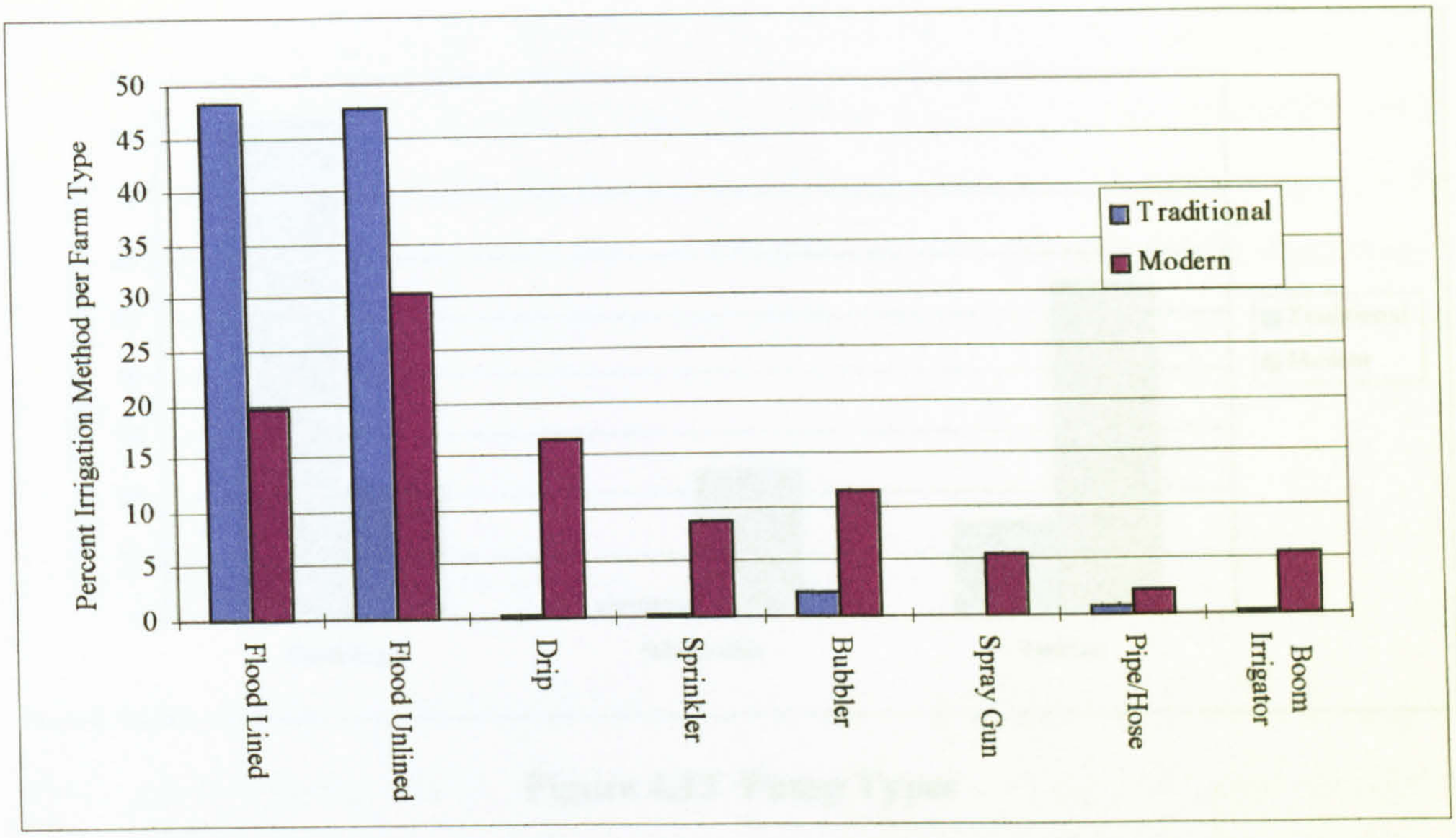


Figure 4.12 Irrigation Methods

The adoption of pressure irrigation is also a function of cropping patterns, with the use of sprinklers for irrigating grass, bubblers for tree crops and drip for vegetables. Nevertheless surface irrigation is still extensively used on these farms, with 50% of the cropped area flood irrigated by either lined or unlined channels to *gayl* and *gelba*.

Three main pump types are used on the Batinah coast for the pumping of irrigation water: the single impeller centrifugal, multistage turbine and multistage submersible. While the centrifugal pump is generally the least expensive and simplest in terms of maintenance, its performance is limited by the suction lift which in practice is a maximum of no more than 7 or 8 metres. With the conversion of the traditional animal draft pumping systems in the 1960's onwards, centrifugal pumps were usually installed due to the relatively shallow water levels and low cost. While the pump duty, that is discharge volume and head, was low compared to turbine and submersible pumps, it was adequate for the small traditional farms, with surface irrigation. Water is pumped into a surface storage reservoir and released to lined or unlined distribution channels.

On modern farms with larger cropped areas and therefore higher system duties, submersible and turbine pumps have been more widely installed, and account for nearly 80% of pumps on these farms, Figure 4.13.

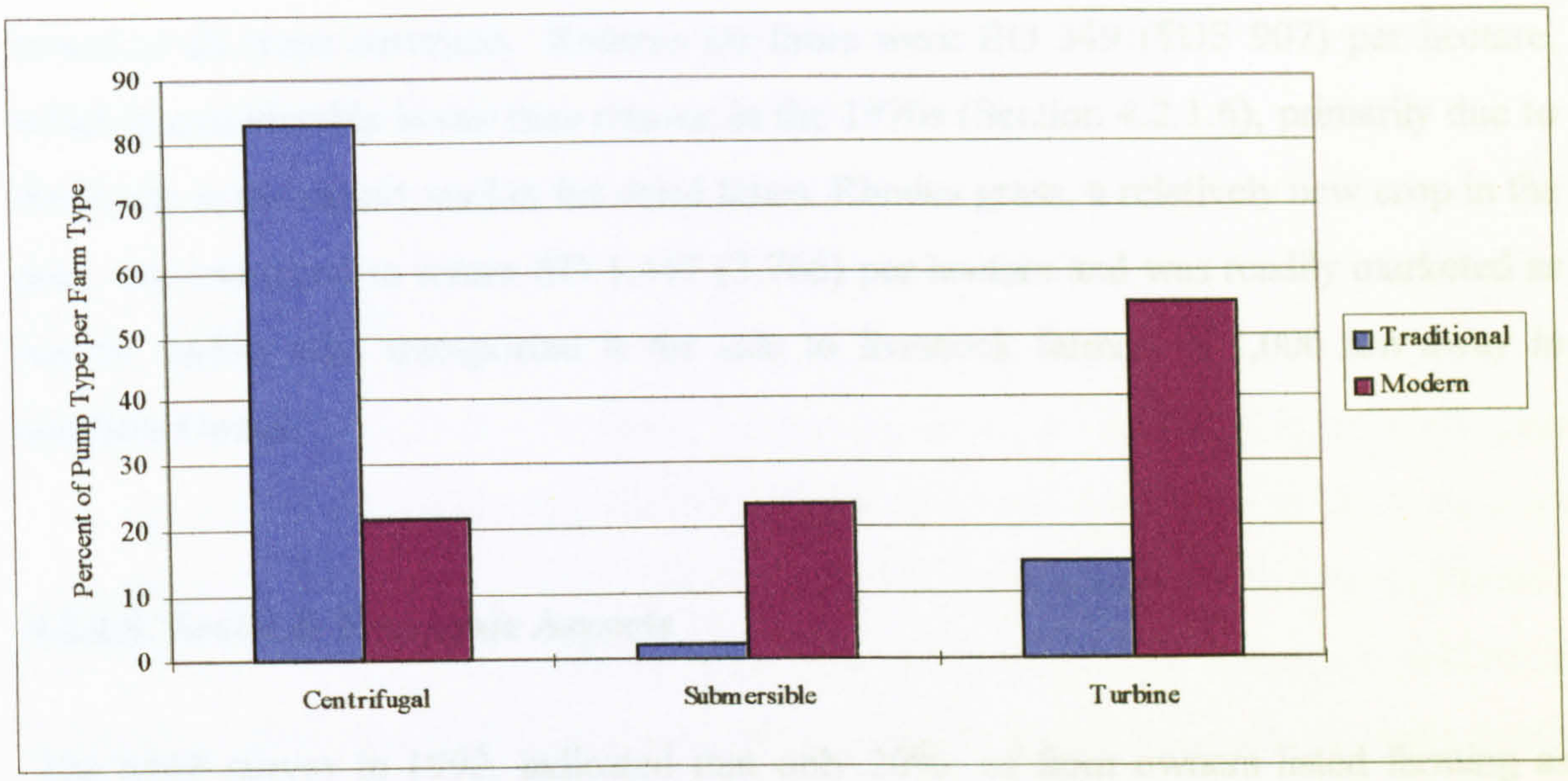


Figure 4.13 Pump Types

4.2.2.6. Water Demand

Based on the NWIP survey, net water demand (that is net loss of water from the aquifer through evaporation and evapotranspiration) for modern farms is calculated to be in the order of 106 Mm^3y^{-1} (MWR 1996b & 1996c). For the net cropped area of 4,487 ha, this is the equivalent of more than 23,500 m^3ha^{-1}. The combined water demand of traditional and modern farms is estimated to be approximately 123 Mm^3y^{-1} (MWR, 1999a). which is more than double the annual freshwater recharge to the aquifer (Section 3.3.4, estimated at 50 Mm^3y^{-1}).

4.2.2.7. Farm Productivity and Returns

A farming systems survey of farms on the South Batinah conducted by MAF in 1992, though limited in sample size to 50 farms, provides some useful estimates of crop productivity and returns (MAF, 1992). The survey included farms within the wilayat of Barka, as well as Masna'ah and Suwaiq to the north. The sample represented a cross section of farm sizes, from less than 2 feddans (0.8 ha) to more than 10 feddans (2.4 ha).

Date production for the farms was the equivalent of 1.88 tons per hectare, with an estimated net value per hectare of RO 213 ($US 553), though returns per farm are not mentioned in the associated report. Alfalfa production was in excess of 54 tons (green) per hectare with net returns of RO 1,777 ($US 4,620) per hectare, the highest unit area

return of all crops surveyed. Returns for limes were RO 349 ($US 907) per hectare, which is considerably lower than returns in the 1970s (Section 4.2.1.6), primarily due to the slump in the export market for dried limes. Rhodes grass, a relatively new crop in the area, was estimated to return RO 1,447 (3,766) per hectare and was readily marketed as hay to traders who transported it for sale to livestock farmers a 1,000 km away in southern Oman.

4.2.2.8. Social & Economic Aspects

The MAF survey in 1992, indicated that only 20% of farm owners listed farming as their main occupation (MAF, 1992) with 52% of owners working in government service and 28% in business or other occupations, which contrast with the findings of surveys made in the 1970's (Section 4.2.1.6). Along with the shift away from farming by farm owners, there has been an increase in the use of expatriate labour. More than 80% of farms employed one or more expatriate labourers, which included 50% of farms of less than 2 feddan (0.8 ha). The majority of the expatriate labour force is from the Indian subcontinent (Bangladeshi 62%, Pakistan 15% and Indian 13%), usually non-Arabic speaking and often without previous farming experience or skills.

Off-farm income is the major source of household income, which on average contributes more than RO 7,700 ($US 20,020) per year. For many farms, farm income is very low or negative. Farming has the principal objective of supplementing household food supply. The farm is also the place of recreation during holidays and weekends.

4.3. IMPACT ON WATER RESOURCES

As described in Chapter 3 (Sections 3.3.4 and 3.3.5) there has been a progressive deterioration in water resources since 1970. The more than tripling in demand for water has resulted in both a depression of groundwater levels and a deterioration in water quality. It is estimated that water demand by traditional farms was equivalent to or less than the average groundwater through-flow, which maintained an equilibrium between demand and supply. The decline in water levels and intrusion of sea water into the aquifer indicate that much of the more recent abstraction has depleted stored water within the aquifer and is in essence water mining. The current levels of abstraction are

unsustainable and may ultimately result in irreversible damage to the aquifer and a reduction in the number of farms and cultivated area.

4.3.1. Water Levels

In the early 1970's groundwater levels were at or above sea level within the study area (see Figure 3.16). By 1994 water levels had declined to below sea level in the study area, with a cone of depression of more than 5 metres below sea level in the area of Rumais, Wadi Taww (Figure 3.16). Hydrographs from monitoring wells indicate a decline in water levels from the 1970's onwards. While there is limited recovery of water levels following local rainfall and recharge, the overall tendency is a continued decline (Figure 3.14). During the period 1970-80 water levels were declining at the rate of 0.04 to 0.15 my^{-1} and from the early 1980's onwards the rate increased to more than 0.30 my^{-1}. It is estimated that the reduction in groundwater storage is the order of 36 Mm^3y^{-1} (MWR, 1999a).

One of the direct impacts of declining water levels on farming has been reduced well yields, particularly in the shallower dug wells on traditional farms nearer the coast. As water levels drop, suction head on centrifugal pumps increases, thereby reducing pump performance and abstraction rates. In many cases well yield has declined to the point whereby pumping can only be sustained for a short period and pumping becomes a cycle of pumping for 1 to 2 hours operation followed by 3 to 4 hours recovery.

4.3.2. Water Quality

The deterioration in quality of groundwater has been systematically monitored by the MWR and its predecessor organisations since the early 1980's. The interface between sea water and fresh water within the aquifer has progressively moved inland over the period 1980-95. As described in Chapter 3 (Section 3.3.5) during the period 1983-97 the area with water of EC greater than 6,000 μScm^{-1} expanded by 64% (MWR, 1999c). Over the same period there was a similar increase in the area with water greater than 2,000 μScm^{-1}, which may be a result of the recirculation of water and build up of leachates. With water levels below sea level and the inland migration of the saline front, there is no through-flow of groundwater to the coast and in essence the catchments are

closed with the resource fully committed.

4.4. MANAGEMENT STRATEGIES

The problems associated with over commitment of water resources have been apparent for sometime. PAWR, the predecessor oganisation to MWR highlighted the potential impact of saline intrusion in the mid 1980's and the need to implement strategies to avert the problem. MAF has also been active in monitoring, studying and implementing strategies to reduce water demand. Some strategies have been specifically targeted to the study area, while others have been part of wider general water conservation programmes.

4.4.1. Strategies Implemented

Since the mid 1980's a number of strategies have been implemented both to improve water supply to the lower coastal plain and to reduce water demand by the agricultural sector on the Batinah coastal plain as a whole. But these strategies were largely introduced in an un-coordinated way, as piecemeal measures in attempts either to increase water supply or to limit the expansion of demand, as listed below.

4.4.1.1. Recharge Dams

Three recharge dams were constructed in the early 1990's by MAF to improve recharge to the coastal aquifer. The dams are located 10-12 kilometres inland from the coast and approximately 3-5 kilometres upstream of the zone of intensive cultivation. The purpose in constructing the dams was to intercept flood waters on the coastal plain which would otherwise be largely lost to the sea and recharge the coastal aquifer, to increase water supply and quality to coastal wells.

Halban and Ma'awil dams are located within the Taww and Ma'awil catchments respectively, while the Taww dam straddles the surface water boundary between the catchments (more recent classified as a tributary catchment of Ajal North (MWR, 1999a)). The dams have a combined storage volume of 18.8 Mm^3 (Table 4.5). Based on monitoring records it is estimated that the dams have contributed approximately 47 Mm^3

of recharge (MWR, 1999b) in the period 1991-97. While the dams have contributed to recharge, the volumes are alone insufficient to meet the increase in water demand. Concerns have been expressed by farm owners, particularly of traditional farms, that the dams have primarily benefited the modern farms closer to the dams. MWR has recently commissioned a study to investigate the impact of the Halban dam on surface and ground water flows in Wadi Taww.

Table 4.5 Recharge Dams

Dam	Year of Completion	Storage Volume (Mm^3)	Recharge Volume (Mm^3)
Halban	1992	3.7	6.71
Taww	1992	5.1	11.88
Ma'awil	1991	10.0	27.81
Total		**18.8**	**46.40**

Source: MWR, 1999b

4.4.1.2. Modern Irrigation Programme

A programme to promote the use of modern irrigation methods was established by MAF in 1990 (MWR, 1992). It was established as part of a national Soil Survey and Land Classification project, with technical assistance from FAO. The programme initially concentrated on the development and promotion of modern irrigation systems on farms within the lower catchments of Taww and Ma'awil. This was partly due to the location of the Soil Survey Project base at the MAF Research Station at Rumais, Wadi Taww, but also due to the severity of saline intrusion within the catchments.

The purpose of the programme was to encourage the conversion of farms from traditional surface flood irrigation systems, predominantly basin and furrow methods, to "modern" pressurised methods. These methods included the use of bubblers (Figure 4.15) for tree crops, drip for vegetables (Figure 4.16), field sprinklers (Figure 4.14) for grasses and hydrants for alfalfa (Figure 4.17). The systems were based on a set of standard specifications for design, materials and installation, (MAF, 1992). The design was adapted from standard micro-irrigation specifications (Table 4.6) taking into consideration traditional surface irrigation methods. For example, on tree crops the *gelba*

was retained with the delivery of water by two bubblers (Figure 4.15), with a combined discharge of 450 litres per hour (l h^{-1}), the objective being to replicate surface flooding within the *gelba*. While alfalfa can be grown successfully under sprinkler irrigation, there is a local preference for surface irrigation and a belief that overhead irrigation will lead to lodging and poor seed production. Therefore in the interest of promoting the programme, hydrants were specified under the programme (Figure 4.17).

Table 4.6 Modern Irrigation Programme

Crop	Irrigation Method	Duty	Capital Cost (RO ha^{-1})
Datepalms	Bubbler (2 per tree)	450 l h^{-1}	682
Mango	Bubbler (2 per tree)	450 l h^{-1}	723
Limes	Bubbler (2 per tree)	450 l h^{-1}	923
Grass	Field Sprinkler	15 mm h^{-1}	855
Alfalfa	Hydrant	5 - 10 l s^{-1}	341
Vegetables	Drip	2 l $h^{-1}m^{-2}$	708

The systems provided under the programme included a standard headworks, comprising of screen filter and fertiliser injector, as well as uPVC mainline, control valves and submain and lateral pipes. Where necessary it also included the renovation or replacement of the well pump, to meet the new system duty, particularly the higher operating head required for sprinklers, bubblers and drippers.

Under the programme, farm owners with properties greater than 5 feddans (2.4 ha) were eligible for a stepped subsidy on the total system cost. Farms of 5-10 feddans (2.4-4.8 ha) received 75% subsidy, 10- 50 feddans (4.8 - 21 ha) 50% and 50-100 feddans (21- 42 ha) 30%. Farm owners volunteered to join the programme, with eligibility dependent on farm size criteria and willingness to contribute the balance of the system costs.

The programme was implemented on the Batinah over a three year period, 1991-94. There are no records accessible from MAF to indicate the number of farms and irrigated areas for farms within Wadi Taww and Ma'awil, but results from NWIP provide a good

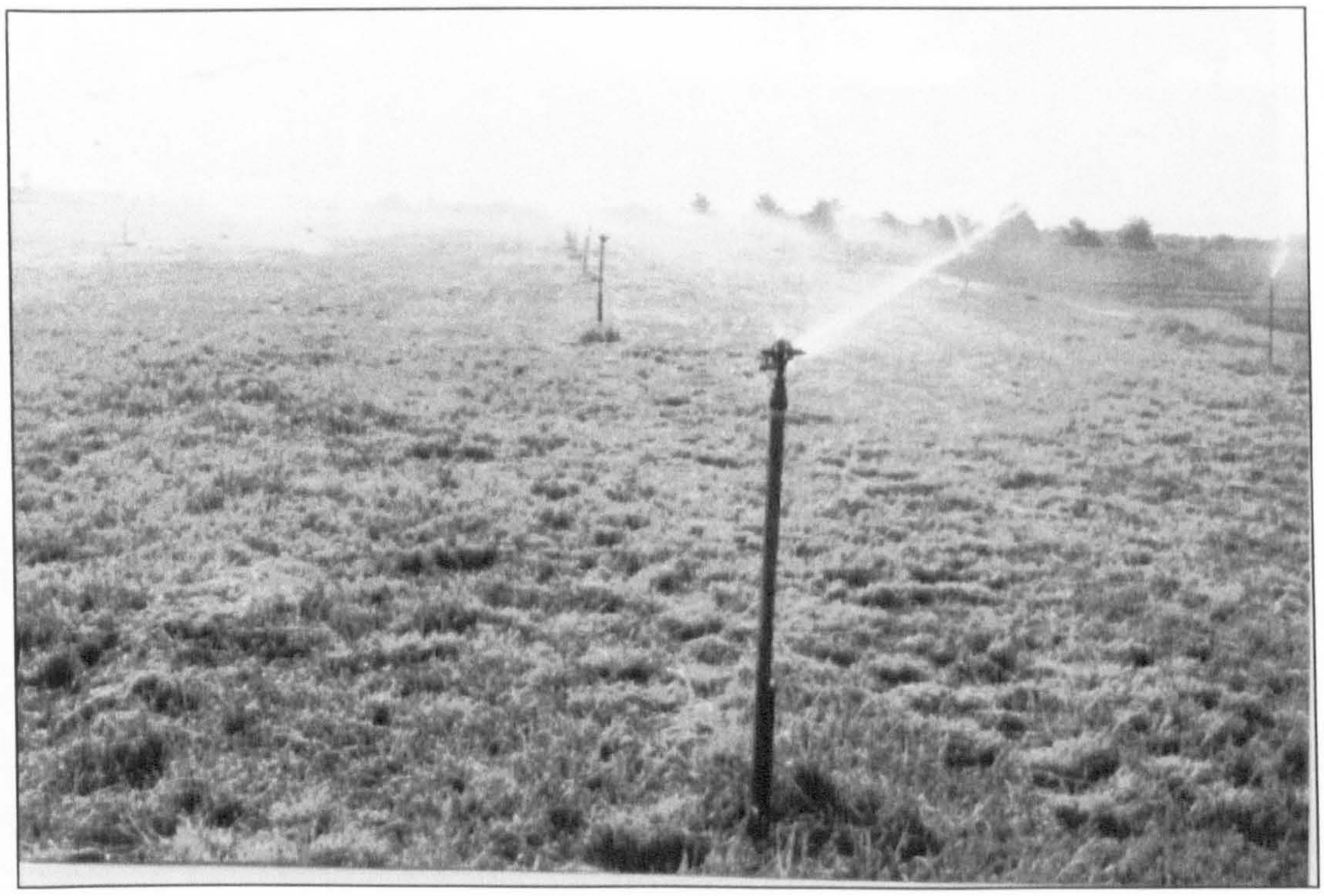


Figure 4.14 Field Sprinklers

Figure 4.15 Bubblers

Figure 4.16 Drippers

Figure 4.17 Hydrant

indication of the extent of coverage. From field observations, evident from the programme plates installed at the farm gate, it is apparent that the vast majority of modern irrigation systems on farms in the area supplied under the programme. As indicated in Table 4.4 the area covered by pressure irrigation methods supplied under the programme (drip, sprinkler and bubbler) is 2,052 ha. Virtually all (98%) of these occur on modern farms, which reflects the non-eligibility of most traditional farms on size criteria (less than 5 feddan property area) to join the programme. Based on average property area, it is estimated that approximately 500 farms were included in the modern irrigation programme.

There is no information available assessing the impact of the programme on individual farm or catchment water consumption. While one of the principal objectives of the programme was to increase irrigation and water use efficiency, there is no evidence to demonstrate that this objective was achieved. Field observations suggest that the main benefit was a reduction in labour requirements for irrigation duties, which freed labourers to carry out other farm duties and, in some cases, expand the cropped area by either intercropping or the development of uncropped land within the farm.

While the Programme may not have realised its objectives, there is nevertheless the potential to reduce overall water demand within the catchments through improved irrigation methods and management. It is estimated that these improvements could save approximately 14 percent of total agricultural water demand or 22 Mm^3y^{-1} (MWR, 1996b & 1996c). This would be a significant contribution towards reducing current levels of demand to sustainable levels.

4.4.1.3. Well Permitting

From the mid 1980's, restrictions on the construction of new wells were promoted as a means to limit agricultural development and demand for water on the Batinah. In 1990 these restrictions were formalised with the declaration by MWR of regulations for well permits for the construction of new wells and deepening of existing wells (MWR, 1990). The MWR Rustaq office is responsible for well permitting within the catchments. Records of the number of applicants for permits provides an indication of trends and effectiveness of the regulations in limiting the expansion of demand. During the period

1991-97 a total of 298 applications were received by the office for new wells of which 149 (50%) were approved. Over the same period 880 applications were received for deepening of existing wells of which 554 (63%) were approved. It is interesting to note that while the regulations include conditions for compulsory installation of water meters, to monitor abstraction limits, none was specified for any of the 702 approved permit applications (total of approvals for new (149) and deepened (554)).

As the records indicate, while permitting has effectively slowed down the installation of new wells and the deepening of existing wells, there was still a considerable expansion of new (5.5%) and deepened wells (10%), 1991-97. The lack of enforcement of conditions to limit abstraction has reduced the effectiveness of the regulations to control the expansion in water demand.

4.4.1.4. Land Allocation

The current water resource problems within the study area stem from land allocation policies and programmes that, during the late 1970's and 80's, encouraged the development of new farms. These programmes were promoted in the then belief that there were sufficient water resources to support an expansion of the cultivated area, particularly in Northern Oman (Gibb, 1976). In support of this expansion, new lands were allocated by the MOH in units of 10 feddans (4.8 ha) or greater. The impact of this expansion within catchments on the southern Batinah, particularly Wadis Taww and Ma'awil, was becoming apparent by the early 1980's with a decline in water level and increasing water salinity.

By the early 1990's there was an awareness of the need to restrict the allocation of new lands on the Batinah. There had been a significant deterioration in water resources it was predicted that demand for water would further increase as new perennial tree crops reached maturity and as allocated but undeveloped lands were brought into production. Therefore since the early 1990's the allocation of new lands has been restricted.

4.4.2. Strategy Options

Current water balance estimates and trends in groundwater levels and water salinity indicate that the area continues to be in imbalance. Unless there are interventions to increase water supply and/or decrease demand, these trends will continue, leading to progressive salinisation of the coastal aquifer. In the "do nothing" scenario, salinisation will lead to the progressive abandonment of farms until an equilibrium is ultimately reached between demand and supply. This process is already well underway. As indicated in Figure 3.17 the zones of water greater than 6,000 μScm^{-1} expanded by more than 44% between 1983-93. The MWR and MAF surveys in the early 1990's indicate that approximately 400 ha of farms were already abandoned, all traditional farms nearest to the coast (MWR, 1996b & 1996c). There are a range of interventions which could contribute to attaining a balance between supply and demand within the catchments, these are considered below.

4.4.2.1. Supply Management

Water supply could be increased to the area through the development and transfer of resources from within the catchment or from outside. There are a number of options to increase water supply, but they would require substantial capital investment and raise a number of technical and social issues regarding the water sources and distribution and use of this water within the area.

a) Water Mining

An alluvial trough, approximately 400 metres deep, transects the upper coastal plain of both Wadis Taww and Ma'awil. The trough occurs upstream of the zone of traditional and modern farms, approximately 15-20 km inland from the coast. Preliminary investigations indicate that there may be somewhere in the order of up to two billion cubic metres of stored potable water within the trough. There is potential to develop this resource for transfer to farms downstream to alleviate the current shortfall in supply. But there are several resource and economic disadvantages in it use for agriculture. Any use to support downstream farms is ultimately unsustainable and would only delay the day when alternative supply or demand strategies would have to be adopted. A more compelling constraint is that give the proximity of the area to the major population centre of Muscat municipality, the resource should be conserved as a strategic reserve for

municipal water supply in case of emergency, for example, failure of desalination water production on which the city is 70% dependent. Alternatively the water could be used to supply drinking water to coastal villages and towns. Development would require infrastructure for abstraction and distribution, wellfields, pumps, pipelines etc. Initial estimates indicate that the cost of water would be in excess of RO 0.100 m^{-3} delivered to the farm gate. At current returns to agriculture few farmers could afford to pay the full cost of water and any scheme would require financial support in the long term. It is therefore unlikely to be acceptable for government funding.

b) Inter-basin transfer

The transfer of water from catchments either on the Batinah to the north, or from interior regions is technically feasible. But given the current imbalance and rising water demand in other areas and a cost of more that 0.200 RO m^{-3}, any such transfer is unlikely to be socially, politically or economically feasible in the short to medium term.

c) Desalination

Desalination is extensively used on the Arabian peninsula for the supply of domestic and industrial water. It is proposed to construct a co-generation electricity and desalination plant at Barka as some stage in the future (Observer, 1998). Water production from the plant will supply domestic and industrial demand to townships on the South Batinah, north and south of Barka, as well as to the greater area of Muscat. It will produce at full capacity approximately 22 Mm^3y^{-1}.

With current water production costs from large scale multistage flash distillation plants in Oman at around 0.800 RO m^{-3} ($US 2.00 m^{-3}) (Mott, 1991a) and two to three time this cost for smaller scale reverse osmosis plants, desalination is unlikely to be economically viable for irrigation in the short to medium term. Based on current farm returns and gross margins per unit volume, for desalination to be feasible as a supply option, current production costs would have to be at least 20 to 30 times lower. There are also a number of other economic and environmental constraints to overcome, including the cost of infrastructure for distribution of water, and the impact of highly saline wastewater if the source is from lower salinity groundwater inland.

d) Treated Waste Water

A major scheme for the collection and treatment of waste water is proposed for the Greater Muscat area (Observer, 1998). As proposed, the scheme would ultimately produce 90 Mm^3y^{-1} of treated waste water, of which 17 Mm^3 is to be used for landscape irrigation within the Muscat area. The balance of 73 Mm^3 could be available for reuse by the agricultural sector. The proximity of Wadis Taww and Ma'awil to the capital area could make it possible to use this water for irrigation or, alternatively, for recharge. The addition of more than 70 Mm^3 to the catchment water balances would make a contribution to redressing the current imbalance. But there are a number of economic, environmental and social constraints to overcome before any agricultural reuse scheme could be feasible.

As currently proposed, the cost of treated waste water from the scheme will be approximately 0.200 RO m^{-3}, which is more than ten times the gross margin of water for most crops on the Batinah. Therefore unless subsidised by the government the cost of water would have to be significantly reduced to less than 0.020 RO m^{-3} before it would be financially feasible for most farms. Any scheme would require construction of infrastructure for the storage and distribution of water to the farm gate, which would further increase the unit cost of water. The impact of treated water on groundwater and its potential for pollution is an environmental issue that would need to be resolved. While treated waste water is used for irrigation of landscape gardens in Oman, to date it has not been used to any extent in agriculture. There could also be reluctance by farmers to the reuse of water on social and religious grounds.

4.4.2.2. Demand Management

There are a number of options to reduce current levels of water demand these including water quotas, central wellfield(s), changes in cropping patterns, relocation of farms and improved irrigation management as discussed below.

a) Water Quotas

For existing well owners there are no regulations limiting the quantity of water that maybe abstracted. The only limitations on water use are well yield, pump duty and on-farm irrigation management. The introduction of a water quota system per farm and/or

well could achieve significant reductions in water abstraction and equitable allocation of water to all water users. Water quotas have been successfully introduced in other countries to regulate demand, as discussed in Chapter Two. There are a number of options for the implementation of quotas, based on property or cropped area, as well as crop type. With the present level of water deficit, the overall allocation of water would have to be significantly lower than current levels of abstraction. Based on estimates of renewable resources and cropped area, average allocation per cropped area would have to be in the order of 15,000 $m^3ha^{-1}y^{-1}$ a 30% reduction on current abstraction rates.

Quotas could in principle encourage more efficient water use at the farm level. Limits on abstraction would encourage the adoption of more efficient irrigation methods and management as farmers seek to maximise the irrigated area and select crops with the highest financial and social benefits. But to date they have not been adopted on the Batinah or anywhere else in Oman. The implementation of a quota system is one of the specific objectives of the water sector that have been identified within national plans, in Vision 2020. While they are perhaps one of the most direct methods of regulating demand by the agricultural sector, they are also perceived as one of the more difficult strategies to implement in the short term. There are currently a number of local and national institutional, financial and social constraints to their adoption.

b) Central Wellfield

One concept that has been investigated to resolve the problem of saline intrusion within Wadis Taww and Ma'awil is the construction of a central wellfield and distribution system to the farm gate. The concept was investigated in a study commissioned by MAF in 1992 (BGRM, 1993) and was based on the construction of a wellfield inland and upstream of farms on the lower coastal plain, which would ultimately replace use of on-farm wells. Similar internal studies have also been carried out by MWR. While such schemes could deliver better quality water to farms, particularly those most affected by saline intrusion, they are essentially a reallocation of existing resources. There are also a number of economic and social constraints. Schemes investigated to date have a capital cost of more than $US 40 million, which if not subsidised by government funding would require water charges well in excess of the gross margin on water for most farms and therefore are not likely to be financially feasible. Any such scheme would also require stringent regulations on continued use of on-farm wells, which is unlikely to be

acceptable to many well owners, particularly those with better quality water.

c) Cropping Patterns

Current levels of water demand could be reduced with a shift in cropping patterns from perennial to winter season crops, particularly vegetables and possibly cereals. Perennial crops comprise about 98% and 85% of the cultivated areas of traditional and modern farms respectively. Irrigation water quality is one of the constraints to the adoption of seasonal crops, with vegetable species generally requiring water less than 5,000 μScm^{-1}. However, it is estimated that the conversion of 50% of existing tree crops and 100% of grass crops to vegetables on the freshwater zone, and to cereal crops on the brackish zone, could reduce net water demand by 20% or the equivalent of 20 Mm^3y^{-1}.

d) Relocation of Farms

One of the options for reducing water demand is a reduction in the number of farms and irrigated area. While there is currently no specific regulation to force the abandonment of farms, a specific objective listed within Vision 2020 is the relocation of farms from the Batinah. It is proposed to persuade farm owners to develop new farms in areas where there are sufficient water resources. The Nejd area in southern Oman is one such area which has large fossil water reserves which have been identified for future development. Initial proposals were based on the relocation of grass production from the Batinah, particularly Wadis Tawv and Maawil to the Nejd, with the targeting of farms greater than 20 feddans. While an inter-Ministerial committee was established in 1996 to establish criteria for selection of farms and allocation of new lands in the Nejd, there has been little progress to date.

e) Irrigation Management

The potential to reduce water demand through improved irrigation methods and management has been recognised for some time, with the establishment of a "modern irrigation programme" by MAF and the NWIP by MWR. Traditional basin and surface flood methods are still widely adopted on 62 % of farms. When used on the high permeability soils in the area and combined with limitations of labour and irrigation management can lead to low levels of application efficiency.

Based on the NWIP methodology it is estimated that the upgrading of surface flood

methods, to pressure irrigation, drip, bubbler and sprinklers, could reduce net water demand by 14% or the equivalent of 22 Mm^3y^{-1} (MWR 1996b & 1996c). But these are untested theoretical values, based on an assumed improvement of current levels of average irrigation efficiency from less than 40%, for unlined flood, to 90% for bubbler and drip.

While the "modern irrigation programme" contributed to the promotion of improved irrigation methods, it was limited, in terms of coverage, to 560 farms and focused on the provision of 'hardware' with limited support or training of on-farm managers in system operations and maintenance. Experience suggests (Dutton, 1999; Stephen, 1993) that there is considerable potential for improvements in the management of both surface flood and 'modern' irrigation systems.

CHAPTER FIVE

RESEARCH METHODOLOGY AND PROGRAMME

5.1. INTRODUCTION

As indicated in Chapters Three and Four saline intrusion is a progressive and on-going water resources management problem within the catchments of Wadis Taww and Ma'awil. To date it has led to the contamination of about one-third of the wells, and the abandonment of a number of farms near the coast. If no remedial measures are implemented it could ultimately lead to the saline contamination of a large proportion of wells on the lower catchments and the destruction of a significant proportion of currently cultivated lands.

There has been no research on the Batinah to investigate the relationship between saline intrusion and trends in water abstraction and water use, and the impact of these trends on the impact and benefits of proposed demand management strategies. It is predicted that saline intrusion will lead to a decline in abstraction rates as farms are progressively affected by deteriorating water quality and as less salt tolerant crops are abandoned. The deterioration of water quality and reduction in abstraction rate will reduce the potential effectiveness and benefits of any proposed demand management strategy. The spatial and temporal relationship(s) between the deterioration of water quality and declines in abstraction is likely to be a key factor in whether demand management will be effective in reducing saline intrusion.

5.2. RESEARCH OBJECTIVES

The study investigated the following objectives:

1) Water Abstraction and Salinity: To investigate the spatial and temporal relationship(s) between water quality and abstraction.
2) Irrigation Management: To evaluate current levels of irrigation efficiency of surface and sprinkler irrigation methods on a sample of farms.
3) Demand Management: To evaluate the impact of the spatial and temporal changes in abstraction on saline intrusion and the relative effectiveness of demand management in reducing the rate of saline intrusion.

5.3. STUDY METHODOLOGIES

To achieve the research objectives the research programme comprised the following:

- Field research programme - the monitoring of water quality, abstraction and water demand on a group of study farms over the period 1994/5-1998/9.
- Study of irrigation management on sample(s) of study farms to determine efficiency of application over the period 1997/8-1998/9.
- Analysis of the findings of the field research programme, to evaluate the correlation between water quality and water abstraction.

5.3.1. Field Research Programme

The study farms comprise a group of 138 farms located within the lower catchments of Wadis Taww and Ma'awil. These farms are all located within the zone of intensive cultivation on the lower coastal plain and the zone suffering from progressive saline intrusion. The farms were predominately the recently developed 'modern' farms, but also included a small number of the older traditional farms nearer the coast.

The study farms were the source of data for the study of the impact of changes in water quality on water abstraction and use. Data collection included the routine monitoring of groundwater quality, water abstraction, surveys of cropping patterns and irrigation methods, as well as the study of irrigation management on sample and case study farms.

5.3.1.1. Study Farm Selection Criteria

The study farms were selected from a slightly larger group of farms (146) involved in the MWR "Water Metering Project on the South Batinah" (WMP). The project was implemented in two phases, the first starting in 1994 and the second in 1996. It included the selection of farms within Wadis Taww and Ma'awil as well as the two adjacent wadis to the south, Manumah and Ma'abelah. The number of farms and the criteria for farm selection are listed below:

a) Phase One: comprised 27 farms (Figure 5.3), including 14 selected on criteria of owner status, that is farms owned by senior government officials, including Ministers and Undersecretaries. The rationale for selection being that these farm owners would help gain support in higher government administration for the adoption of more widespread water quota and metering strategies. The balance of

13 farms was selected from NWIP data on farms in the area, with selection being random , rather than following any specific criteria (MWR, 1994c).

b) Phase Two: comprised 119 farms located within the lower catchments of Wadi Taww and the southern third of Wadi Ma'awil (Figure 5.3). The location of the farms was based on well known geographical features on the Batinah coastal highway, between Bait Al Barakah and Barka roundabouts. The rationale for the designation of this area was that, due to the extent of saline intrusion, it was the area most likely to be selected for the preliminary establishment of a demand management system based on water quotas. Selection criteria within this location were also based on cropped area as determined by the NWIP. The selected farms were cropped (fully or partially) and has a total property area greater than 20 feddans (8.4 hectares) (MWR, 1996c).

The 138 study farms were selected from the group of 141 WMP project farms located within the lower catchments of Wadis Taww and Ma'awil and were privately owned farms on which cropping was the principal activity. The three excluded farms were a MAF research station, a large government farm and a poultry farm.

Neither the WMP farms nor, therefore, the study farms were selected as a representative sample of the population within the lower catchments of Wadis Taww and Ma'awil as a whole, but were a sample of farms on which demand management strategies were most likely to be targeted in the future. This was the group of new modern farms upstream of the traditional farms nearer the coast, though it did also include four farms of the latter group.

The 138 study farms are about 4% of the total and approximately 8% and 0.5% of the modern and traditional farms respectively. The distribution for both categories of farm varied between the catchments. It was 12% and 4% of modern farms in Taww and Ma'awil respectively, while for traditional farms it was 1% and less than 0.5% respectively.

Figure 5.1 illustrates the location of the study farms with 96 and 42 located within Wadis Taww and Ma'awil respectively.

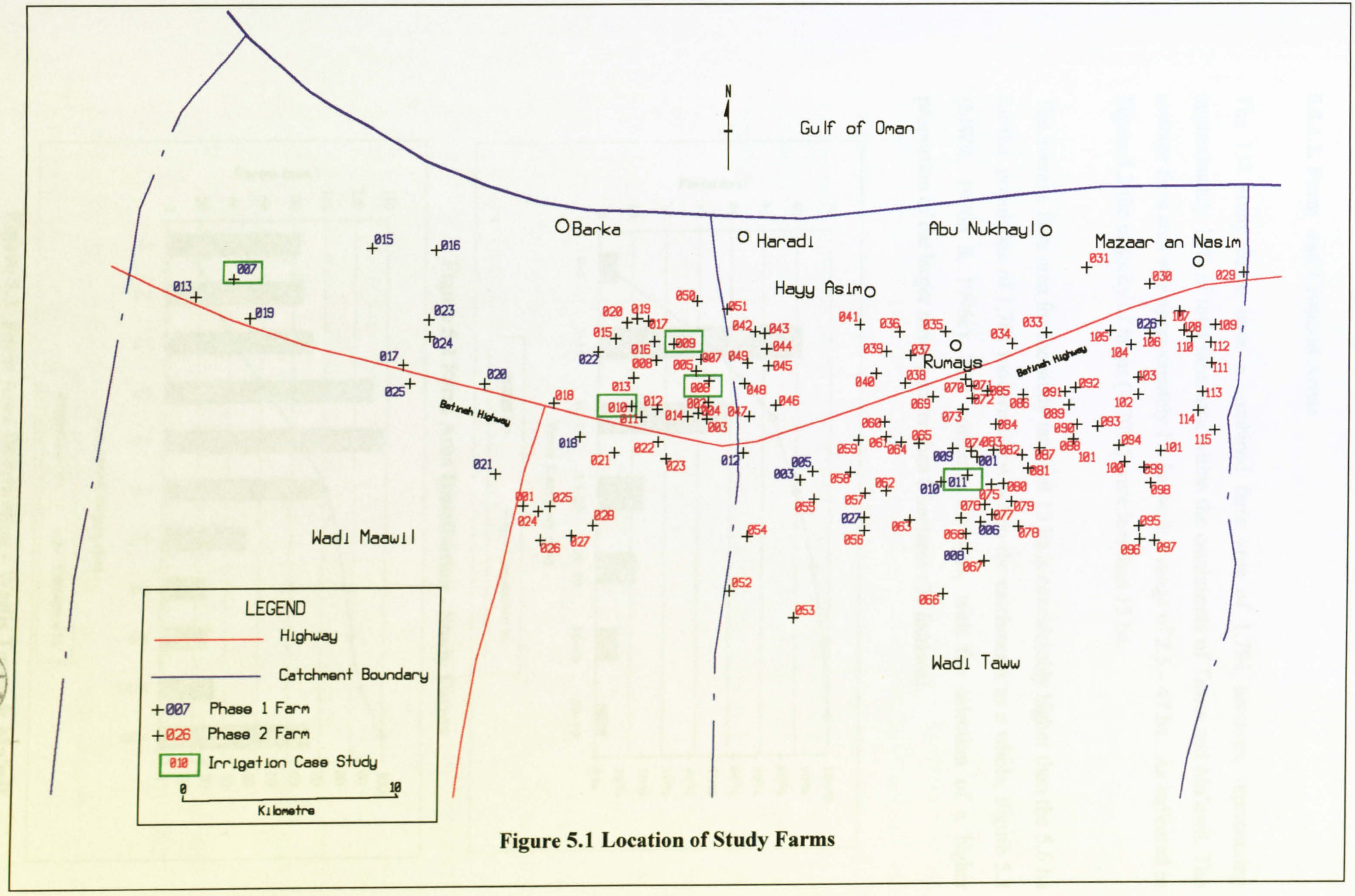


Figure 5.1 Location of Study Farms

5.3.1.2. Farm and Cropped Areas

The 138 study farms have a combined farm area of 1,784 hectares, representing approximately 16% of total farm area within the catchments of Taww and Ma'awil. The average farm area was approximately 13 ha, with a range of 2.5 - 47 ha. As indicated in Figure 5.2 the majority of farms (> 70%) were less than 15 ha.

The average farm area for the study farms at 13 ha is considerably higher than the 5.6 ha for the population of 1,761 modern farms within the catchments as a whole, Figure 5.3 (MWR, 1996b & 1996c). This confirms the bias, with the selection of a higher proportion of the larger farms greater than 8 hectares (20 feddans).

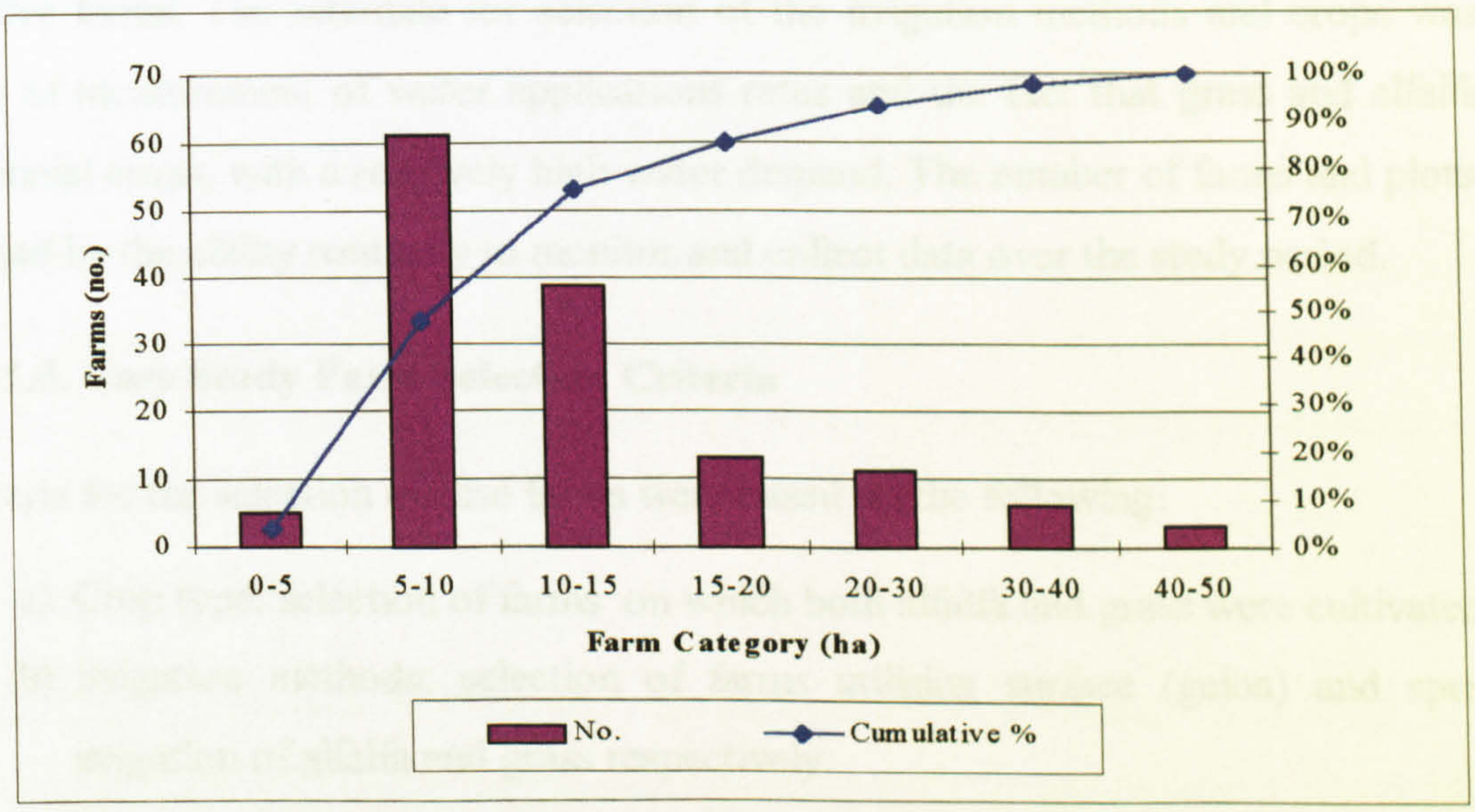


Figure 5.2 Farm Area Distribution - Study Farms

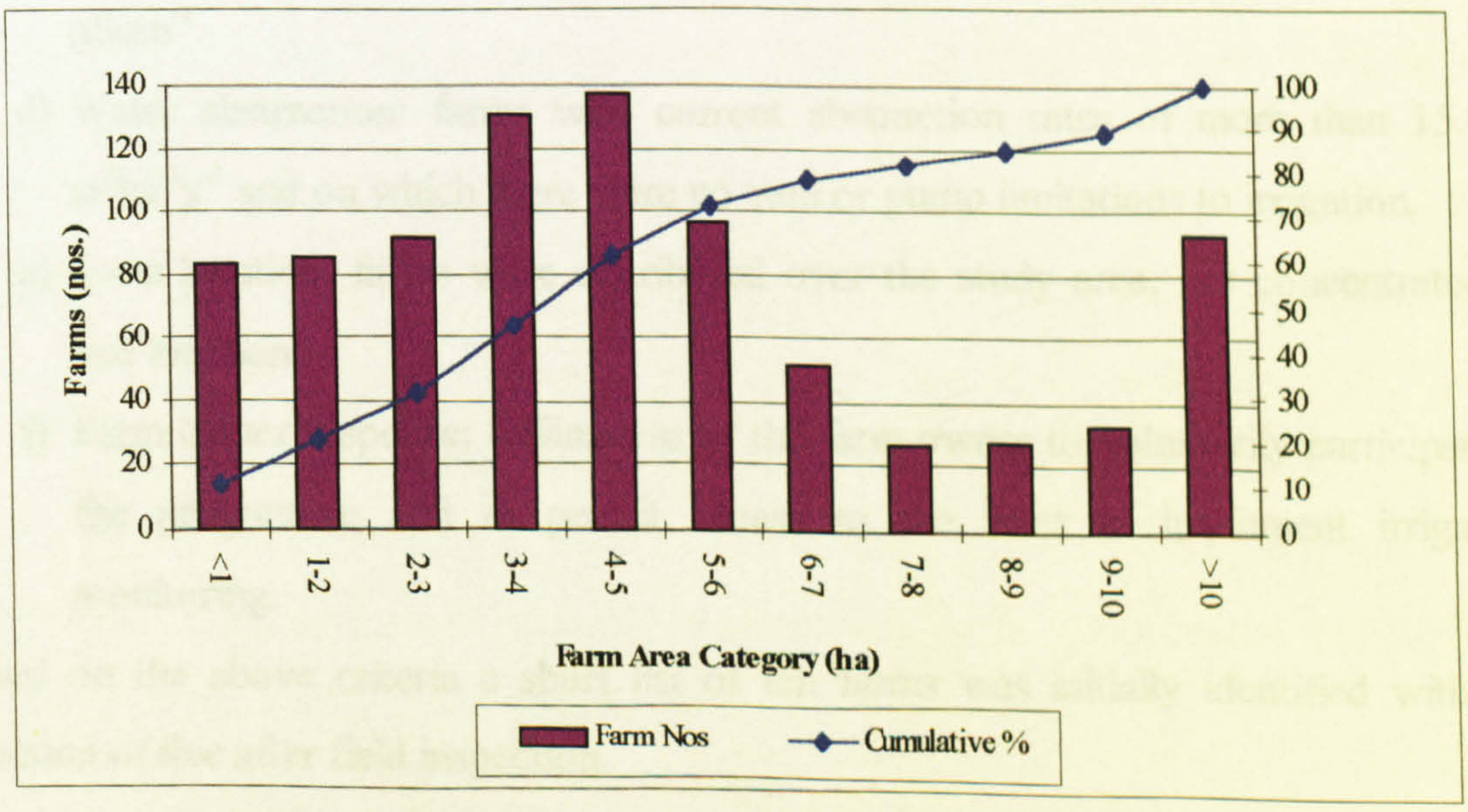


Figure 5.3 Farm Area Distribution - Wadis Taww & Ma'wil

The total cropped area of the study farms was 1,124 ha or approximately 62% of their total farm area. The balance of land was covered with buildings, such as a dwelling and animal shelters (2%) and areas that were not currently developed (36%). The latter represented a significant proportion of the total area, which could be brought into production at some future time, further increasing water demand.

5.3.1.3. Case Study Farms

For the evaluation of irrigation management a sample of "case study farms" was selected for detailed study from the study farms. The purpose of the detailed study was to evaluate current irrigation management practices on a small sample of farms. The methodology adopted was to study irrigation practices for two irrigation methods, sprinkler and surface flooding, and two fodder crops, grass and alfalfa, on selected plots on five farms. The rationale for selection of the irrigation methods and crops was the ease of measurement of water applications rates and the fact that grass and alfalfa are perennial crops, with a relatively high water demand. The number of farms and plots was limited by the ability routinely to monitor and collect data over the study period.

5.3.1.4. Case Study Farm Selection Criteria

Criteria for the selection of case farms were based on the following:

a) Crop type: selection of farms on which both alfalfa and grass were cultivated.
b) Irrigation methods: selection of farms utilising surface (gelba) and sprinkler irrigation of alfalfa and grass respectively.
c) Water quality: selection of farms with water quality of EC less than 10,000 μScm^{-1}.
d) Water abstraction: farms with current abstraction rates of more than 15,000 $m^3ha^{-1}y^{-1}$ and on which there were no well or pump limitations to irrigation.
e) Farm location: farms were distributed over the study area, not concentrated in one location.
f) Farm owner response: willingness of the farm owner to voluntarily participate in the programme and to permit access to the farm to implement irrigation monitoring.

Based on the above criteria a short list of ten farms was initially identified with the selection of five after field inspection.

5.3.1.5. Location

Figure 5.1 illustrates the location of the case study farms, with four located within the catchment of Wadi Ma'awil and one in Wadi Taww.

5.3.1.6. Trial Plots

Trial plots were selected within each case study farm, following a survey and mapping of crops and irrigation methods. Selection of the alfalfa and grass plot areas was based on the status of the crop and suitability for metering of water application. A single sprinkler lateral was selected for grass plots, while multiple linked *gelba*, irrigated from a single turn-out (valve), were selected for alfalfa plots. On two farms the original alfalfa plots were discontinued by the farm manager and alternative plots were subsequently selected, as discussed in Chapter Six.

5.3.2. Survey and Monitoring Methods

A variety of survey and monitoring methods were employed to collect information and to monitor water abstraction, water quality, irrigation application, soil moisture and salinity levels on the study and case study farms as described in the following subsections.

5.3.2.1. Water Meters

Water meters were used to measure water abstraction rates from all operational wells on the study farms and irrigation application volumes on plots on the case study farms. The meters recorded accumulated water flow on the meter register in cubic metres. Dataloggers were installed in the case study farm grass plots to record volumes on a continuous basis.

A variety of water meter types, makes and models were installed on the study farms, as indicated in Table 5.1. Two types of meters were installed: helical vane with helical impeller mounted in the meter bore and proportional meters in which a proportion of flow is diverted to a by-pass on which flow is measured. The helical vane is accurate to within plus or minus 2% of nominal flow, while the proportional meter is accurate to within plus or minus 5% of nominal flow.

Table 5.1 Water Meter Types, Makes and Models - Study Farms

Type	Make	Model
Helical Vane	Kent	Helix 3000
Helical Vane	Schlumberger	Woltex
Helical Vane	Meinecke	WP-D
Helical Vane	Madallena	WMAC
Proportional	Schlumberger	Irrimag

To measure total pumped volume, meters were installed on the well headworks as close as practical to the wellhead and upstream of all offtakes and mainline branches. The meter was of the same nominal diameter as the existing headworks. Where possible the meter was installed in the horizontal position, Figure 5.4 with ten and five times the nominal pipe diameter upstream and downstream respectively, to minimise turbulent flow. If there was insufficient straight pipe upstream of the meter, a flow straightener was installed. When it was not possible to install the meter horizontally due to constraints of the headworks configuration, the meter was installed vertically on the wellhead as indicated in Figure 5.5. Records of meter readings and water quality were stored and analysed in a Paradox (4.0) database. Details of the analysis and quality control are presented in Chapter Six.

Figure 5.4 Horizontal Water Meter Installation

On the alfalfa and grass trial plots on the case study farms, water meters were installed at the inlet to the irrigation zone (sprinkler lateral or gelba(s)), Figures 5.6 and 5.7. The meters were used to measure accumulated inflow to the plot, with readings being recorded on a daily or weekly basis. As indicated above, dataloggers (Meinecke) were installed on water meters on the grass plots to provide information on frequency and rate of irrigation. The datalogger recorded in increments of 0.1 m^3 on a continuous basis.

Figure 5.5 Vertical Water Meter Installation

All water meters were periodically calibrated to check accuracy at minimum (Qmin) and maximum (Qmax) design flow respectively. Where necessary the meter was re-calibrated to meet an acceptable level of accuracy of reading for helical vane (+/- 2%) and proportional (+/- 5%) meters. The results and impact of meter calibration are further discussed in Chapters Six and Seven.

Figure 5.6 Water meter - Alfalfa Plot

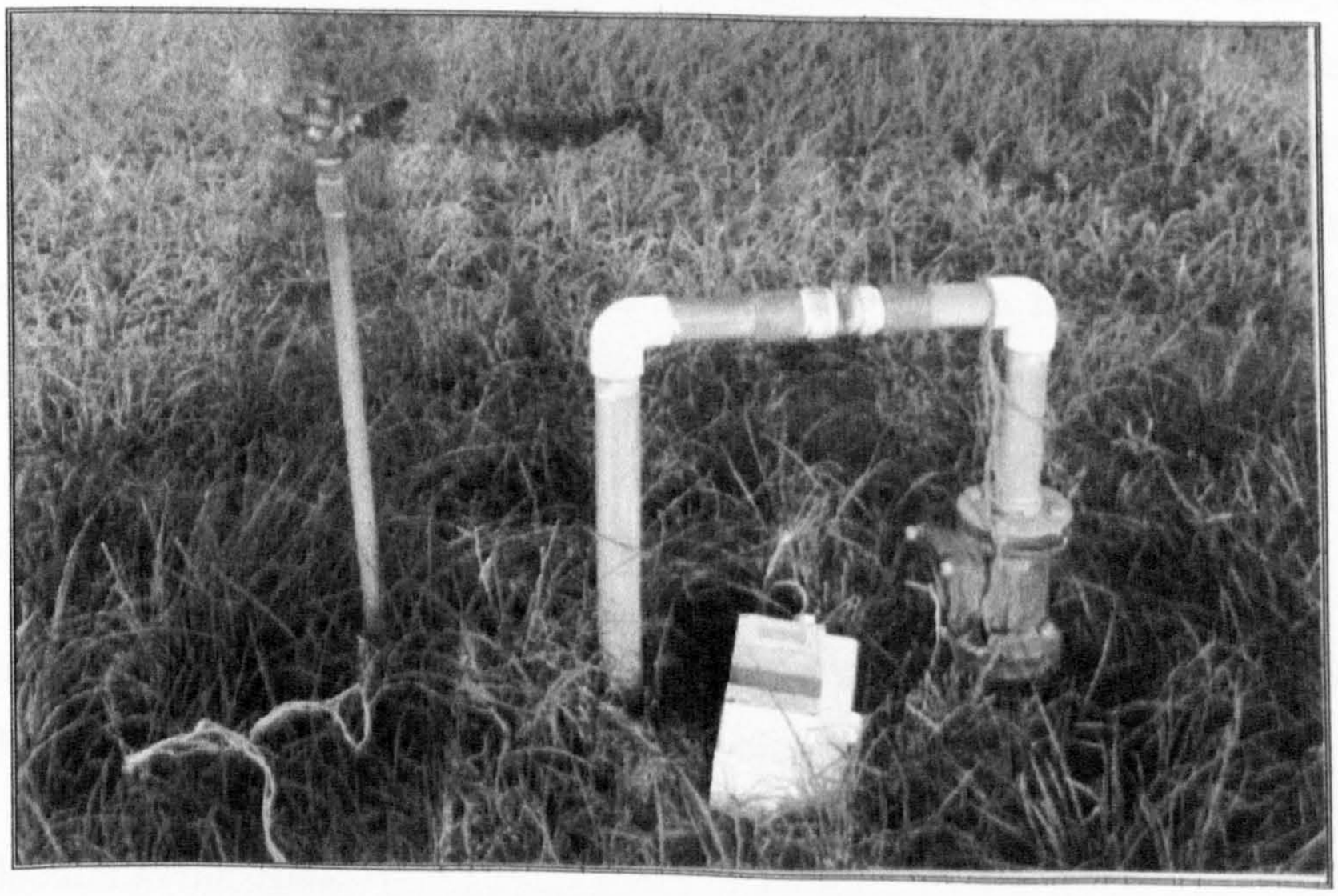


Figure 5.7 Water meter and datalogger - Grass Plot

5.3.2.2. Farm and Crop Surveys

While the MWR National Well Inventory provided a useful starting point in compiling information, all study farms were surveyed several times over the study period to confirm the farm boundaries and to monitor changes in cropping patterns and irrigation methods. This information provided the basis for the calculation of farm water demand and estimates of farm water use efficiency.

Two survey methods were employed. First, all farms were identified on the previous MAF survey maps of the Southern Integrated Study (MAF, 1992). The farm boundaries were digitised and entered into a CAD program (IRRICAD), to produce a farm boundary plot and to provide farm area. The second on-farm survey method involved one or more visits to all farms in order to survey farm boundaries and cropped areas using hand-held bearing compass and measuring wheel. Farm cropping pattern maps were produced from the field data and updated in subsequent visits. Details of crop type, cropped area, percent of canopy area and irrigation method were recorded from the survey and entered into an Excel database.

5.3.2.3. Water Quality

The monitoring of groundwater quality was an important component of the study. Along with the monthly water meter readings on all study farms, water samples were collected from wells to record electrical conductivity. The water EC and temperature were measured at point of sampling using an electrical conductivity meter manufactured by Wissenschaftlich Technische Werkstatten, model LF 92. The EC meter was checked monthly against a standard solution of 8,900 μScm^{-1} and re-calibrated if required.

5.3.2.4. Irrigation Management - Soil Moisture, Salinity and Uniformity

The study of irrigation management on the case study farms, included a number of methods to monitor water distribution and soil water:

Time Domain Reflectrometry

A Trime FM time domain reflectometer (TDR) was used to provide direct measurement of soil moisture levels within selected plots on the case study farms. Two TDR

measurement methods were adopted. These involved either an access tube installed at up to 90 cm depth or a portable three pin probe to 15 cm depth, as illustrated in Figure 5.8.

The TDR is a non-destructive method of measuring the volumetric soil water content. The technique is based on velocity and the transit time of an electromagnetic wave passing through the sample material. The wave is generated by the TDR processor and travels along the coaxial cable to the measuring rods (2 or 3) or probe and is reflected at the end of the rods/probe and travels back the same way. Because the travel distance (twice the length of the cable and rods), the velocity of the wave can be transformed to a transit time measurement. The large difference in dielectric constant between water ($\varepsilon r = 81$) and soil ($\varepsilon r < 5$) makes it possible to derive the water content from the transit time and measured dielectric constant.

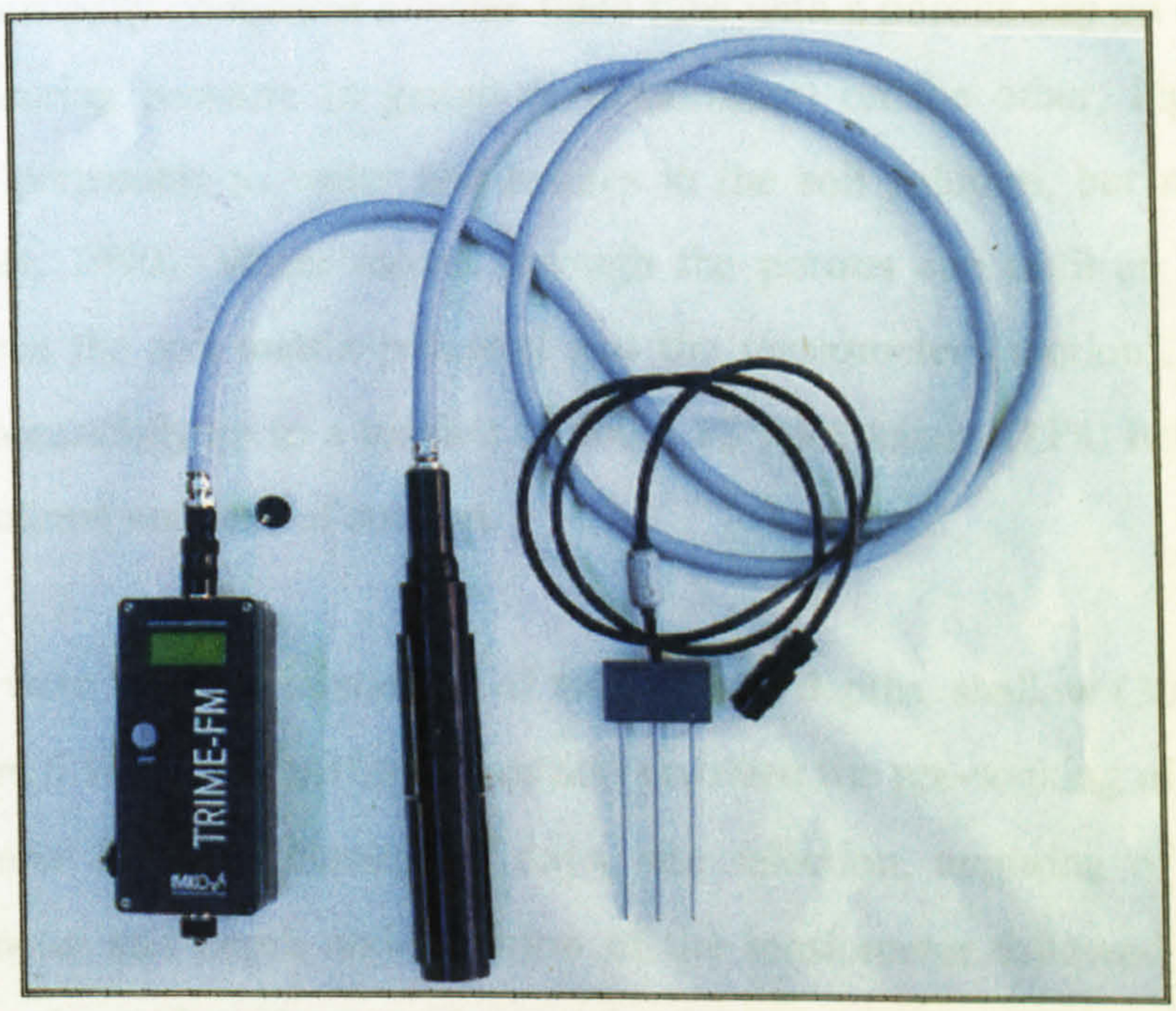


Figure 5.8 Time Domain Reflectometer

The TDR measurement provided information on soil water content for plots and enabled calculation of soil water balances and hence the determination of appropriate irrigation schedules. TDR access tubes were installed adjacent to soil tensiometers and soil moisture extraction tubes, Figure 5.10. Where possible soil volumetric water content was correlated with soil moisture tensions measured by tensiometers at the same depth (Appendix Z) to determine the soil moisture retention curve. Readings were compared with soil content measurements for the same site and/or soil type recorded in the MAF

soil survey of the southern Batinah (MAF 1992. These comparisons provided a check on the degree of accuracy of the TDR readings and the basis for field capacity levels adopted in the plot water balances in Chapter Seven.

The TDR was also used to evaluate the distribution efficiency between *gelbas* within the alfalfa plots, with access tubes installed in a series of inter-linked *gelbas*. Soil water content was measured pre- and post irrigation.

Soil Tensiometers

Soil tensiometers were installed on all trial plots on the case study farms. The soil tensiometer is a relatively simple, non-destructive and practical method of measuring soil moisture tension *in situ*. It is also adopted as the basis for the monitoring of on-farm irrigation scheduling as it provides a direct measurement of soil moisture tensions. A soil tensiometer principally comprises a water-filled tube with a porous cup on one end and a means of measuring pressure (a gauge or manometer) on the other, Figure 5.9. The porous cup is permeable to water and solutes in the soil solution, but not to the soil matrix (Stewart, 1990). Water moves through the porous cup until an equilibrium is reached between the soil matrix potential and the tensiometer (suction). Tensiometers can operate successfully up to a tension of about 85 kiloPascals (kPa) before cavitation of the water column and loss of suction.

Tensiometers were installed in stations of two, at two depths, shallow (30 cm) and deep (60 cm), Figure 5.10. The installation method involved the pre-soaking of the porous tip in distilled water for approximately 7 days, site selection, auguring of a hole of the specified diameter and depth and insertion of the tensiometer followed by filling with distilled water, algaecide and evacuation.

Figure 5.9 Soil Tensiometer

Figure 5.10 Tensiometer Station

Catch-Cans

The coefficient of uniformity of sprinkler irrigated plots was determined by measurement using catch-cans to collect precipitation within the wetted radius of the sprinkler. Two types of catch-can were developed for the purpose, both manufactured from locally available materials, and designed to suit operating conditions, which were:

- Funnel and uPVC Drainage Pipe: comprising a plastic funnel of 98 mm diameter, connected with 15mm polyethylene tube to the collection bottle (1.5 l) and

mounted inside either 0.60 or 1.00 m (dependent on height of measurement) section of uPVC drainage pipe (100 mm nominal diameter), Figure 5.11. (This catch-can was manufactured by the author.)

- Funnel and Aluminium Pipe: comprising a plastic funnel mounted and sealed inside a section of aluminium pipe (100 mm nominal diameter), with collection bottle fitted inside the pipe and supported with a steel pin, Figure 5.11.

Sprinkler precipitation rate was measured with the catch-cans at two heights, 0.45 and 0.90 m. For single irrigation events catch-cans were installed at 0.45 m, with measurements taken with grass height less than 0.30 m. For multiple irrigation events over a period of 20-30 days catch-cans were installed at a height of 0.90 m to avoid interference from the grass.

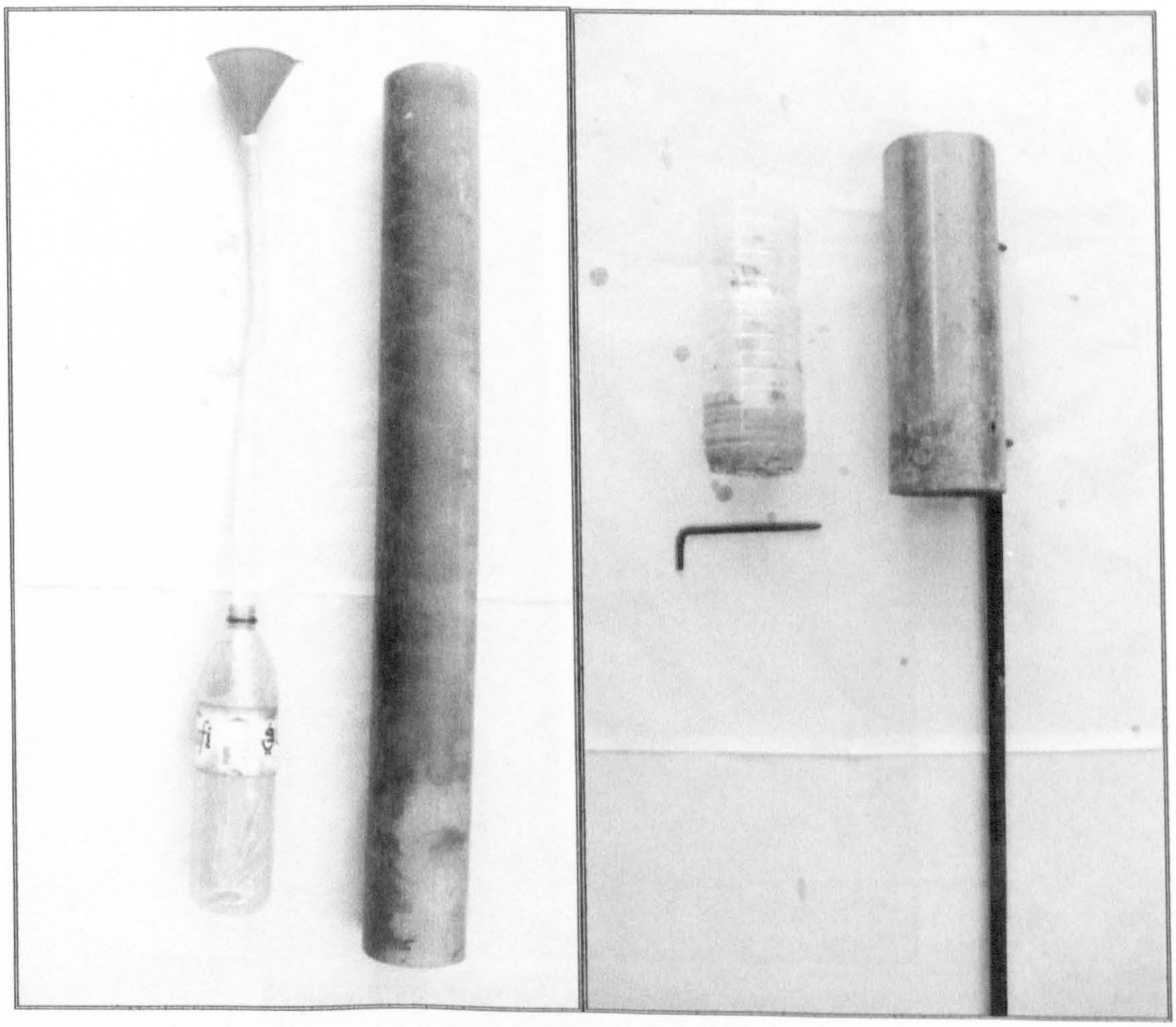


Figure 5.11 Catch-Cans for Measurement of Sprinkler Uniformity

Soil Moisture Extraction

Soil moisture extraction tubes (SME) were installed in all plots on case study farms for the monitoring of soil water salinity. SMEs are a relatively simple, practical and non-destructive method for sampling soil moisture extracts. They comprise a tube (15mm), porous cup at one end, plug, sample tube and clip at the other, Figure 5.12. The SME is installed at the specified location, a vacuum is applied to the tube with a hand syringe via the sample tube which is sealed with the clip. The vacuum draws a soil moisture sample into the SME, from where it is subsequently extracted (after 1-2 days later). SMEs were installed adjacent to the soil tensiometers and TDR access tubes as illustrated in Figure 5.10. Soil extracts were periodically collected (every 1-2 months) to monitor changes in soil salinity.

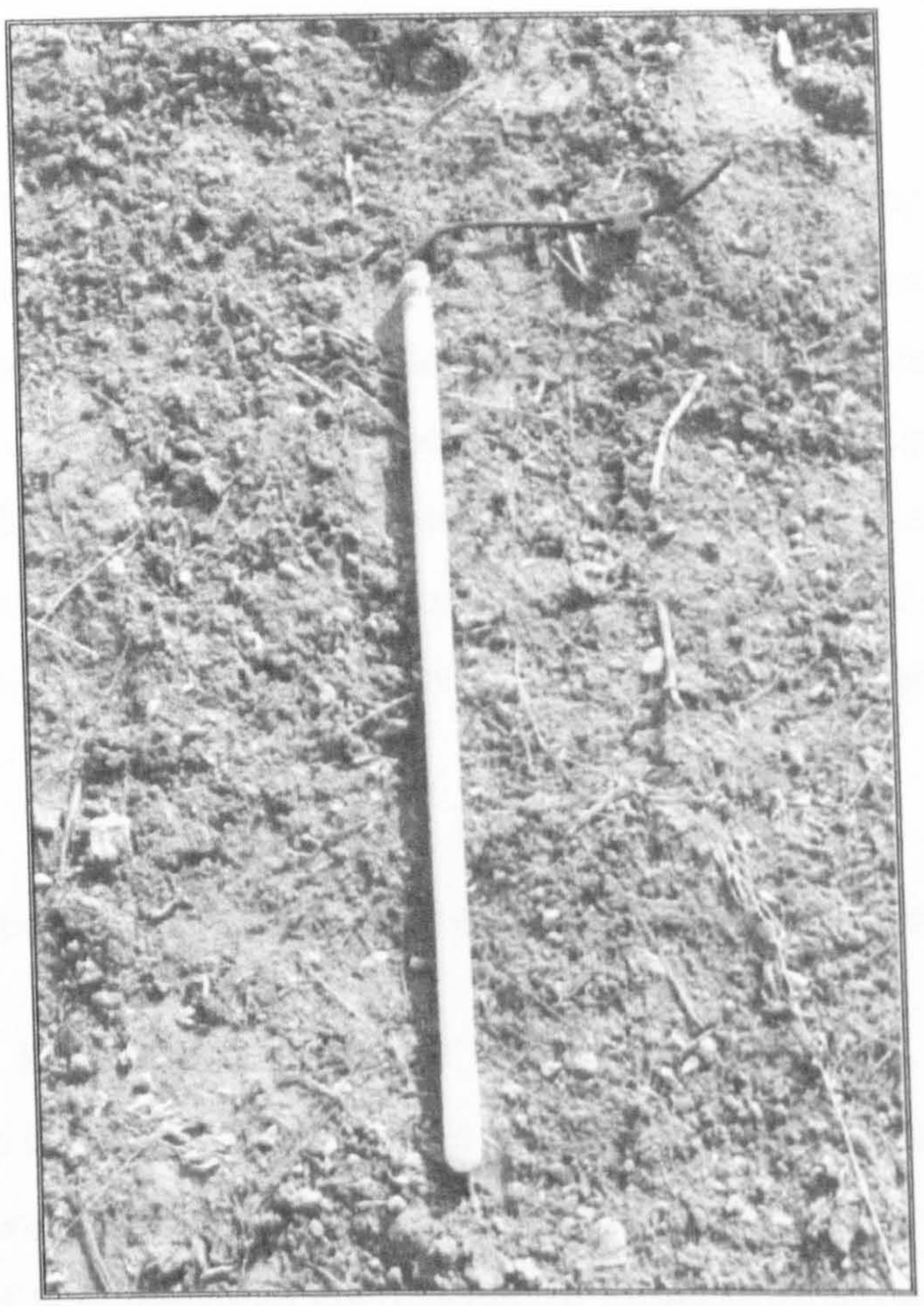


Figure 5.12 Soil Moisture Extraction Tube

5.3.2.5. Farm Owner and Manager Meetings

Meeting farm owners and managers was an important part of the research programme. These ranged from informal meetings during routine data collection visits to structured

interviews. The most direct contact was on the five case study farms where the highest level of monitoring was undertaken and where irrigation trials were implemented on the alfalfa and grass plots. The willingness of the farm owners to participate in the programme was one of the selection criteria for these farms. Preliminary meetings were held with the owners at which the background and purpose of the programme were presented and discussed. The voluntary nature of the programme was stressed and the full cooperation of the farm owner and manager requested.

5.3.3. Data Analysis

To investigate the research objectives a number of data analysis methods were applied, as listed in the following subsections.

5.3.3.1. Impact of Saline Intrusion

The research objective is to investigate the relationship between changes in water quality due to saline intrusion and abstraction from wells within the study area. At the farm level, water abstraction is a function of climatic conditions, cropped area, crop types and irrigation method. Abstraction rates are based on the calculated irrigation demand, that is the total water demand to meet crop and leaching requirements as well as losses to percolation and surface evaporation. Apart from seasonal climatic factors abstraction rates may vary due to changes in crops and cropped areas, water quality and irrigation methods.

To evaluate the impact of changes in water quality on abstraction, the analysis included:

- Farm Water Demand: calculation of monthly water demand per farm based on climate, crop types and area, irrigation method and water quality. This includes use of the Cropwat software for calculation of reference evapotranspiration (ETo) and standard and field measured coefficients for crops (Kc) and irrigation efficiencies, respectively (FAO, 1992). Crop type and areas are based on measured areas from field surveys.

- Irrigation Management: evaluation of irrigation efficiency for sample plots was based on the following:-

- Soil water balance for sample plots on the case study farms, based on monitored application rates from meter readings, calculated crop water demand and soil moisture content and tension from TDR and soil tensiometer readings. The soil water balance was calculated using the Soil Scheduler software (Shayya, W, 1993).
- Application uniformity of irrigation methods, based on field measurements from catch-cans, surface water distribution and flow rates for bubblers and drippers, with analysis based on Christiansen's coefficient (CU) (Benami & Ofen, 1983).

- Statistical Analysis: calculation and comparison of the relationship and trends in farm water demand (above) and changes in water quality. This included the derivation of the correlation between abstraction and water quality, both spatially and temporally. It also included the correlation between water quality and other variables such as crop type and area, and irrigation methods. A variety of tools is employed to demonstrate this relationship graphically and with maps, including ARCVIEW 3 software.

5.3.3.2. Demand Management

Saline intrusion is predicted to have a significant impact on water demand and therefore abstraction within the study area. While water demand is expected initially to increase due to increased leaching requirement it is anticipated ultimately to decline as cropped area declines due to the phytotoxic affects of increasing water and soil salinity levels. A progressive decline in water abstraction and increase in water salinity may affect the benefits of the potential and therefore the effectiveness of demand management strategies.

The analysis of the impact of changes in abstraction on saline intrusion, water use, and groundwater depletion was evaluated using the Barka Profile groundwater model. The model is a representative 'slice' of the hydrogeological and water use conditions of the catchments (Appendix AE). It provided comparative analysis of the rates of change in saline intrusion and groundwater depletion. It also provide predictions of water levels for selected well locations, as indicators of trends in water levels.

5.4. STUDY IMPLEMENTATION

The research programme was implemented over a five and half year period from May 1994 to December 1999. This was a longer period than originally proposed at the commencement in October 1993 or the during the subsequent upgrade in 1997. It was largely due to delays in establishing and completing the case study component of the programme, initially associated with the acquisition of the TDR and soil tensiometers and latterly with the implementation of the irrigation monitoring. One advantage of these delays was that the programme provided a longer data set of abstraction readings, which was useful for indicating trends in water use with time and the impact of saline intrusion.

During this period the programme involved the implementation of field activities, often concurrently, to investigate the research objectives. Figure 5.13 summarises the research programme and associated activities.

	Year	94				95				96				97				98				99			
	Qtr	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
	Field Activities																								
I	**Study Farms (140)**	◀	Phase I farms						▶	◀	Phase II farms												▶		
a)	Installation of water meters																								
b)	Monitoring of water abstraction																								
c)	Monitoring of water quality																								
d)	Cropping pattern surveys																								
e)	Irrigation method surveys																								
II	**Case Study Farms (5)**															◀									▶
a)	Farm Selection																								
b)	Farmer meetings																								
c)	Farm surveys & plot selection																								
d)	Installation water meters																								
	Phase I																								
e)	Monitoring irrigation management															◀					▶				
	Catch can trials																								
	Irrigation applications																								
	Phase II																								
f)	Irrigation management trials																				◀				▶
	Farm meetings																								
	Installation soil tensiometers																								
	Installation of TDR access tubes																								
	Installation of SME tubes																								
	Derivation of irrigation schedule																								
	Monitoring of application rates																								

Figure 5.13 Research Implementation Programme

CHAPTER SIX

RESEARCH RESULTS

6.1 INTRODUCTION

This chapter presents a description of the study farms and results of the research programme as outlined in Chapter 5. These results include data from the monitoring of water quality and abstraction from 368 wells on the 138 farms of the study area. They also include data from, periodic farm surveys recording changes in crop area and types, as well as irrigation methods, over the research period, 1994-99. The detailed evaluation of irrigation management carried out on the five case study farms provided details of irrigation application rates and soil water tension on trial plots of grass and alfalfa. The uniformity of irrigation was evaluated for sprinklers and bubblers on a sample of twenty farms.

The chapter is supported by appendices listing the full results of the various components of the research programme. It presents analysis of the results of these components to quantify water quality, water abstraction, crop types and areas and current irrigation efficiency, but it does not include comparative analysis of the changes in water quality, water demand or demand management strategies. This information will be presented in Chapter 7 as part of the evaluation of the study hypotheses.

6.2 RESEARCH PERIOD

As outlined in Chapter 5 the research was carried out over a five-year period from March 1994 to December 1999. The activities during this period included:

- Monitoring of abstraction
- Monitoring of water quality
- Surveys of crop areas
- Surveys of irrigation methods
- Evaluation of irrigation application and soil water tension on five case study farms
- Evaluation of the coefficient of uniformity of sprinkler and bubbler irrigation on 20 sample farms

The study farms consisted of two groups (Phases 1 and 2), on which the above

mentioned monitoring and surveys were carried out as follows:

- Phase 1: March 1994 to July 1999
- Phase 2: May 1996 to July 1999

6.3 STUDY FARM DESCRIPTION

The 138 study farms, located within the catchments of Wadis Taww and Ma'awil of the southern Batinah, were selected in two phases (25 farms in phase 1 and 113 in phase 2), as described in Chapter Five. Figure 5.1 shows the location of the farms, as well as the five case study farms for the more detailed evaluation of irrigation management.

6.3.1 Wells

At the commencement of the programme there were a total of 363 operational wells and boreholes (73 and 290 on Phases 1 and 2 farms respectively). Operational wells were classified as wells on which an operating pumping system was installed. During the research period an additional five wells were installed giving a total of 368 wells that were operational for all or part of the research period.

The MWR inventoried 358 of the wells as part of the NWIP in the early 1990s on which an inventory plate (listing the well inventory number) was fixed either on the side of the wellhead or on an adjacent structure. At the time of water meter installation five wells were found without an inventory plate. These wells may have been missed during the NWIP inventory or installed subsequently. For the purposes of the study, they were assigned nominal well numbers in the series 000/001 to 000/005. The five wells installed during the research period were assigned nominal well numbers 000/006 to 000/010. The number of wells per farm varied from 1 to 10. Nearly 60% of farms had 1 or 2 operational wells and fewer than 15% of farms had more than 5 wells, Figure 6.1.

Of the 368 wells that were operational for all or part of the research period, 62 became permanently non-operational during that period. These included 13 wells on abandoned farms, 43 wells no longer in use due to removal of pump, low water or high salinity and six wells on one farm on which access was denied from January 1998 onwards. By the end of July 1999 a total of 306 operational wells remained, representing the equivalent of 83% of the original total.

Appendix B lists farm and well numbers along with start and end dates of abstraction readings and operational status at the end of meter reading in July 1999.

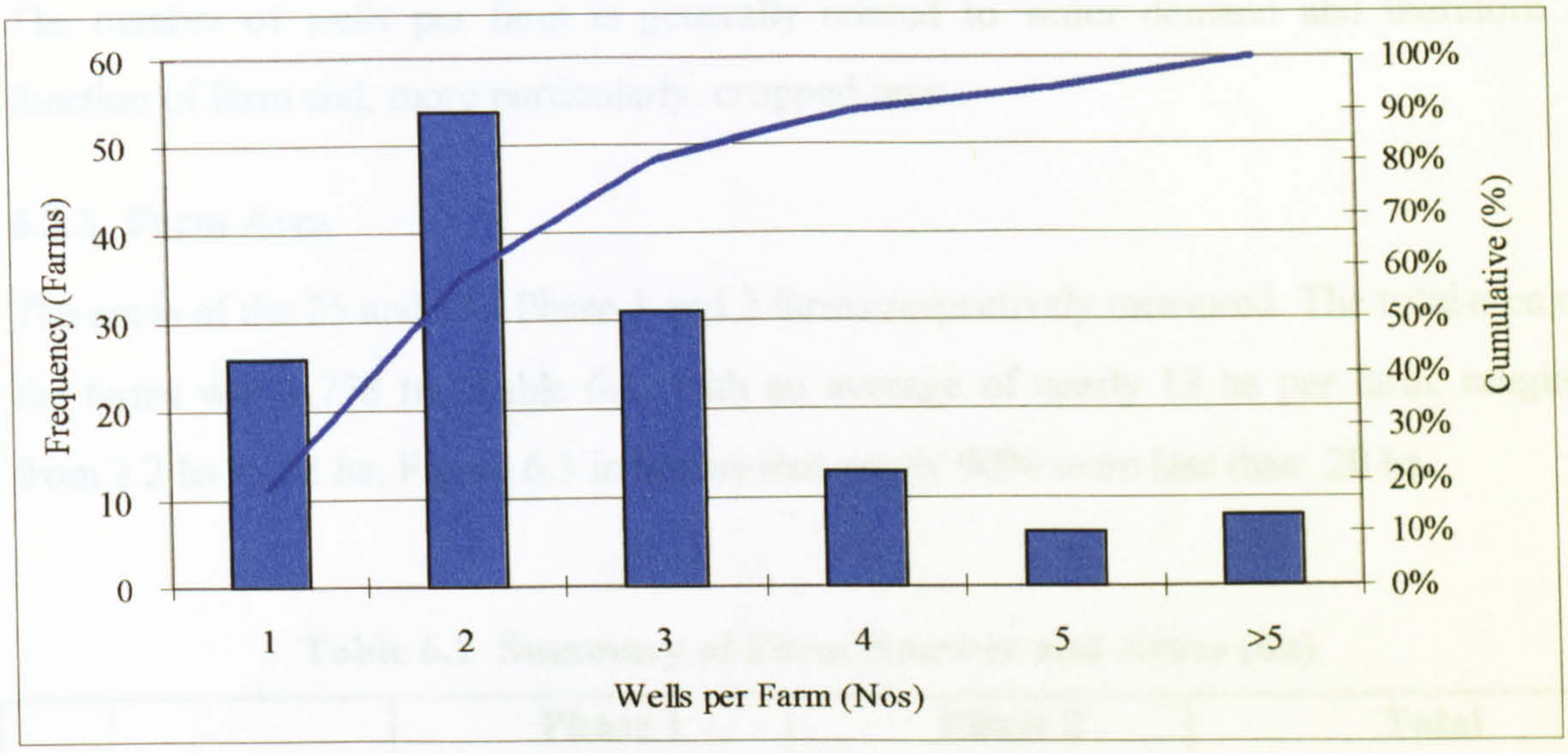


Figure 6.1 Frequency of Wells - Study Farms

The number of operational wells per month over the period March 1994 to July 1999 is presented in Figure 6.2. There were approximately 72 wells operational over the period March 1994 to April 1996. This increased to 354 in May 1996 with the installation of water meters on Phase 2 farms. It should be noted that there was a three month installation period prior to the commissioning of water meters in both Phases 1 and 2. Between May 1996 and July 1999, pumps were installed on five additional wells and 61 wells became non-operational. A number of wells were also temporarily non-operational during the research period, generally due to pump repairs or difficulties associated with electricity supply. The duration of non operation ranged from a few days to several months.

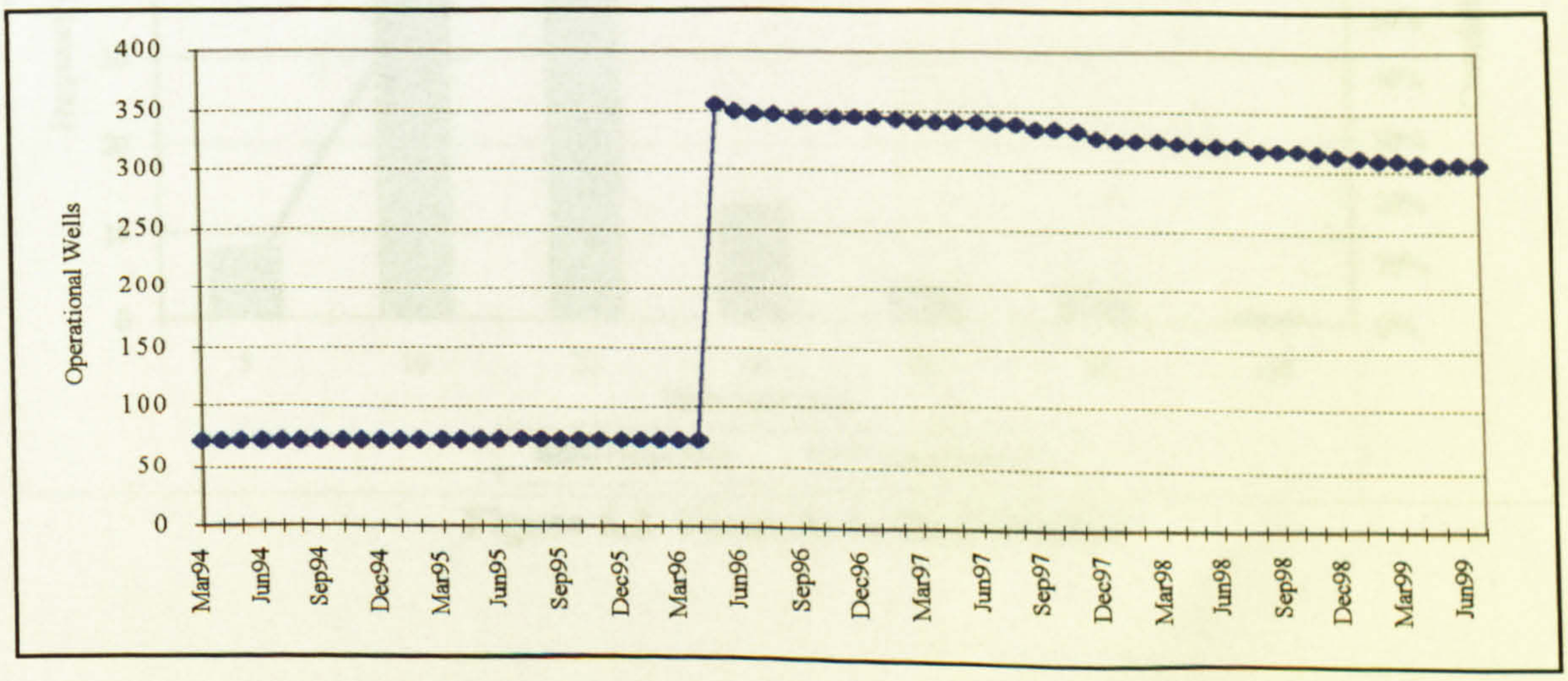


Figure 6.2 Operational Wells

The distribution of the number of wells per farms is illustrated in Figure 6.4, which shows no apparent relationship between the number of wells per farm and farm location. The number of wells per farm is generally related to water demand and therefore a function of farm and, more particularly, cropped area.

6.3.2 Farm Area

The areas of the 25 and 113 Phase 1 and 2 farms respectively measured. The total area of the farms was 1,758 ha, Table 6.1, with an average of nearly 13 ha per farm, ranging from 3.2 ha to 52 ha. Figure 6.3 indicates that nearly 90% were less than 20 ha.

Table 6.1 Summary of Farm Number and Areas (ha)

	Phase 1	Phase 2	Total
Farms (No)	25	113	138
Property Area (ha)	294	1,464	1,758
Average (ha)	11.76	12.95	12.74
Maximum (ha)	50.00	51.65	51.65
Minimum (ha)	3.49	3.21	3.21
Median (ha)	8.84	10.13	9.85

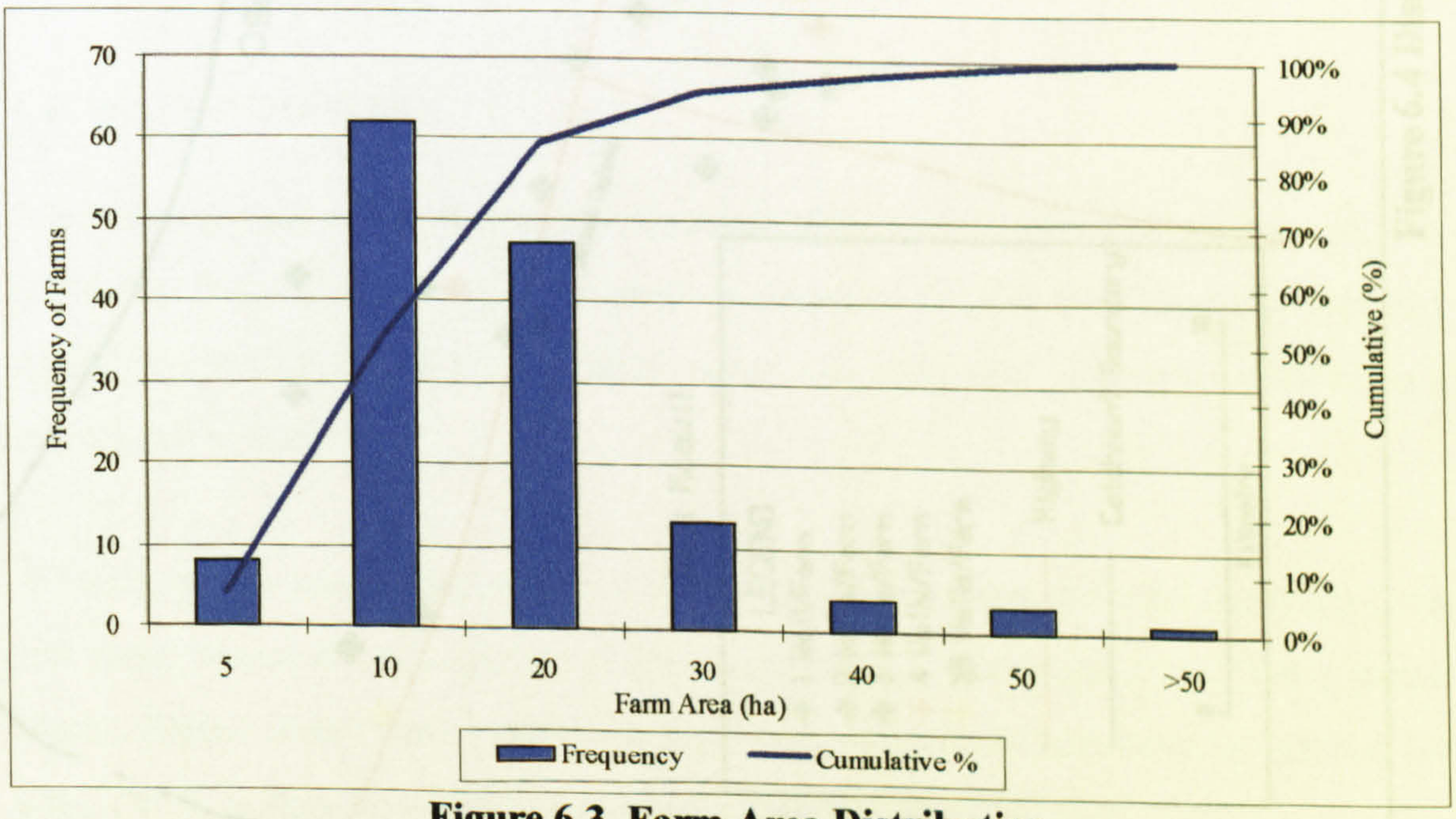


Figure 6.3 Farm Area Distribution

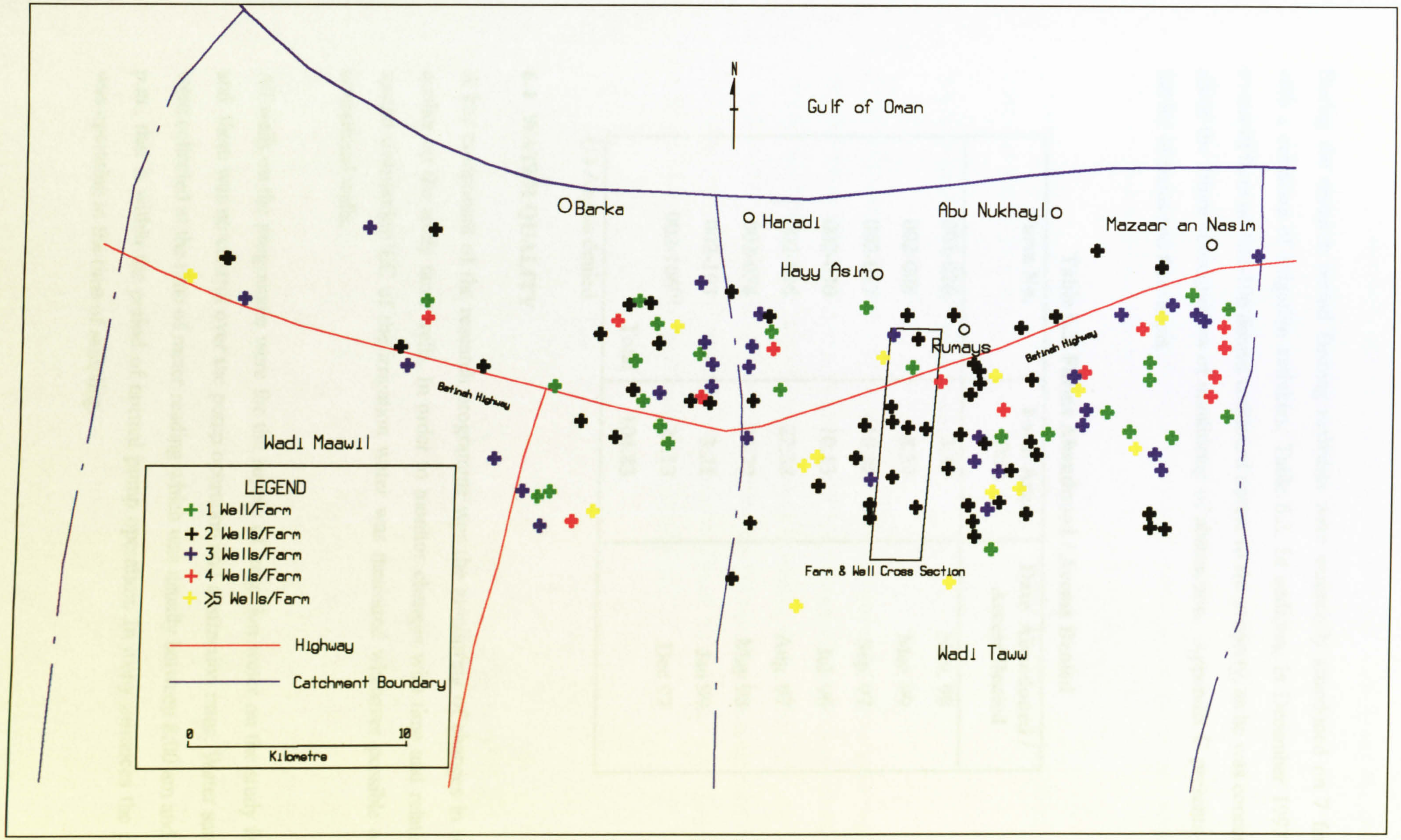


Figure 6.4 Distribution of Well Density per Farm

During the research period farming activities were essentially abandoned on 7 farms, with a cessation of irrigation activities, Table 6.2. In addition, in December 1997 the owner of farm no 002-106 denied continued access to the property, as he was concerned about the future consequences of monitoring of abstraction. Appendix C presents the full list of farms and farm areas.

Table 6.2 Farms Abandoned / Access Denied

Farm No.	Farm Area (ha)	Date Abandoned / Access Denied
001-026	3.49	Nov. 98
002-008	8.57	Mar. 99
002-017	10.20	Sep. 97
002-030	10.13	Jul. 96
002-046	22.38	Aug. 97
002-058	26.72	May 98
002-103	3.21	Jan 99
002-106[1]	20.13	Dec 97
Total	104.83	

(1) Access denied

6.4 WATER QUALITY

A key component of the research programme was the monitoring of changes in water quality on the study farm wells. In order to monitor changes with time and related to spatial distribution EC of the irrigation water was measured whenever possible on all operational wells.

All wells on the programme were for the supply of irrigation water on the study farms, and there was no control over the pump operation and abstraction rates. Water samples were collected at the time of meter reading which was usually between 8:00 am and 2:00 p.m., that is within the period of normal pump operation. In many instances the pump was operating at the time of sampling.

The electrical conductivity was monitored in a total of 368 wells during the research period. As previously discussed, some wells were operational for the full period while others were used for only a part of the period. A total of 8,316 water quality measurements were recorded, from a potential of approximately 14,775 sample months. Some of the difference between actual and potential sample number was due to the temporary non-operation of wells and pumps and in some cases temporary non-access to the farm such as locked gates or well head.

Appendix D presents monthly electrical conductivity readings for all operational wells over the research period.

6.4.1 Overall Trends in Water Quality

A plot of average monthly water quality indicates that while there is variation between months, the trend was of increasing EC, Figure 6.5. Average electrical conductivity (EC) was around 2,500 μScm^{-1} in April 1994, readings increasing to in excess of 3,500 μScm^{-1} by July 1999. Variability between average monthly EC was due to a number of factors including number of wells sampled. The abandonment of high salinity wells during the research period tended to reduce the average monthly EC.

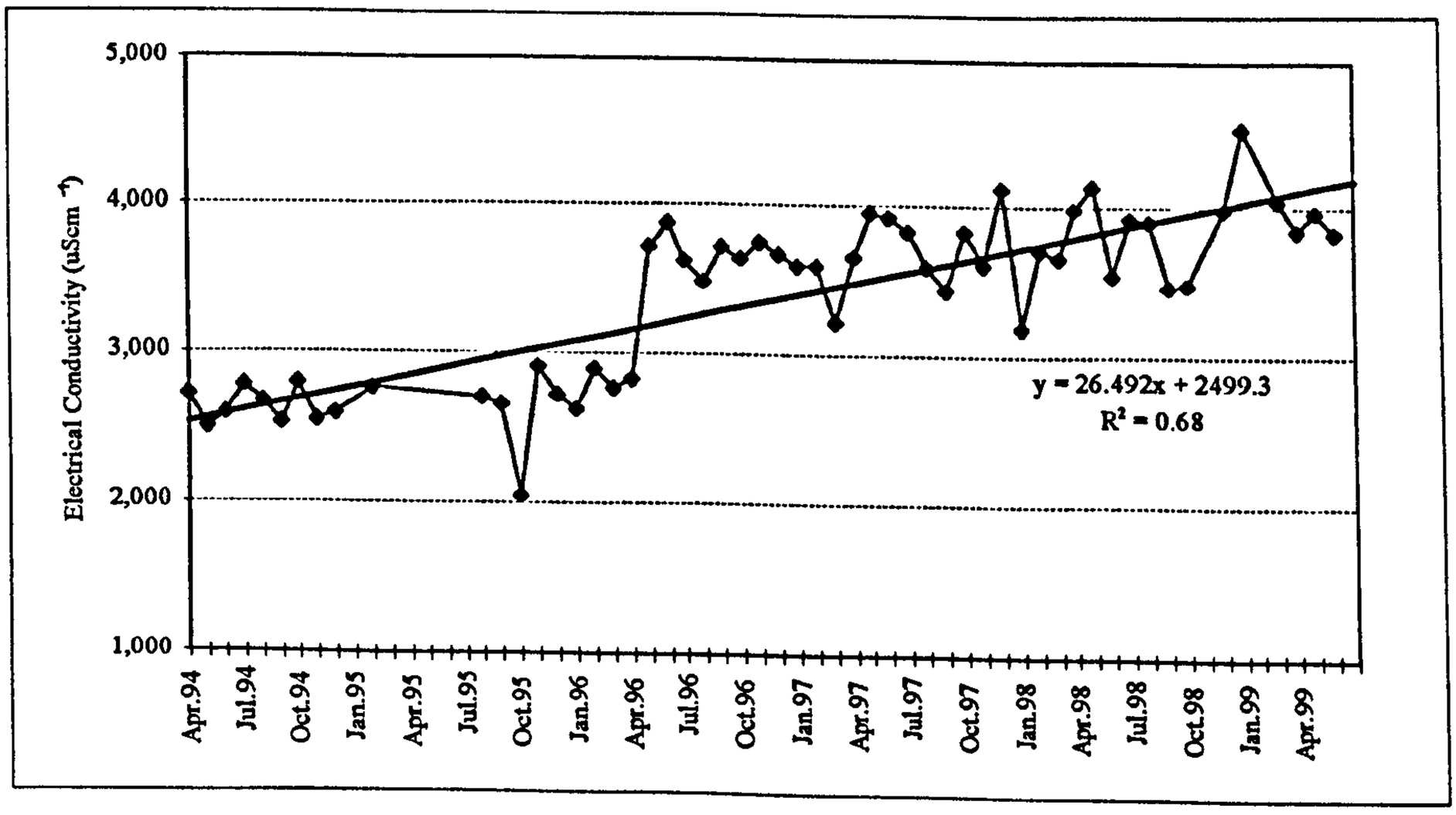


Figure 6.5 Overall Trend in Water Salinity - 1994-99

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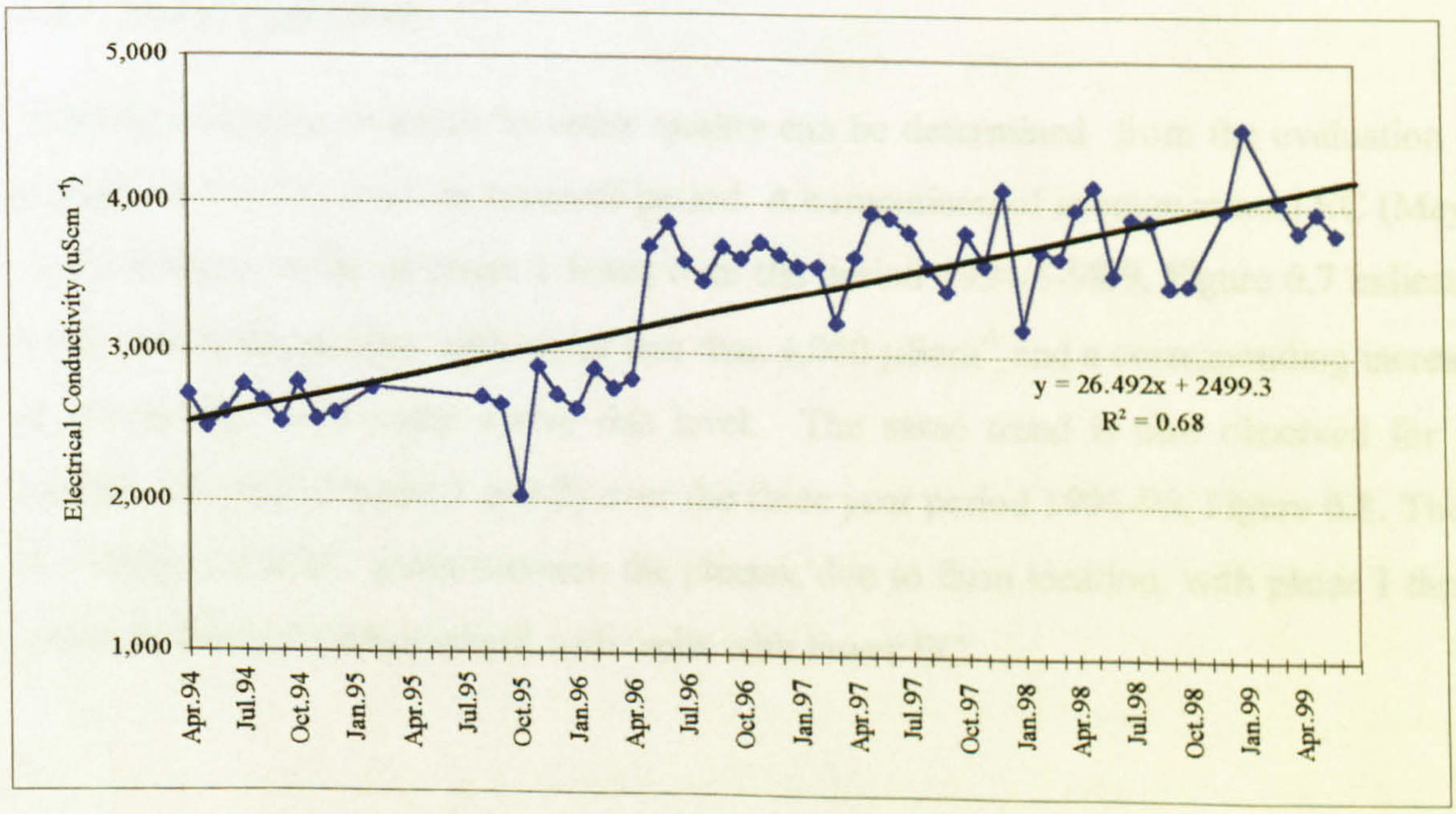

Figure 6.5 Overall Trend in Water Salinity - 1994-99

Figure 6.6 shows the differences in monthly EC value for wells on phase 1 and 2 farms. They ranged from 2,000 to just over 3,000 μScm^{-1} for wells on phase 1 farms and from 3,500 to 5,000 μScm^{-1} for wells on phase 2 farms. There was considerable variation between average monthly EC for both groups of wells. This again was due to variations in number of wells sampled per month and the EC of individual wells.

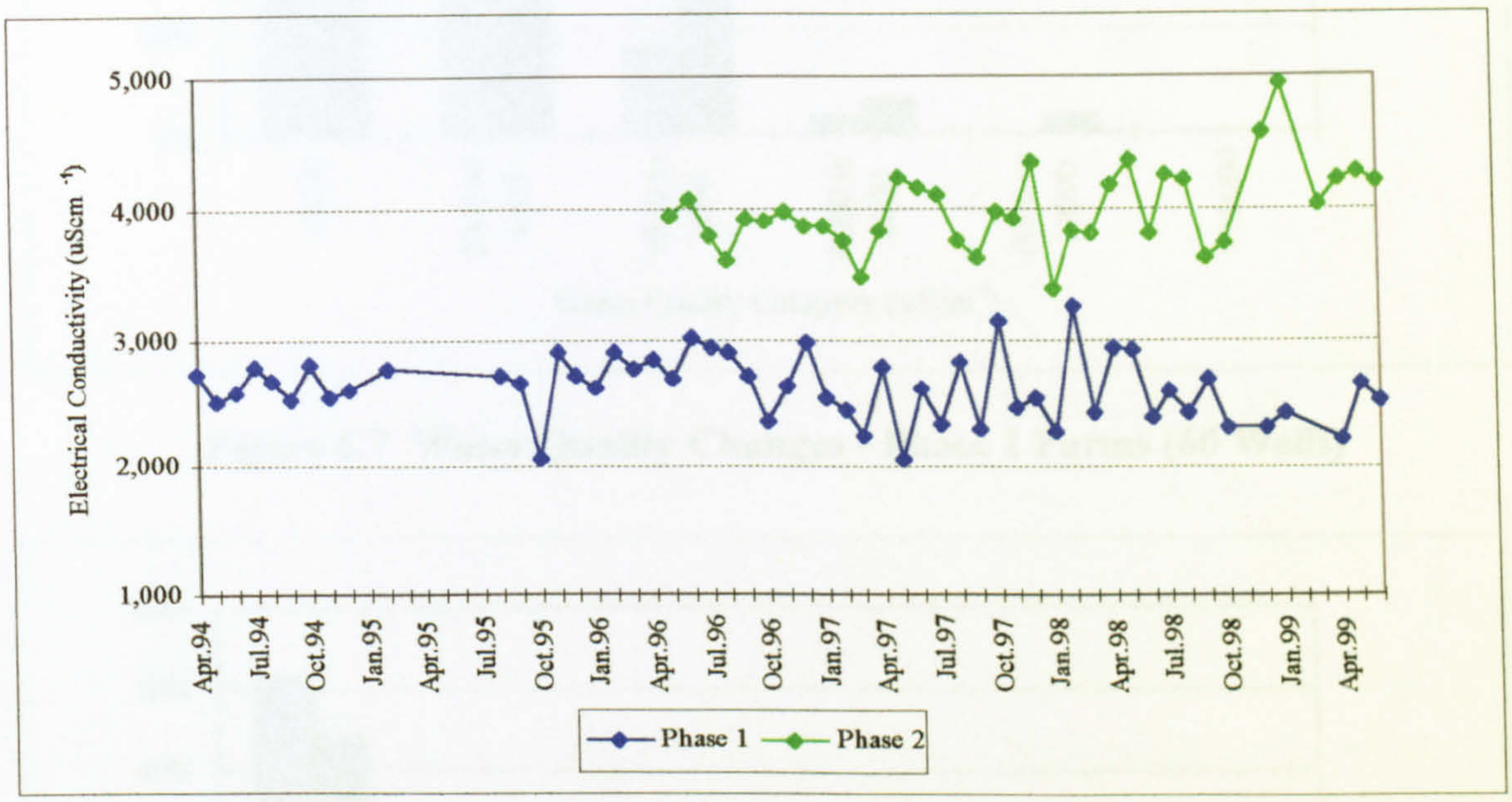

Figure 6.6 Overall Water Quality (Phases 1 and 2)

6.4.2 Salinity per Well

A better indication of trends in water quality can be determined from the evaluation of changes in well EC over the research period. A comparison of average annual EC (May - April) between wells on phase 1 farms over the period 1994/5-98/9, Figure 6.7 indicates a decrease in the number with water less than 4,000 μScm^{-1} and a corresponding increase in the number with water above this level. The same trend is also observed for all operational wells (Phases 1 and 2) over the three year period 1996-99, Figure 6.8. There is a difference in EC levels between the phases, due to farm location, with phase 1 farms generally located further inland with wells with lower EC.

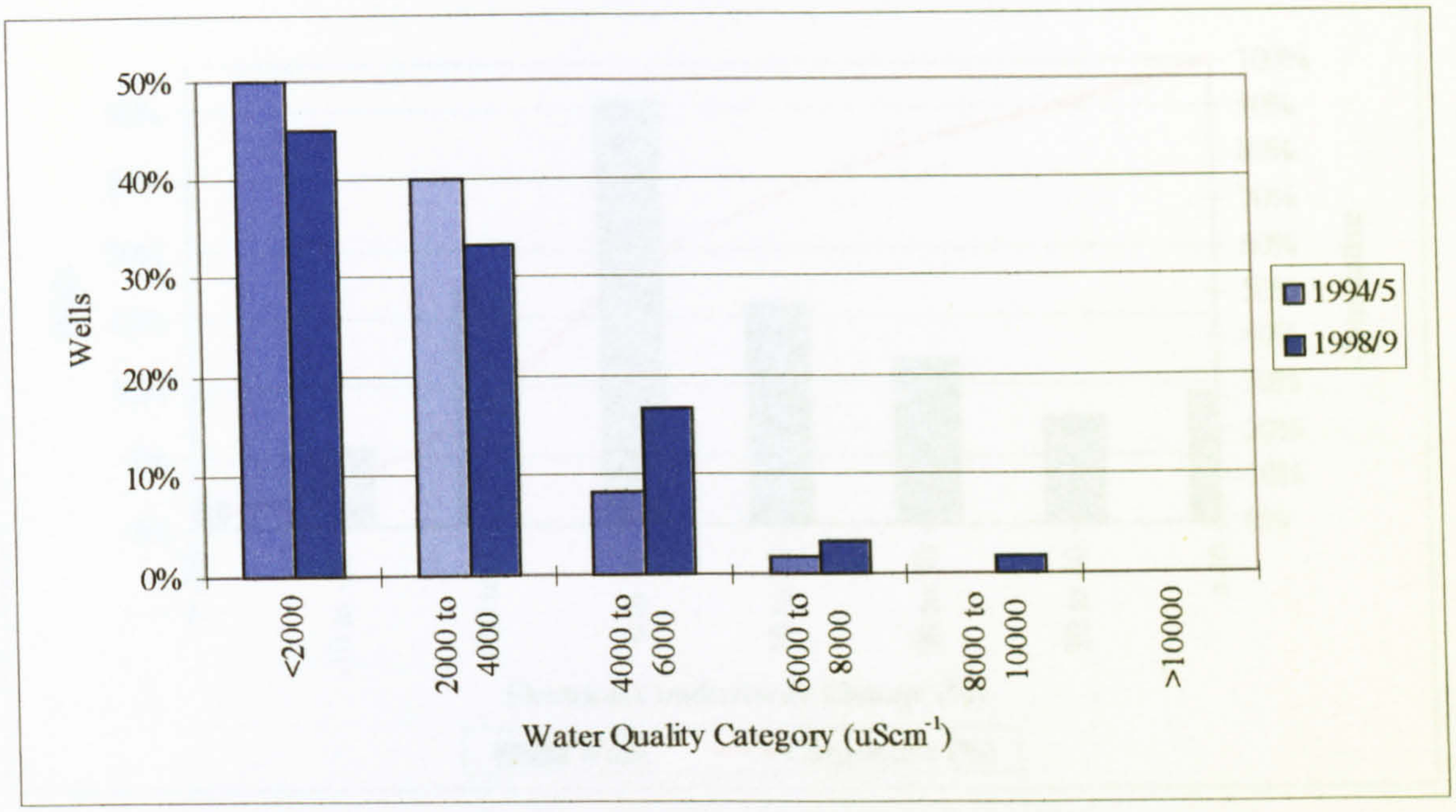

Figure 6.7 Water Quality Changes - Phase 1 Farms (60 Wells)

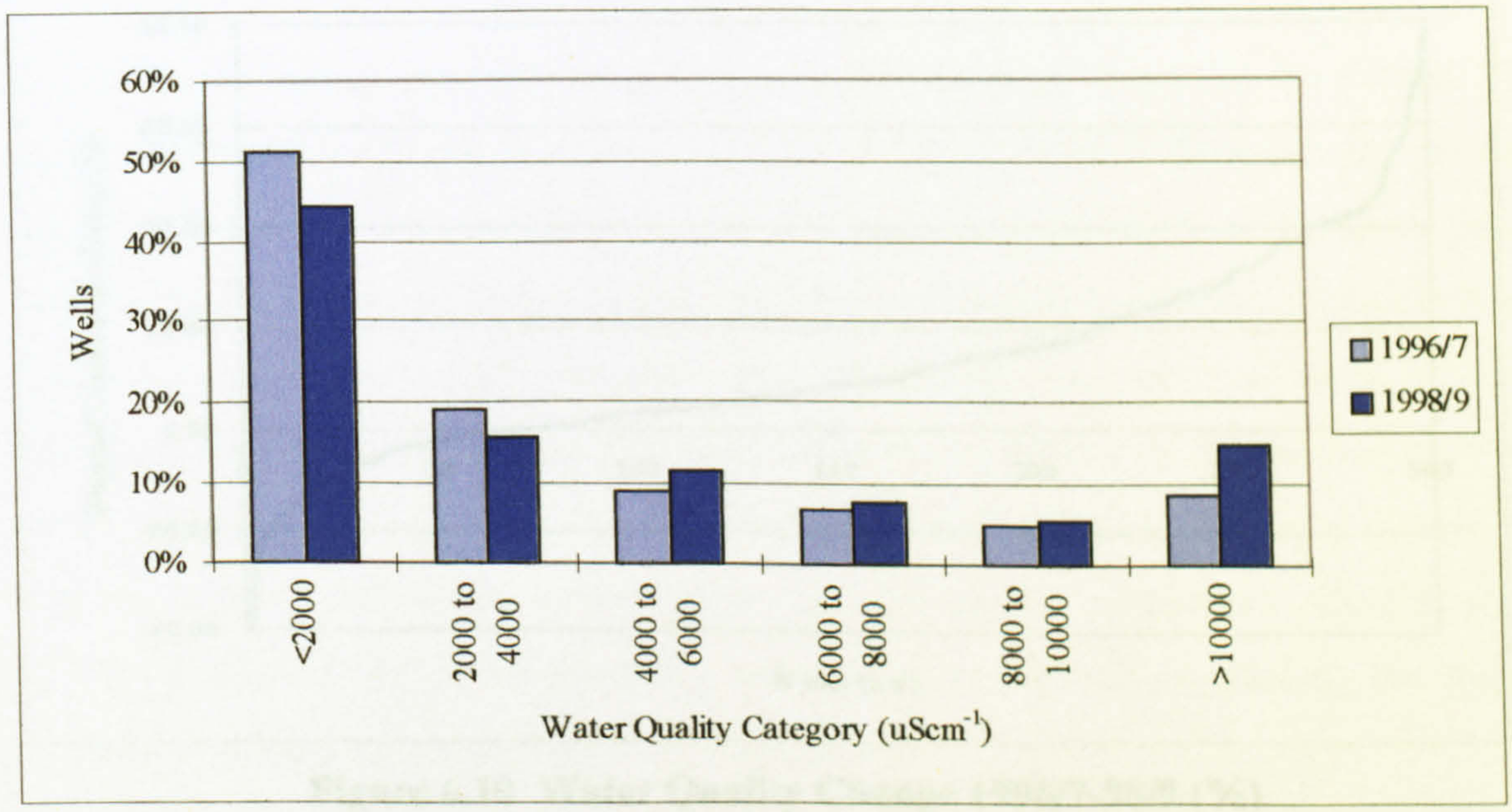

Figure 6.8 Water Quality Changes 1996/7-98/9 (301 wells)

Figure 6.9 illustrates the distribution of changes in EC by water quality class in the period 1996/7-98/9, with positive values representing an increase in EC and negative values a decline. On approximately 75% of operational wells EC increased, and increased by more than 10% on 45% of wells. The distribution is skewed towards increases, Figure 6.10, in terms both of the number of wells and the magnitude of the increase.

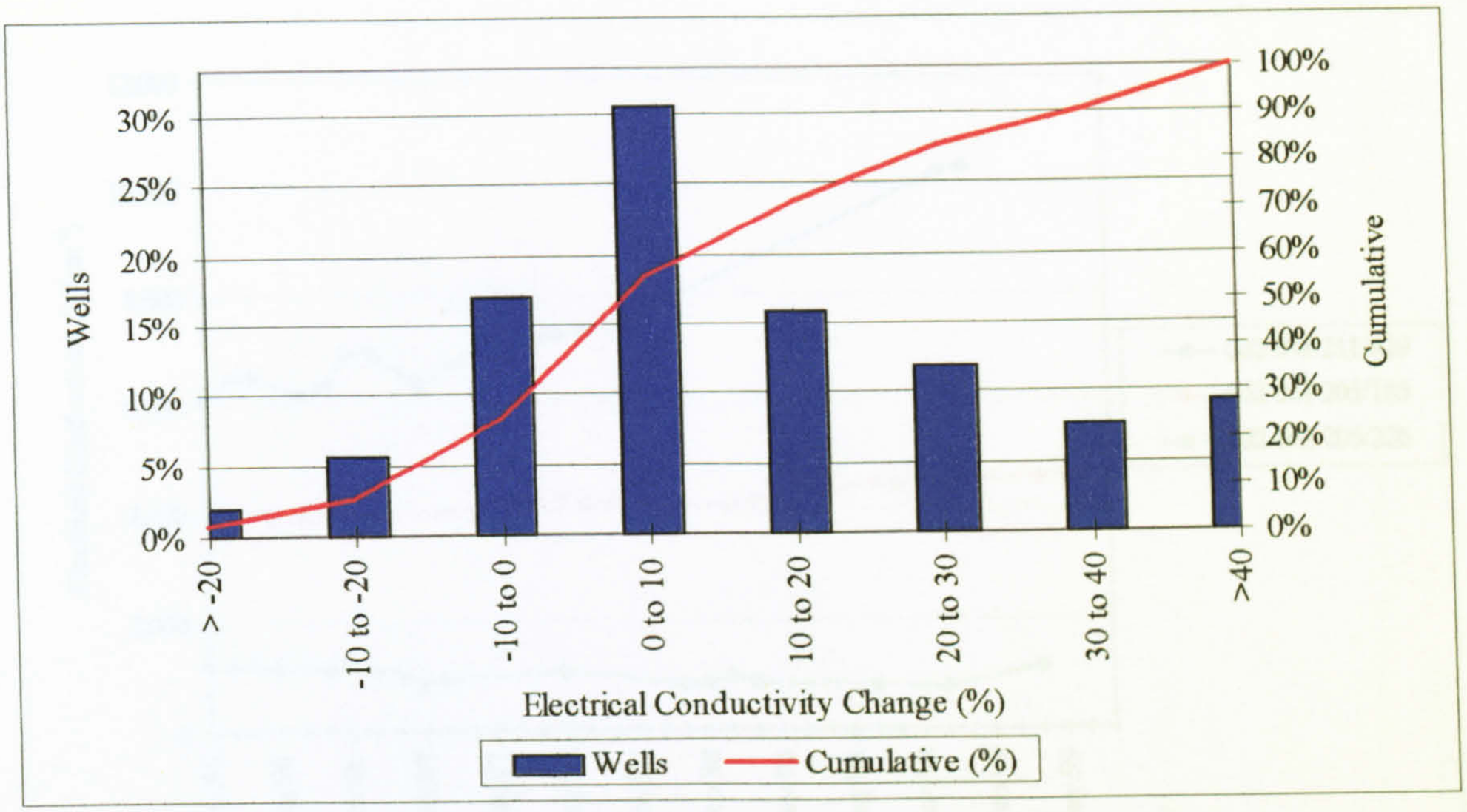

Figure 6.9 Change in Well EC 1996/7-1998/9 (all wells)

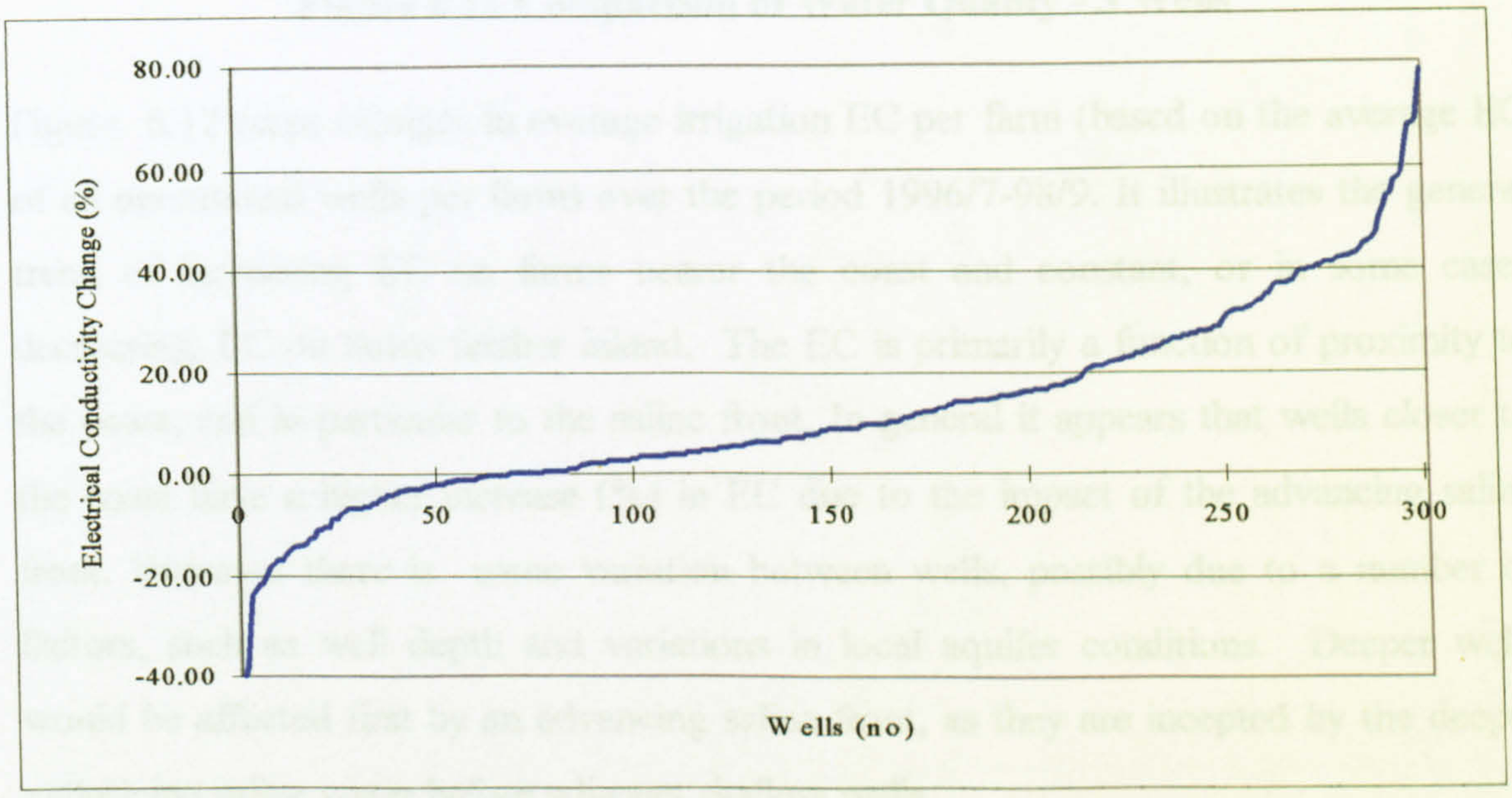

Figure 6.10 Water Quality Change 1996/7-98/9 (%)

Figure 6.11 compares changes in water quality for three wells located on three farms. The wells represent a cross section, Figure 6.12, perpendicular to the coast. The first well (on farm 002-038) is approximately 5 km from the sea and the second and third wells (on farms 002-061 and 002-063) are 10 and 14 km from the sea respectively. The largest increase in EC occurred in the first well (211/429), from 6,000 to more than 10,000 μScm^{-1} (37% rise) in the 3 year period. A smaller increase (16%) was recorded for the second well (205/185), and EC on the third well (205/226) was constant at around 1,000 μScm^{-1}.

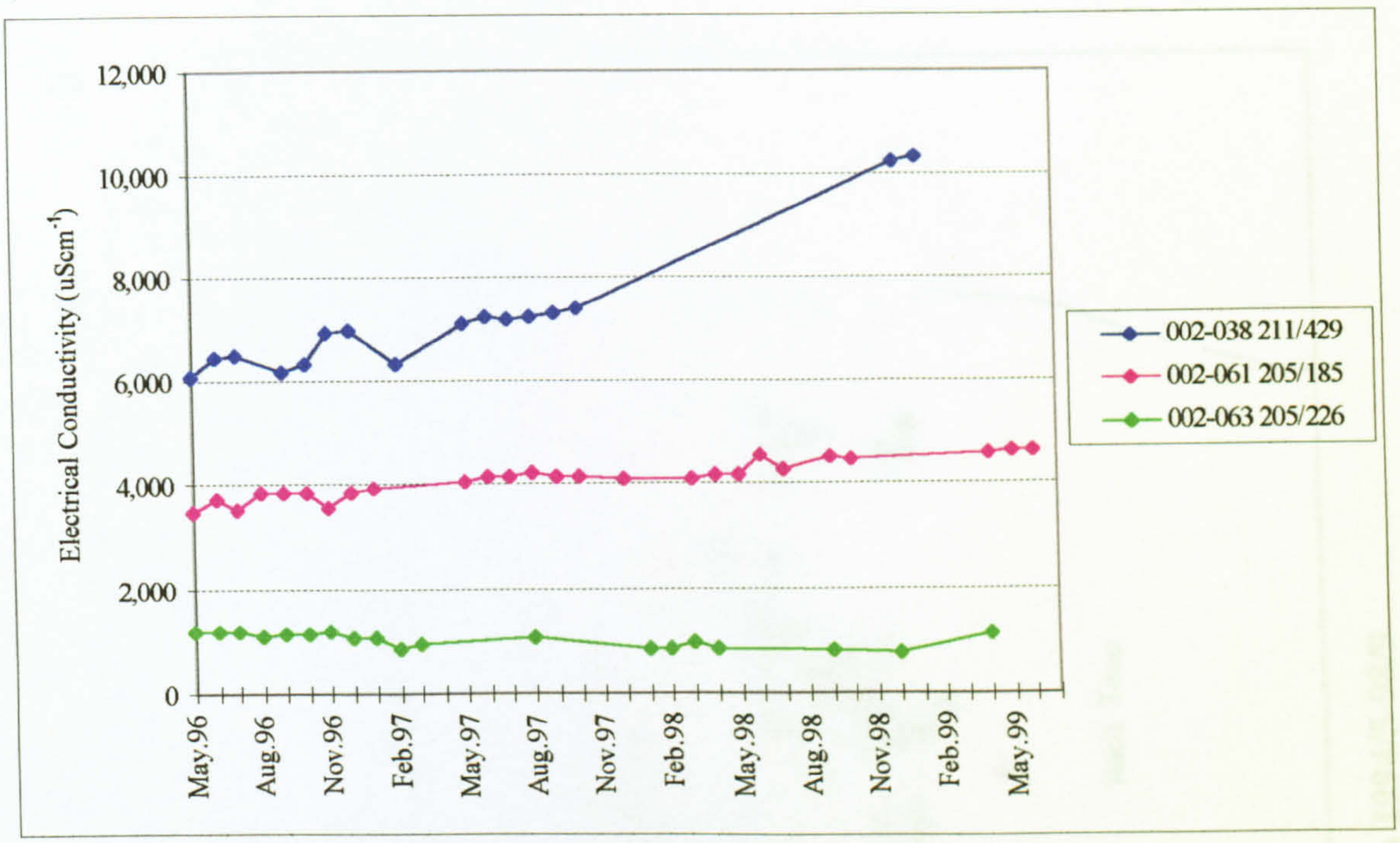

Figure 6.11 Comparison of Water Quality - 3 Wells

Figure 6.12 maps changes in average irrigation EC per farm (based on the average EC of all operational wells per farm) over the period 1996/7-98/9. It illustrates the general trend of increasing EC on farms nearer the coast and constant, or in some cases decreasing, EC on farms further inland. The EC is primarily a function of proximity to the coast, and in particular to the saline front. In general it appears that wells closer to the coast have a higher increase (%) in EC due to the impact of the advancing saline front. However there is some variation between wells, possibly due to a number of factors, such as well depth and variations in local aquifer conditions. Deeper wells would be affected first by an advancing saline front, as they are incepted by the deeper underlying saline water before adjacent shallow wells.

Figure 6.13 maps the distribution of average annual irrigation EC per farm in 1996. Note the concentration of high EC farms between the Batinah Highway and the coast, particularly within Wadi Taww.

Figure 6.14 plots the average annual irrigation EC for the 1998/98 year, indicating an increase in the farms with EC greater than 6,000 μScm^{-1} south of the highway.

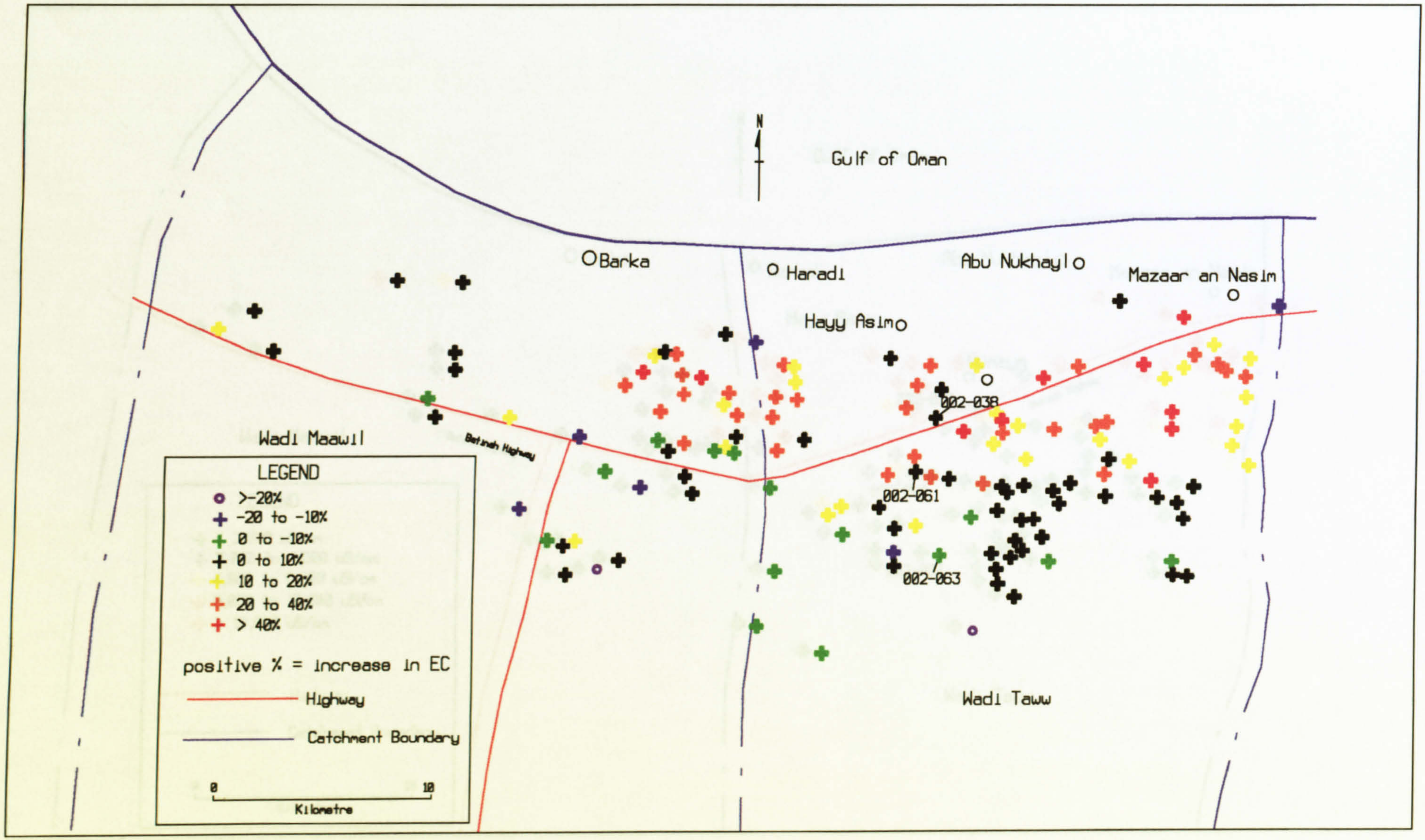

Figure 6.12 Changes in Irrigation EC (uScm^{-1}) per Farm 1994/5-98/9

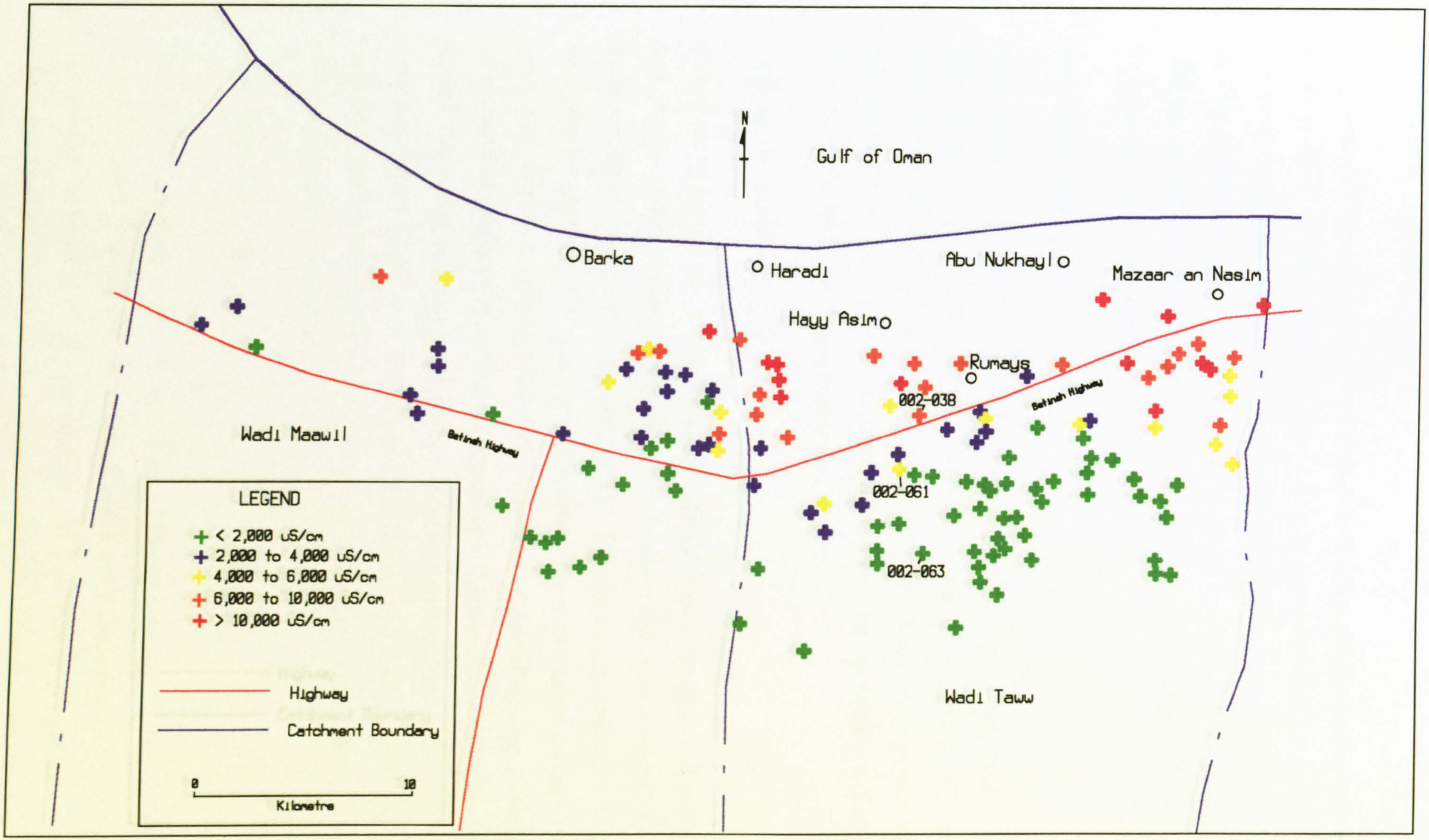

Figure 6.13 Irrigation EC (uScm^{-1}) 1996/7

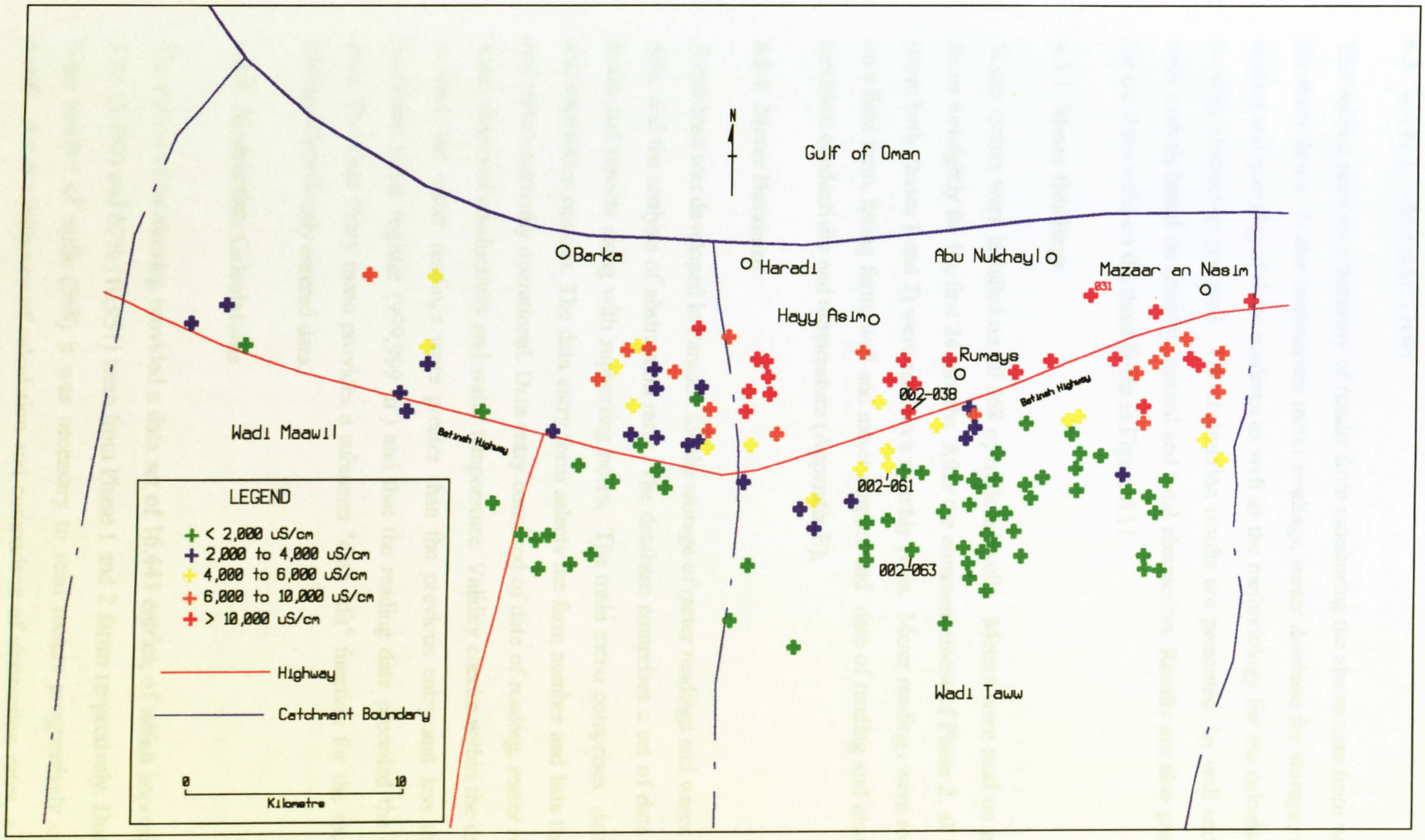

Figure 6.14 Irrigation EC (uScm^{-1}) 1998/9

6.5 WATER ABSTRACTION

This section presents a summary of results from monitoring the abstraction from wells on the study farms. It also summarises meter readings, meter database for storage, quality control and querying of these readings as well as the methodology for the calculation of monthly abstraction per well. The abstraction results are presented by well and farm, with analysis based on monthly, annual and total abstraction. Results are also presented for the three wells on the three farms in Figure 6.11.

6.5.1 Meter Readings

Water meters were installed on all 368 operational wells. Meters were read on phase 1 farms fortnightly for the first 24 months. After the commencement of Phase 2, all meters (from both Phases 1 and 2) were read on a monthly basis. Meter readings were recorded on a field form, listing farm, well and meter number and date of reading and also water electrical conductivity and temperature (Appendix E).

6.5.2 Meter Database

A database was developed in Paradox for the storage of meter readings and water quality data, and the analysis of abstraction rates. The database comprises a set of data tables, forms and reports along with supporting notes. The main menu comprises data entry and abstraction options. The data entry form selects the farm number and lists the wells and meters currently operational. Data entry consisted of date of reading, meter reading, water electrical conductivity and water temperature. Validity checks within the database verified that meter readings were greater than the previous entry and less than the maximum meter register (999,999 m^3) and that the reading date preceded the current date. The Data Entry menu provides a submenu "data edit" function for the recall and editing of previously entered data.

6.5.3 Abstraction Calculations

The period of monitoring provided a data set of 16,443 entries, of which approximately 33% (5,492) and 67% (10,951) were from Phase 1 and 2 farms respectively. Due to the large number of wells (368) it was necessary to read meters progressively over the month. For the purposes of calculation and comparison of abstraction rates, a method

was developed within the Metering Database for the computation of abstraction rates. Abstraction was calculated at the well and farm levels, as well as in total. The method was based on the calculation of abstraction rates over the query period, the total being the combination of pro rata daily rates over the query period, as presented in Appendix E.

6.5.4 Abstraction per Well

6.5.4.1 Monthly Abstraction per Well

The monthly abstraction per operational well ranged from less than 100 to 29,835 m^3, while the average was 5,385 m^3. Maximum abstraction per well varied between years, from about 21,000 m^3 in 1994/5 and 1995/6, to more than 29,000 m^3 per month in the period 1996/7-98/9, Table 6.3. The average abstraction ranged from 4,709 to more than 5,500 m^3 per well per month over the five years. Minimum values for the period were zero as some wells were only intermittently operational or were temporarily non-operational.

Table 6.3 Monthly Abstraction per Well (m^3 per month)

	1994/5	1995/6	1996/7	1997/8	1998/9
Average	5,124	4,709	5,510	5,540	5,389
Maximum	21,471	20,557	29,282	28,958	29,835

Appendix F details monthly abstraction per well.

6.5.4.2 Annual Abstraction per Well

The annual abstraction per operational well ranged from less than 100 to nearly 275,000 m^3, Table 6.4, while the average varied from 53,417 m^3 in 1995/6 to 60,721 in 1998/9. The maximum annual abstraction of 274,791 m^3 was recorded in 1996/7, and diminished to 210,569 m^3 in 1995/6. The minimum annual rate per well was at or close to zero for all years as some wells were non-operational for prolonged periods. Appendix F summarises annual and total abstraction per well.

Table 6.4 Annual Abstraction per Well 1994/5-98/9

	1994/5	1995/6	1996/7	1997/8	1998/9
Average	58,122	53,417	62,408	60,610	60,721
Maximum	217,425	210,569	274,791	265,765	268,876

6.5.4.3 Total Abstraction per Well

The total abstraction per well varied widely, ranging from less than 1,000 to nearly one million cubic metres. It also varied between phases due to the difference in the length of the period of readings. For the 73 wells in Phase 1, for the 5-year period May 1994 to April 1999, the total was more than 20 Mm^3, with an average of 278,809 m^3 per well, Table 6.5. While for the 290 Phase 2 wells (May 1996 to April 1999) it was almost 54 Mm^3, with an average of 182,216 m^3 per well.

Table 6.5 Total Well Abstraction for 368 Study Farm Wells

Well Abstraction	Phase 1(1)	Phase 2(2)
Total	20.35 Mm^3	53.75 Mm^3
Average	278,809 m^3	182,216 m^3
Maximum	995,407 m^3	744,742 m^3

(1) May 1994 to April 1999 (2) May 1996 to April 1999

6.5.4.4 Abstraction on Cross Section Wells

Figure 6.15 plots the monthly abstraction for the three wells identified in the cross section discussed in Section 6.4.2. Monthly abstraction rates were significantly higher for the second well (205/185) than for the first and third wells (211/429 and 205/226 respectively), ranging from 6,000 to 10,000 m^3 per month.

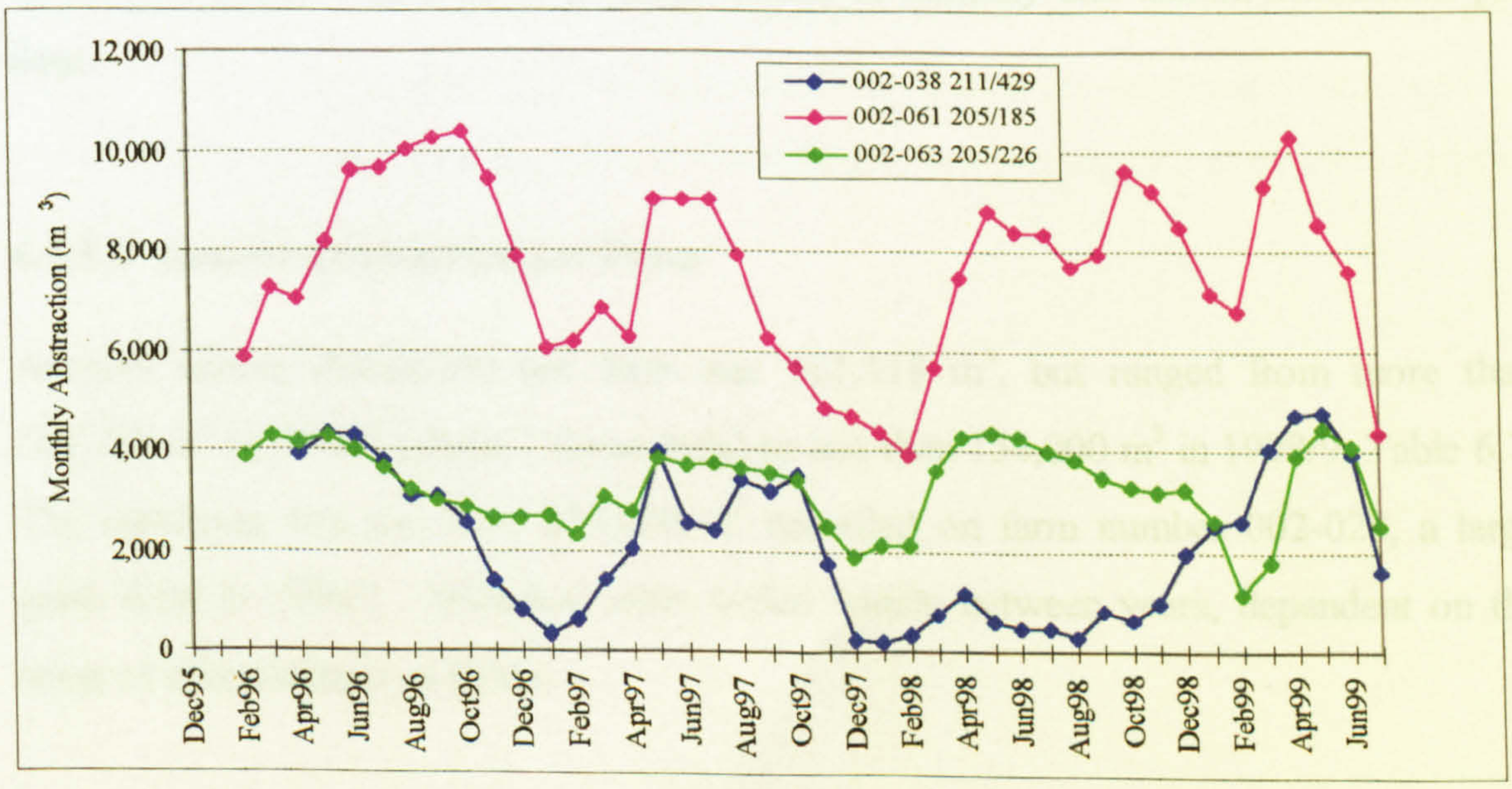

Figure 6.15 Monthly Abstraction - Cross Section Wells

6.5.5 Abstraction per Farm

At the farm level abstraction rates, both annual and monthly, varied widely between farms, dependent on factors such as number of wells, crop area and type, irrigation method and water quality.

6.5.5.1 Monthly Abstraction per Farm

While average monthly abstraction per farm for the period 1994/5 - 1998/9 was 13,560 m^3 (1995/6), it ranged from less than 13,000 to more than 14,000 m^3 (1994/5), Table 6.6. It also varied widely between farms from less than 100 m^3 to nearly 100,000 m^3. Very low abstraction rates were recorded on farms in the process of being abandoned, often with a progressive decline over a number of months.

Table 6.6 Monthly Abstraction per Farm (1994-99)

	1994/5	1995/6	1996/7	1997/8	1998/9	1994/5-98/9
Average	14,143	12,998	13,995	13,659	13,007	13,560
Maximum	76,774	71,240	99,963	96,306	96,540	88,165
Minimum	69	251	9	4	2	67
Median	9,560	9,471	10,345	9,937	9,574	9,777

Figure 6.16 illustrates the distribution of monthly abstraction records per farm. On fifty percent of farms abstraction was less than 14,000 m^3 per month, and less than 16,000 m^3 on 80% of farms. Appendix H presents details of monthly and annual abstraction per farm.

6.5.5.2 Annual Abstraction per Farm

Average annual abstraction per farm was 161,118 m^3, but ranged from more than 169,122 m^3 in 1994/5 (phase 1 farms only) to less than 154,000 m^3 in 1998/9, Table 6.7. The maximum was just over 853,000 m^3 recorded on farm number 002-028, a large grass farm in 1996/7. Minimum rates varied widely between years, dependent on the stage of abandonment of farms.

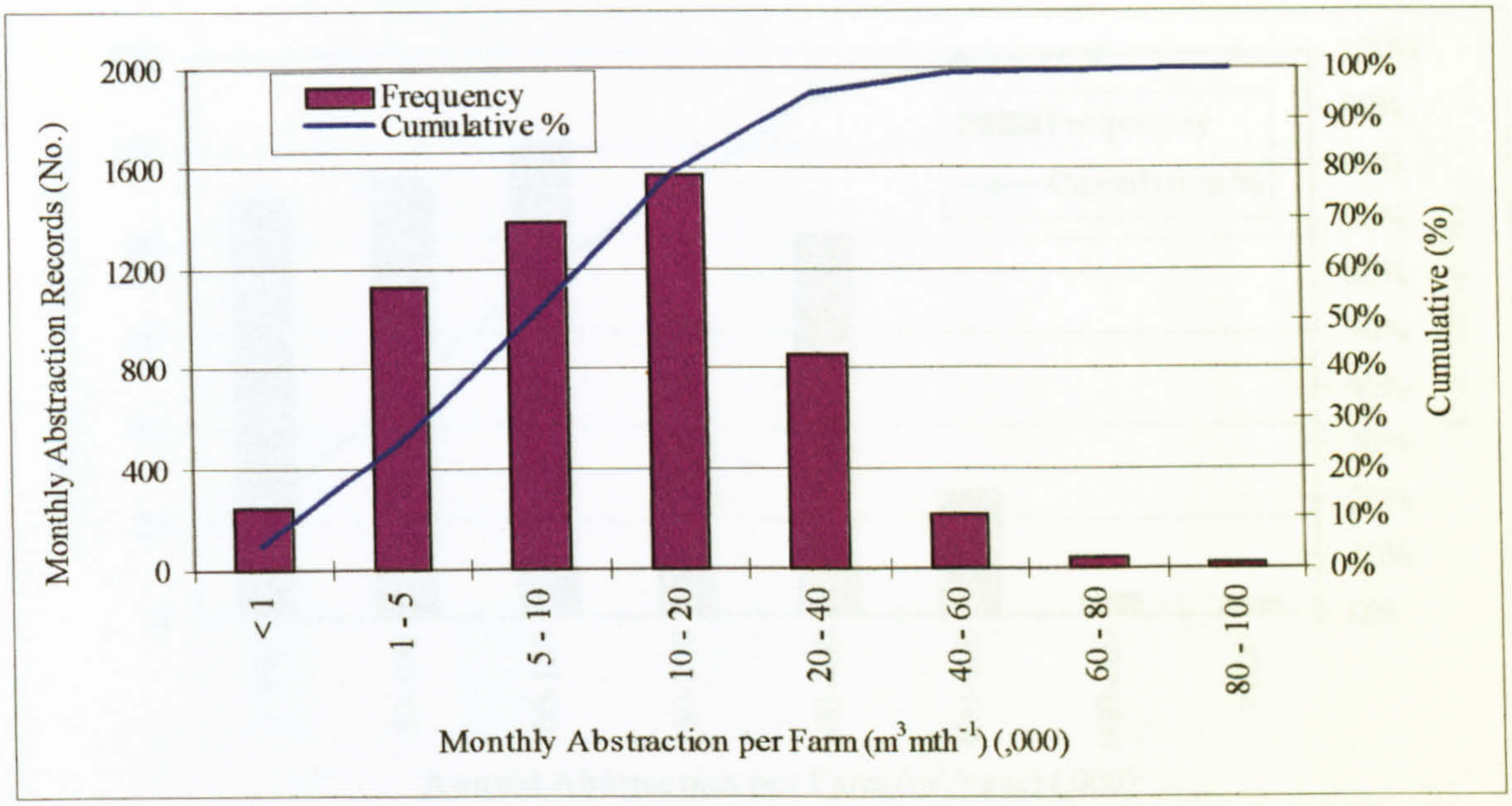

Figure 6.16 Distribution of Monthly Abstraction per Farm

Table 6.7 Annual Abstraction per Farm

	1994/5	1995/6	1996/7	1997/8	1998/9
Average	169,716	155,977	166,421	162,807	153,342
Maximum	733,803	593,570	853,050	823,134	850,390
Minimum	6,394	7,896	121	3,939	16
Median	108,060	117,345	127,153	121,307	122,656

Figure 6.17 illustrates the distribution of average annual abstraction for farms 1996/7-98/9, with abstraction on 40% of farms less than 100,000 m^3y^{-1} and on 75% less than 200,000 m^3y^{-1}. The relationships between abstraction rates per farm and factors such as irrigation method and management and water quality are investigated in detail in Chapter 7.

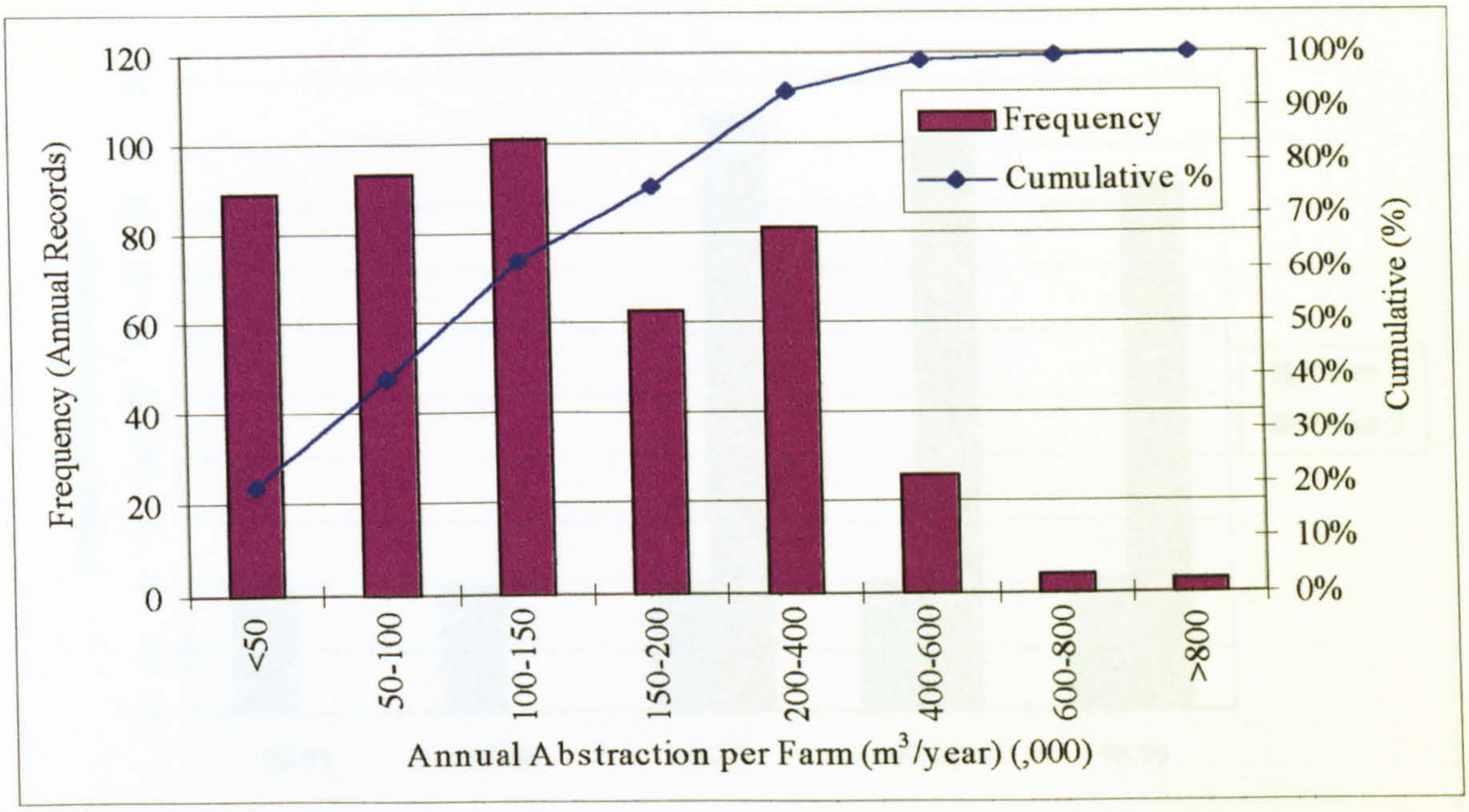

Figure 6.17 Distribution of Annual Abstraction per Farm (1996/7-98/9)

6.5.6 Total Abstraction

The total volume of water abstracted from the monitored wells in the period March 1994 to July 1999 was more than 74 Mm^3, Table 6.8. Total abstraction for Phase 1 farms was more than 20 Mm^3, with the annual rate ranging from 3.90 to 4.24 Mm^3. For Phase 2 farms total abstraction was more than 53 Mm^3, with annual totals declining from 18.94 to 16.59 Mm^3, Figure 6.8. Appendix G presents a summary of monthly and annual abstraction rates per farms.

Table 6.8 Summary of Total and Annual Abstraction

Phases	Annual Abstraction (May-Apr.) (Mm^3)					Total
	1994/5	1995/6	1996/7	1997/8	1998/9	
Phase 1	4.24	3.90	4.03	4.08	4.10	20.35
Phase 2			18.94	18.22	16.59	53.75
Total	4.24	3.90	22.97	22.30	20.69	74.11

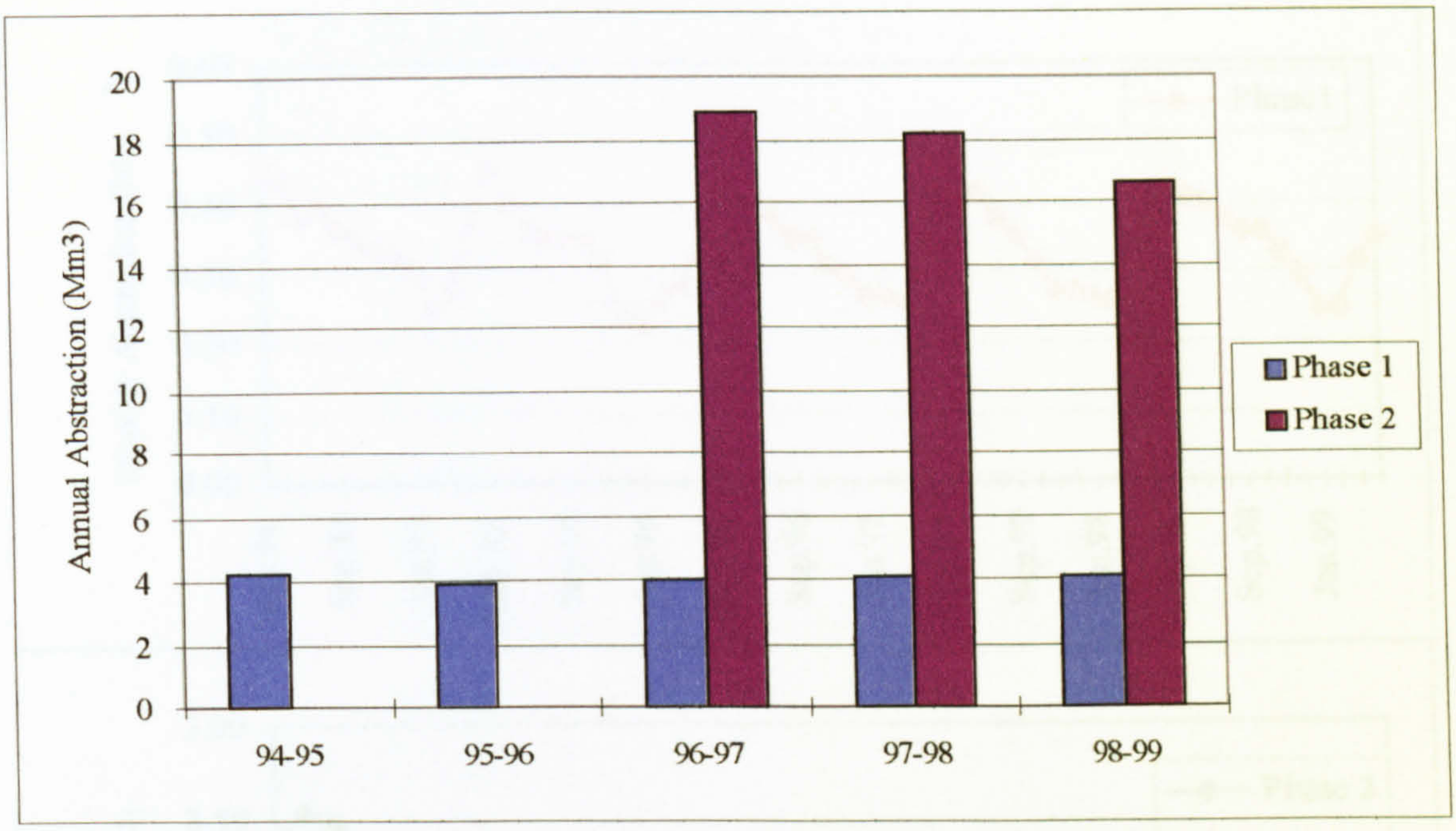

Figure 6.18 Annual Abstraction 1994/5-98/9 for Phases 1 & 2

An evaluation of total monthly abstraction rates for all wells indicates distinct seasonal trends, Figure 6.19, with a peak in May declining to a low in February. This is similar to the seasonal trends in evapotranspiration (Chapter 4). For Phase 1 farms these ranged from a high of just less than 0.50 Mm^3 to about 0.25 Mm^3. For Phase 2 farms the monthly peak was highest in May 1996 at about 2.00 Mm^3 and the peak declined steadily in subsequent years to about 1.60 Mm^3 by May 1999. Minimum monthly values also demonstrated a similar trend, over the same time period. Trends in abstraction and relationships with water quality and cropped area are further investigated in Chapter 7.

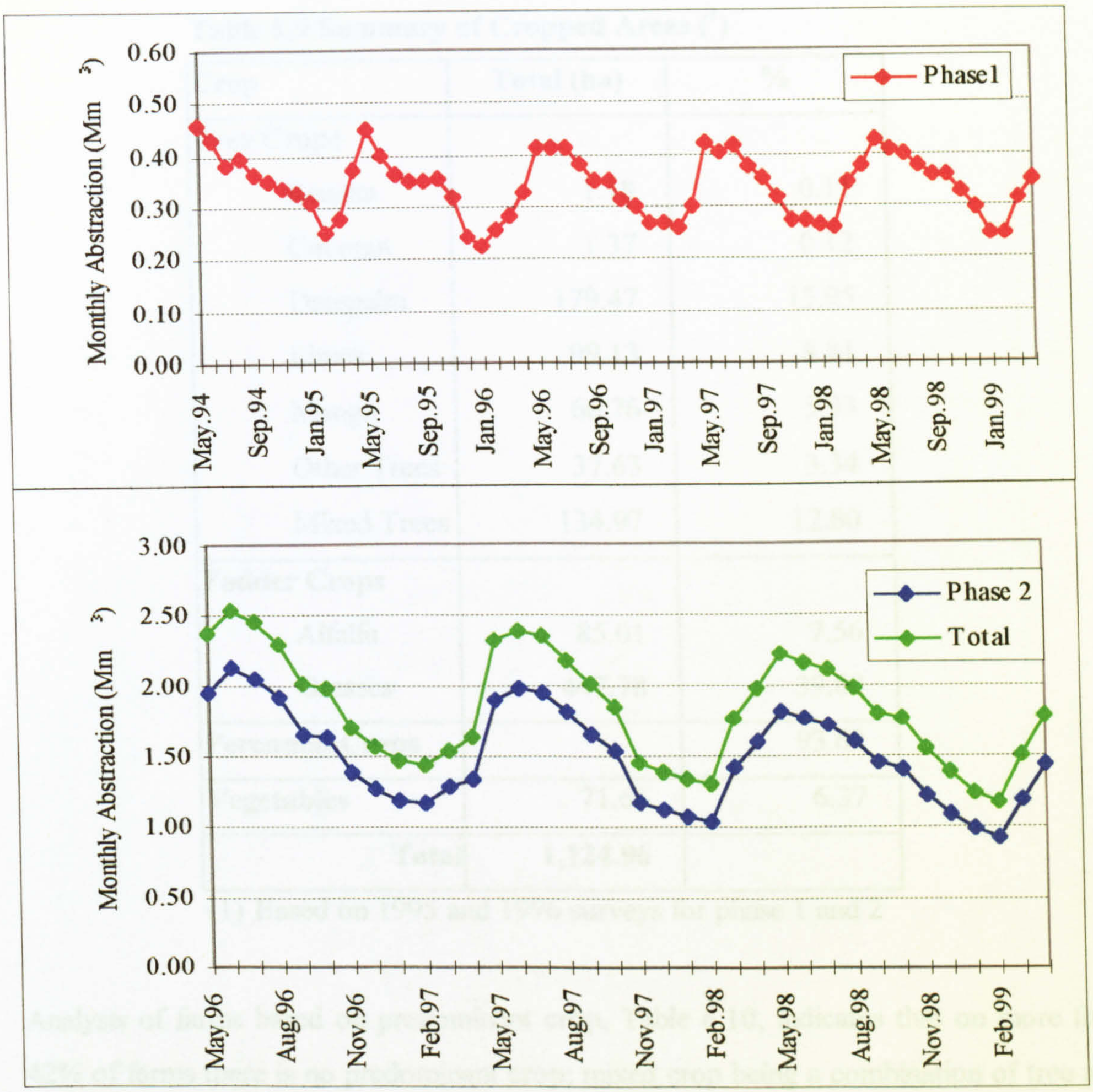

Figure 6.19 Abstraction (Mm^3mth^{-1}) - Phases 1 & 2

6.6 CROPPING PATTERNS

Cropping patterns on study farms were surveyed periodically to monitor changes over the research period. The total cropped area for all farms was initially 1,125 ha, of which perennial tree and fodder crops constituted 94%, Table 6.9, with the balance (6%) in seasonal vegetables. Grass was the largest single crop category (40%) followed by dates (16%) and mixed trees (12%).

Table 6.9 Summary of Cropped Areas ([1])

Crop	Total (ha)	%
Tree Crops		
Banana	1.18	0.11
Coconut	1.37	0.12
Datepalm	179.47	15.95
Limes	99.13	8.81
Mango	66.76	5.93
Other Trees	37.63	3.34
Mixed Trees	134.97	12.00
Fodder Crops		
Alfalfa	85.01	7.56
Grasses	447.78	39.80
Perennial Crops		93.62
Vegetables	71.66	6.37
Total	**1,124.96**	

(1) Based on 1995 and 1996 surveys for phase 1 and 2

Analysis of farms based on predominant crop, Table 6.10, indicates that on more than 42% of farms there is no predominant crop; mixed crop being a combination of tree and fodder crops. On a quarter of farms grass was the main crop, and alfalfa and dates each occupied 10% of the total crop area. Figure 6.20 illustrates the distribution of farms by crop category, showing that most of the "grass" farms are located south of the Batinah highway.

Table 6.10 Farms by Predominant Crop

Category	Alfalfa	Dates	Grass	Limes	Vegetables	Mixed Trees	Mixed Crops
No	14	13	35	4	4	9	59
%	10.14	9.42	25.36	2.90	2.90	6.52	42.75

Appendix I presents details of crop area and type per farm and appendix J percent distribution of crop type per farm.

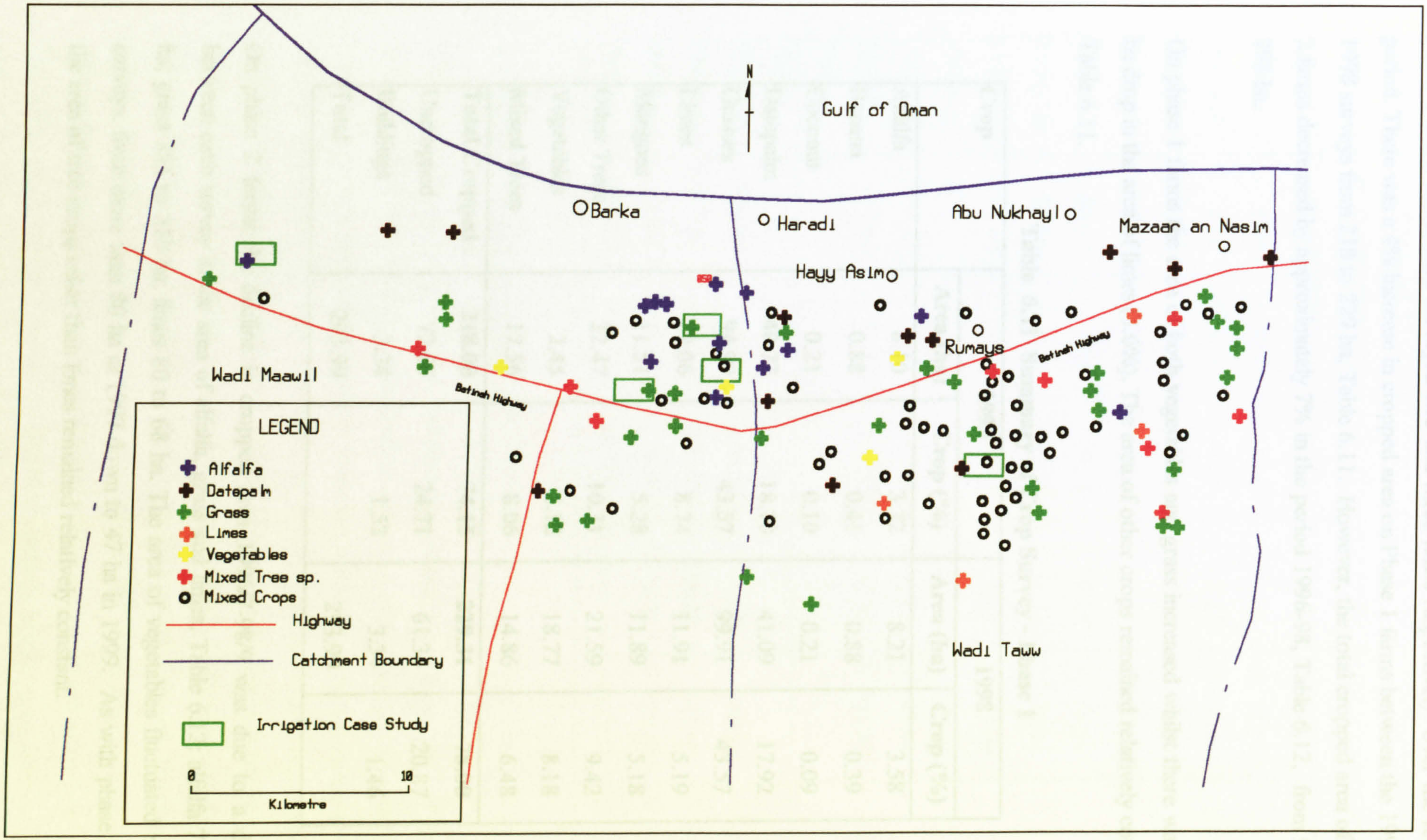

Figure 6.20 Crop Category Distribution

Phase 1 and 2 farms were surveyed two and three times respectively over the research period. There was a 4% increase in cropped area on Phase 1 farms between the 1995 and 1998 surveys from 218 to 229 ha, Table 6.11. However, the total cropped area of Phase 2 farms decreased by approximately 7% in the period 1996-98, Table 6.12, from 906 to 798 ha.

On phase 1 farms the area of both vegetables and grass increased whilst there was an 8 ha drop in the area of limes (3.6%). The area of other crops remained relatively constant, Table 6.11.

Table 6.11 Summary of Crop Survey - Phase 1

Crop	1995		1998	
	Area (ha)	Crop (%)	Area (ha)	Crop (%)
Alfalfa	8.10	3.72	8.21	3.58
Banana	0.88	0.41	0.88	0.39
Coconut	0.21	0.10	0.21	0.09
Datepalm	40.77	18.70	41.09	17.92
Grasses	94.99	43.57	99.91	43.57
Limes	19.06	8.74	11.91	5.19
Mangoes	11.51	5.28	11.89	5.18
Other Trees	22.47	10.31	21.59	9.42
Vegetables	2.45	1.12	18.77	8.18
Mixed Trees	17.56	8.06	14.86	6.48
Total Cropped	**218.00**	**74.15**	**229.31**	**78.00**
Uncropped	72.65	24.71	61.34	20.87
Buildings	3.34	1.53	3.34	1.46
Total	293.99		293.99	

On phase 2 farms the decline in cropped area 1996/7-98/9 was due to a decrease between each survey in the area of alfalfa, grass and limes, Table 6.12: alfalfa 77 to 43 ha; grass 353 to 310 ha; limes 80 to 68 ha. The area of vegetables fluctuated between surveys, from more than 80 ha in 1997 down to 47 ha in 1999. As with phase 1 farms the area of tree crops other than limes remained relatively constant.

Table 6.12 Summary of Crop Surveys - Phase 2

Crop	1996		1997		1998	
	Area (ha)	Crop (%)	Area (ha)	Crop (%)	Area (ha)	Crop (%)
Alfalfa	76.91	8.48	59.68	6.68	43.10	5.40
Banana	0.30	0.03	0.30	0.03	0.08	0.01
Coconut	1.16	0.13	1.16	0.13	1.16	0.15
Datepalm	138.70	15.29	142.76	15.98	141.19	17.69
Grasses	352.80	38.90	339.81	38.03	310.16	38.86
Limes	80.07	8.83	79.47	8.89	68.54	8.59
Mangoes	55.24	6.09	57.53	6.44	55.94	7.01
Other Trees	15.16	1.67	15.85	1.77	15.08	1.89
Vegetables	69.21	7.63	83.06	9.30	47.08	5.90
Mixed Trees	117.40	12.94	113.91	12.75	115.83	14.51
Total Cropped	**906.96**	**61.97**	**893.53**	**61.05**	**798.16**	**54.54**
Uncropped	519.92	35.53	533.03	36.42	626.80	42.83
Buildings	36.63	4.04	36.95	4.14	38.55	4.83
Total	1463.51		1463.51		1463.51	

6.7 IRRIGATION METHODS

The survey of cropping patterns included identification per crop plot of irrigation methods, which were classified according to categories of application. Over 80% of the cropped area was irrigated by modern irrigation methods, of which micro and spray irrigation accounted for 40% and 42% respectively, Table 6.13. Traditional flood methods by *gelba* and *gayl*, with lined, unlined or pipe distribution, was less than 20% of cropped area. The comparison between the initial and final (1998) surveys indicated that there was little change in irrigation methods over the period 1994-98. This is probably due to a number of factors including low returns for some crops which does not encourage investment in irrigation, traditional attitudes towards use of surface irrigation for alfalfa and the virtual cessation of the MAF modern irrigation programme from the mid-1990s. The general deterioration of farming within the area due to the impact of

saline intrusion is not encouraging for on-farm investment.

Micro irrigation (bubbler and drip) was most widely used on datepalms, tree crops and vegetables, accounting for more than two thirds of the irrigated area. Flood irrigation was predominately used on alfalfa (91%) and to a lesser extent on datepalms (33%). Spray methods, both field sprinklers and spray guns, were almost exclusively (98%) used to irrigate grass. There was no major shift between the irrigation methods for crop categories over the period 1995-98. Appendix K summarises irrigation methods per farm.

Table 6.13 Summary of Irrigation Methods (ha)

Survey Year	Micro	Flood	Spray	Total
1994/5-96(1)	450.26	207.76	466.94	1,124.96
%	40.02	18.47	41.51	
1998	428.45	187.44	411.58	1,027.47
%	41.70	18.24	40.06	

(1) Phase 1 farms in 1995 and Phase 2 farms in 1996

Evaluation of the predominant irrigation method (micro, flood and spray) per farm indicates that flood was the main method on a third of farms, Table 6.14, while micro and spray irrigation predominated on 38% and 29% of the farm respectively. Appendix L lists irrigation methods per farm.

Table 6.14 Predominant Irrigation Method per Farm

Irrigation Category	Farm (No)	Farm (%)
Micro	52	37.68
Flood	46	33.33
Spray	40	28.98

A comparison of irrigation methods in the surveys indicated no major shift between crop categories, Table 6.15. Flood remained the predominant method (>90%) for irrigation of alfalfa and spray for grass (98%). Further to above comments these results are reinforced by observation, during the research period, that there were few changes with little public or private investment being made in on-farm irrigation methods.

Table 6.15 Summary of Irrigation Method by Crop Category (%)

1994-96[1]	Micro	Flood	Spray
Alfalfa	0.31	91.40	8.30
Datepalm	65.25	33.85	0.90
Grass	0.19	1.98	97.84
Vegetables	85.44	5.31	9.25
Tree Crops[2]	63.30	13.84	22.85
1998	**Micro**	**Flood**	**Spray**
Alfalfa	0.51	89.54	9.95
Datepalm	64.05	32.62	3.33
Grass	0.40	4.31	95.29
Vegetables	78.52	13.10	8.39
Tree Crops	81.17	17.53	1.30

(1) Phase 1 farms in 1994 and Phase 2 farms in 1996

(2) Trees excluding datepalms

6.8 IRRIGATION MANAGEMENT

The research programme investigated current irrigation management methods on case study and sample farms. This included the evaluation of irrigation application rates and soil water tension on alfalfa and grass trial plots on the five case study farms and the measurement of coefficient of uniformity of sprinkler and bubbler systems on 20 sample farms.

6.8.1 Irrigation Application Rates

6.8.1.1 Case Study Farm - Trial Plots

Following the survey and mapping of crops and irrigation methods, trial plots were selected within each case study farm. Selection of plot areas was based on the crop criteria (alfalfa and grass), the status of the crop (development stage) and suitability of metering of water application. Table 6.16 summarises the cropped area per plot and the number of gelba and sprinklers per plot for alfalfa and grass respectively. A single sprinkler lateral was selected for grass plots, while multiple linked gelba, irrigated from a single turn-out (valve) were selected for alfalfa plots. On two farms, 002-006 and 002-010, the original alfalfa plots were discontinued by the farm manager, and alternative

plots were subsequently selected. Appendix M presents maps of case study farm maps of plot areas for grass and alfalfa.

Table 6.16 Trial Plot Areas

Farm No	Alfalfa (Flood Irrigated)		Grass (Sprinkler Irrigated)	
	Area (m^2)	Gelba (no.)	Area (m^2)	Sprinklers (no.)
002-006	750	32	1080	9
	1363[(a)]	48		
001-007	380	16	720	6
002-009	180	12	1560	11
002-010	135	6	1013	5
	122[(b)]	6		
001-011	670	45	1584	11

(a) New plot established in January 1999
(b) New plot established in November 1998

6.8.1.2 Irrigation Rate - Grass

Irrigation application to the trial plots was monitored with a water meter at the lateral control valve and on four farms with dataloggers. The dataloggers provided information on daily irrigation applications. Figures 6.22 to 6.25 present the individual irrigation applications for four trial plots for up to two years each. Daily application rates varied widely within and between plots, the maximum was over 100 mm for a single application on farm no. 002-010. Average application varied from 8 mm on farm no 001-007 to 26 mm on farm 002-010.

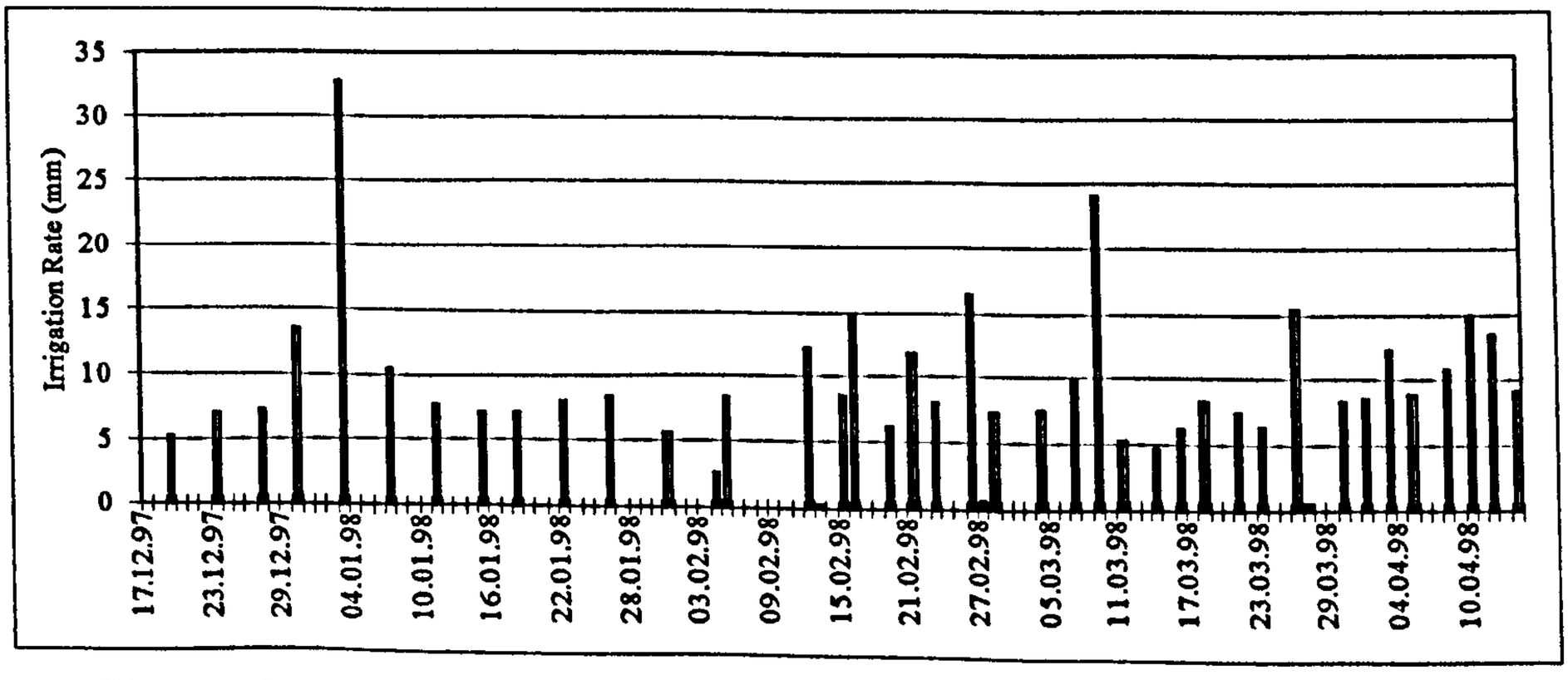

Figure 6.21 Irrigation Application - Farm 002-006 Grass Plot - Sprinkler

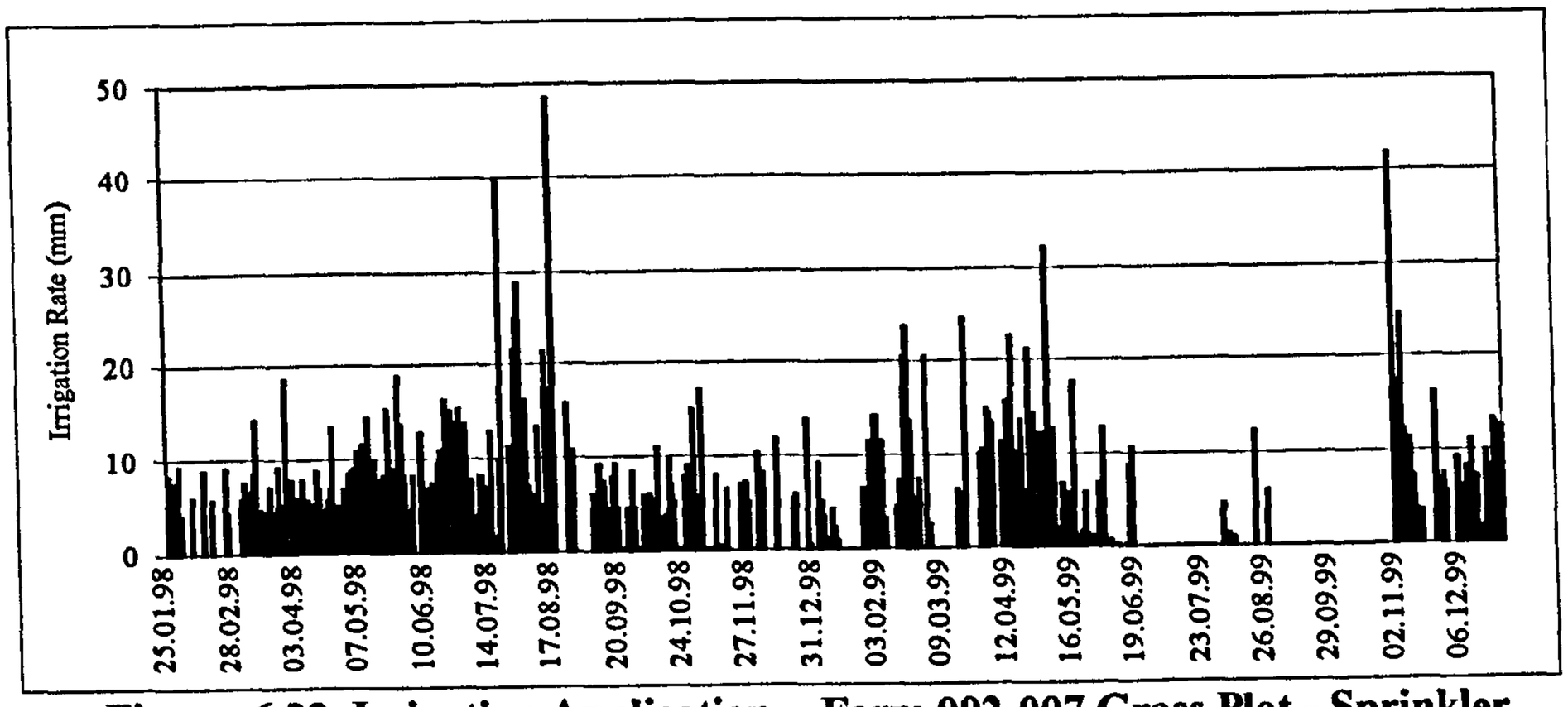

Figure 6.22 Irrigation Application - Farm 002-007 Grass Plot - Sprinkler

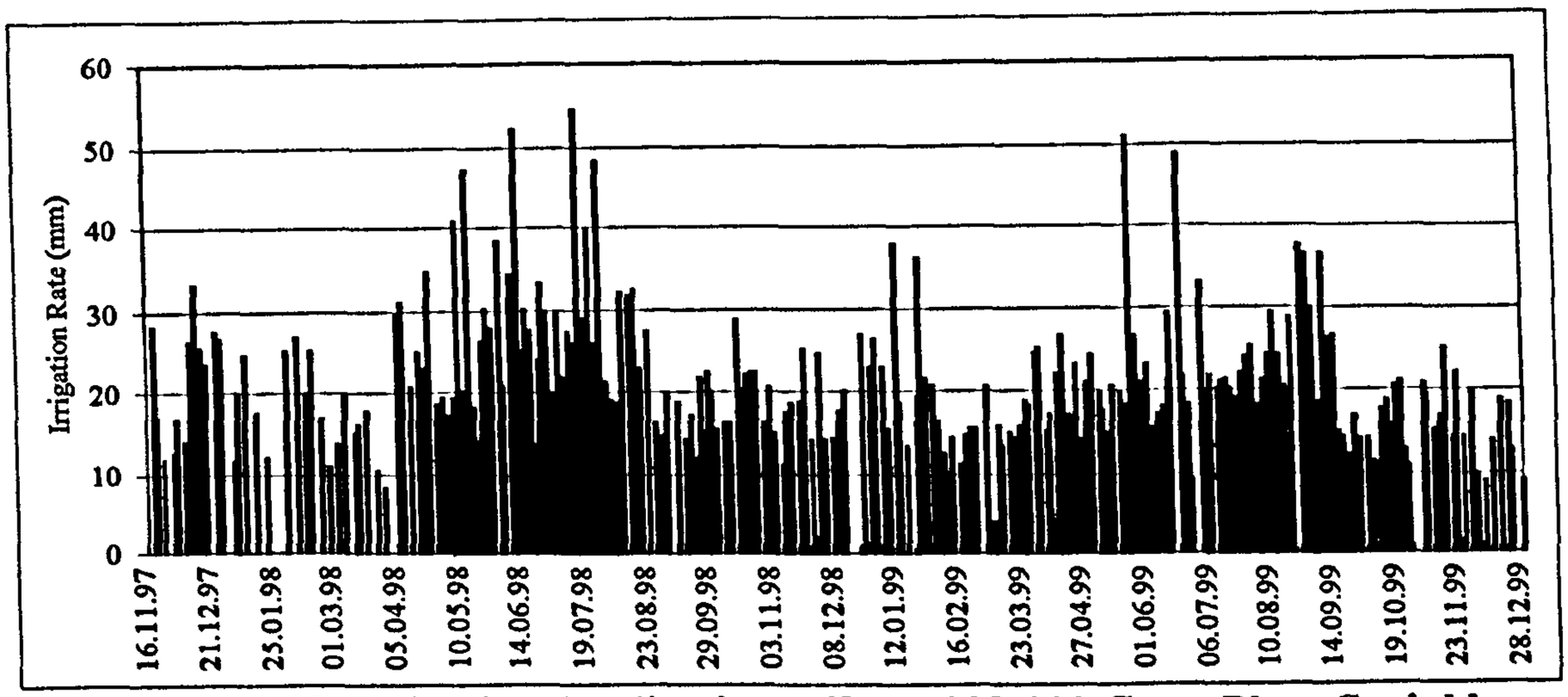

Figure 6.23 Irrigation Application - Farm 002-009 Grass Plot - Sprinkler

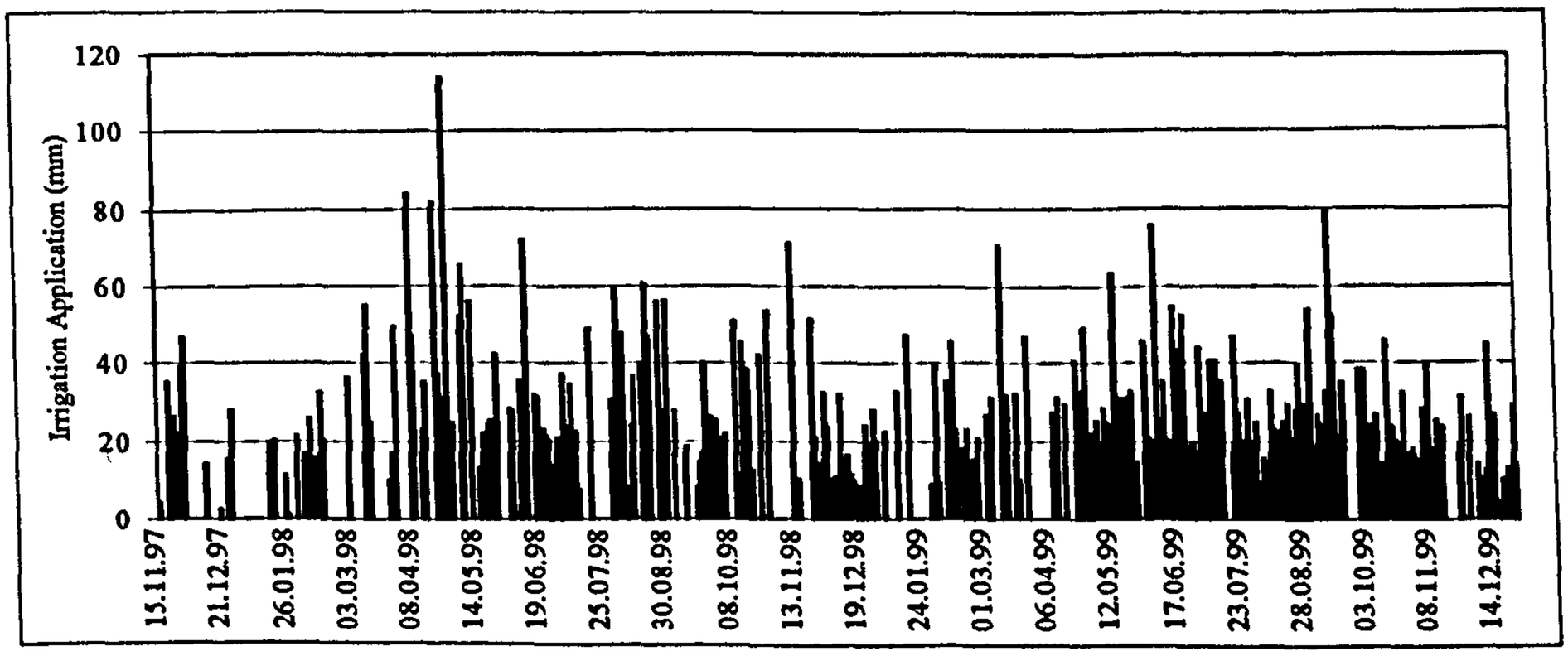

Figure 6.24 Irrigation Application - Farm 002-010 Grass Plot - Sprinkler

The high variability between both application rates and frequency tends to indicate low levels of application efficiency. Chapter 7 analyses irrigation efficiency for the plots based on soil water balance utilizing application rates, crop water requirement and system

coefficient of uniformity. Appendix N presents the result of irrigation application measurements for four grass plots.

6.8.1.3 Irrigation Rate - Alfalfa

Irrigation of the alfalfa trial plots was monitored with a water meter installed at the turnout to the *gelba*. Figures 6.26 to 6.30 present the mean daily irrigation rates for the five plots with rates varying both within and between plots. The average rate varied from a high of more than 23 mm on farm no. 002-009 to less than 14 mm on farm no 001-011.

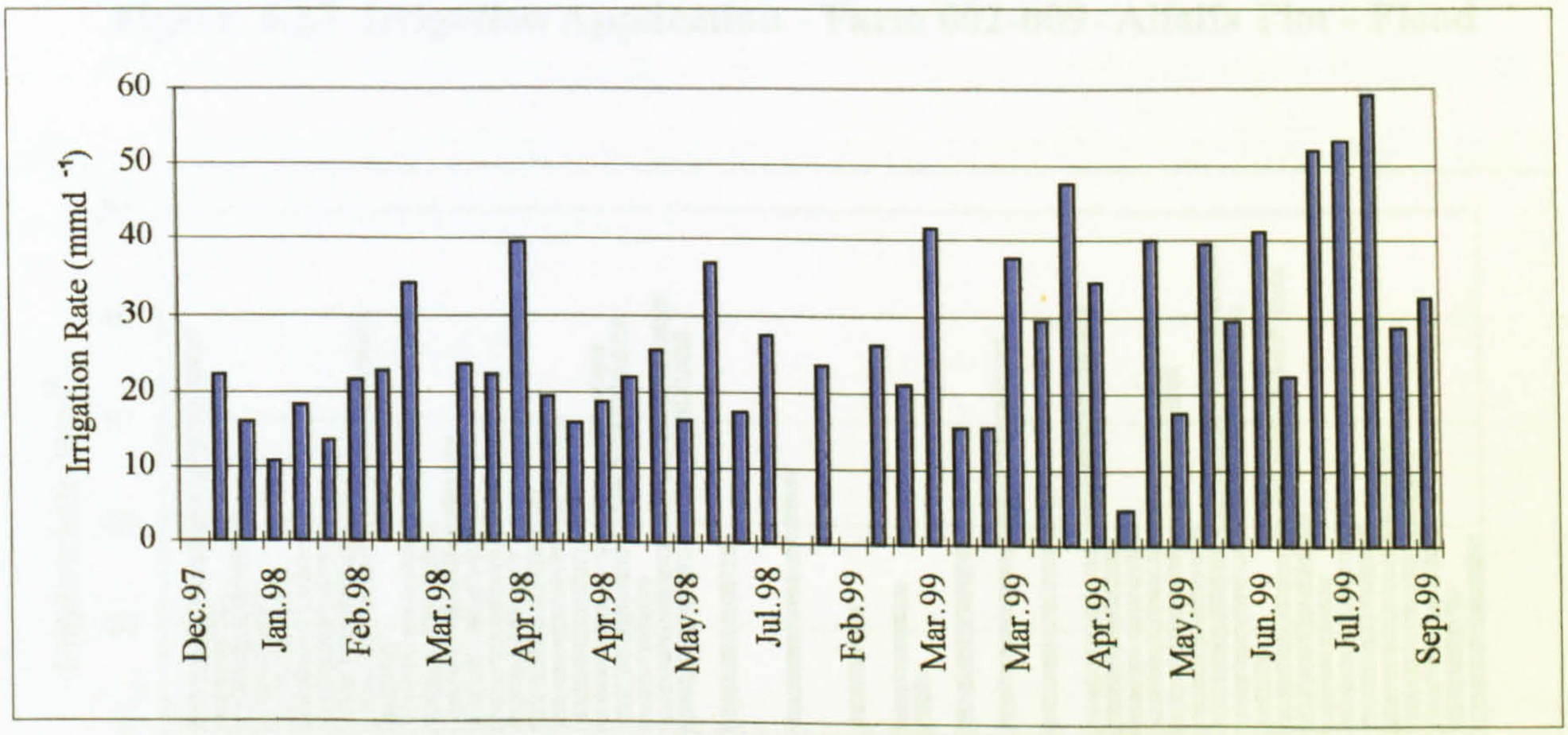

Figure 6.25 Irrigation Application - Farm 002-006- Alfalfa Plot - Flood

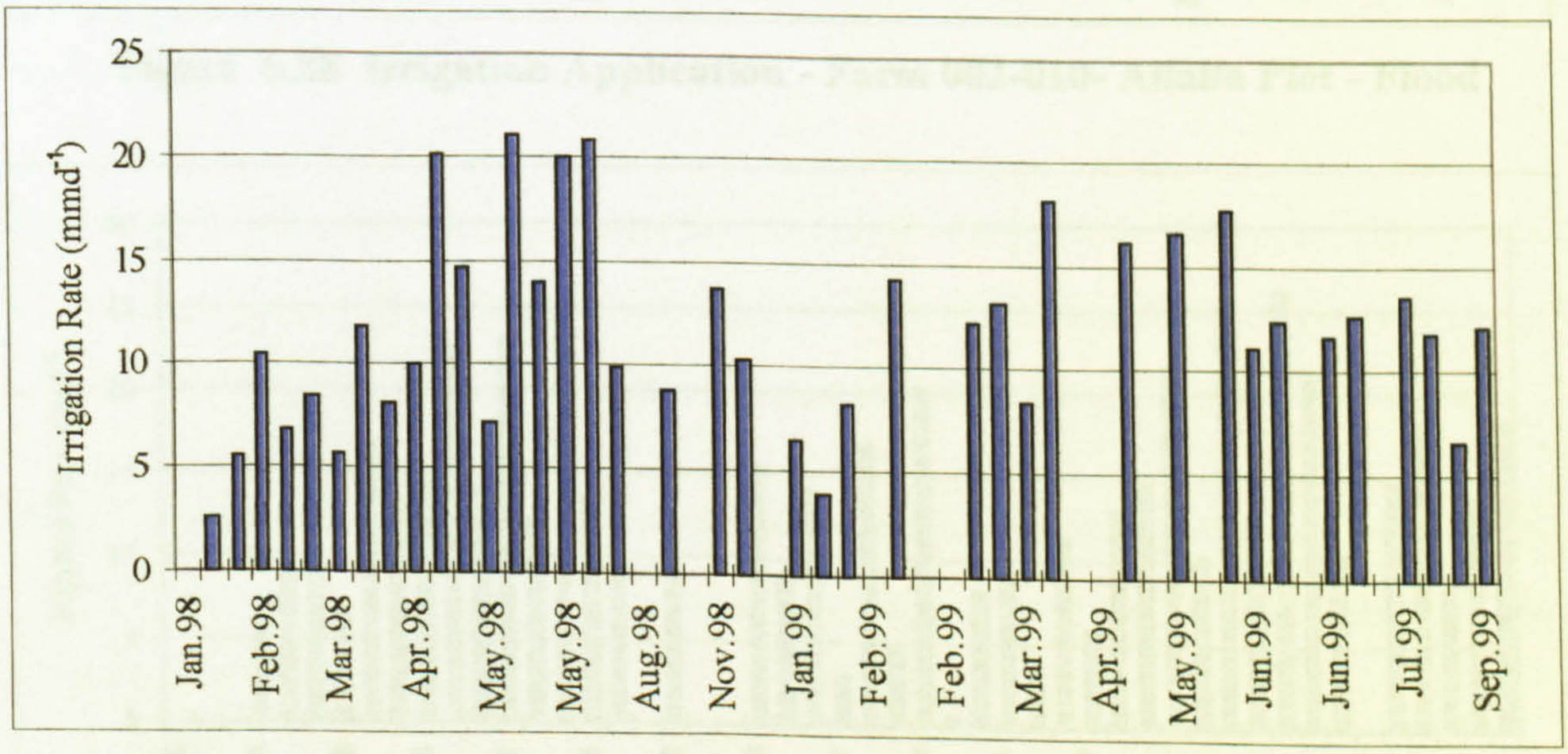

Figure 6.26 Irrigation Application - Farm 002-007- Alfalfa Plot - Flood

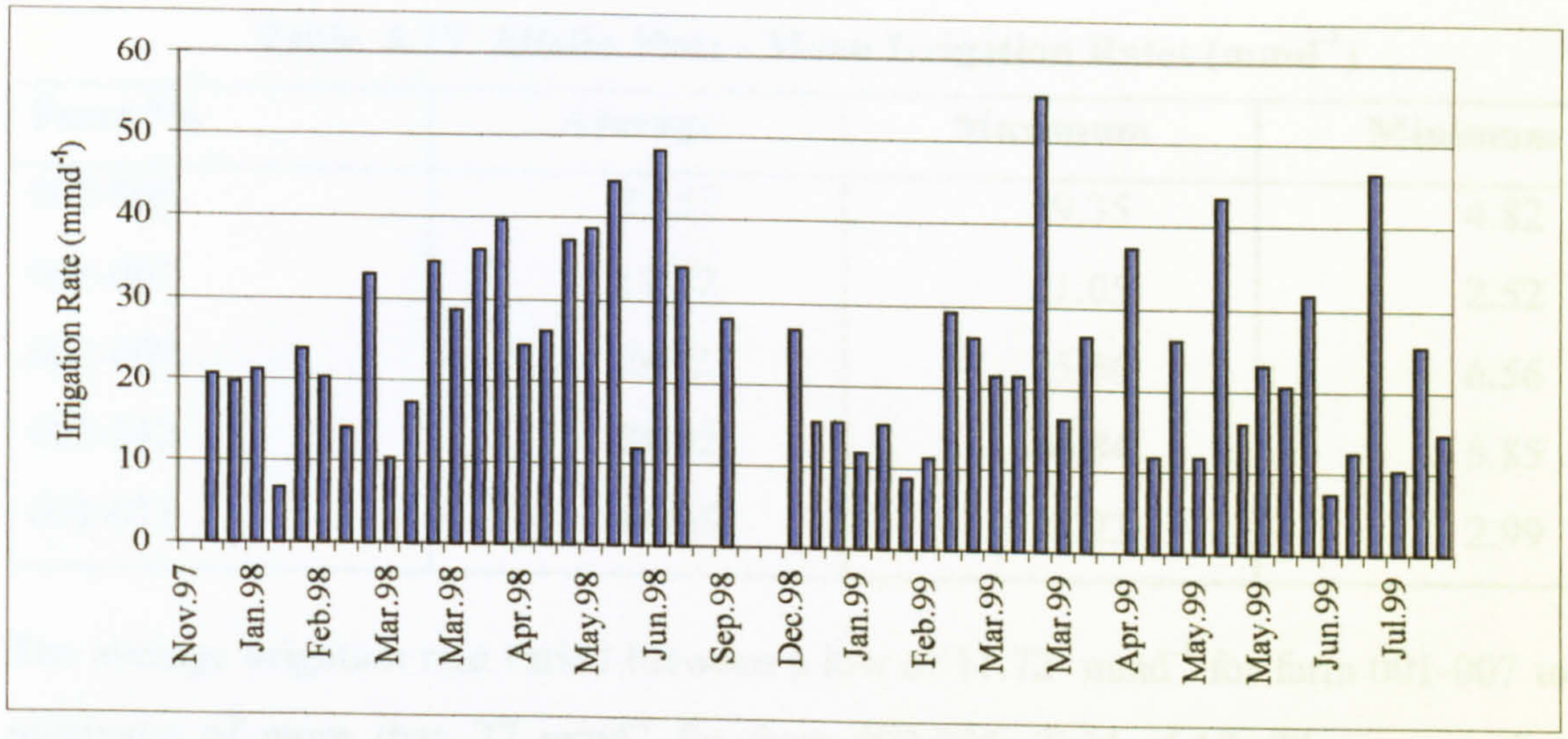

Figure 6.27 Irrigation Application - Farm 002-009- Alfalfa Plot - Flood

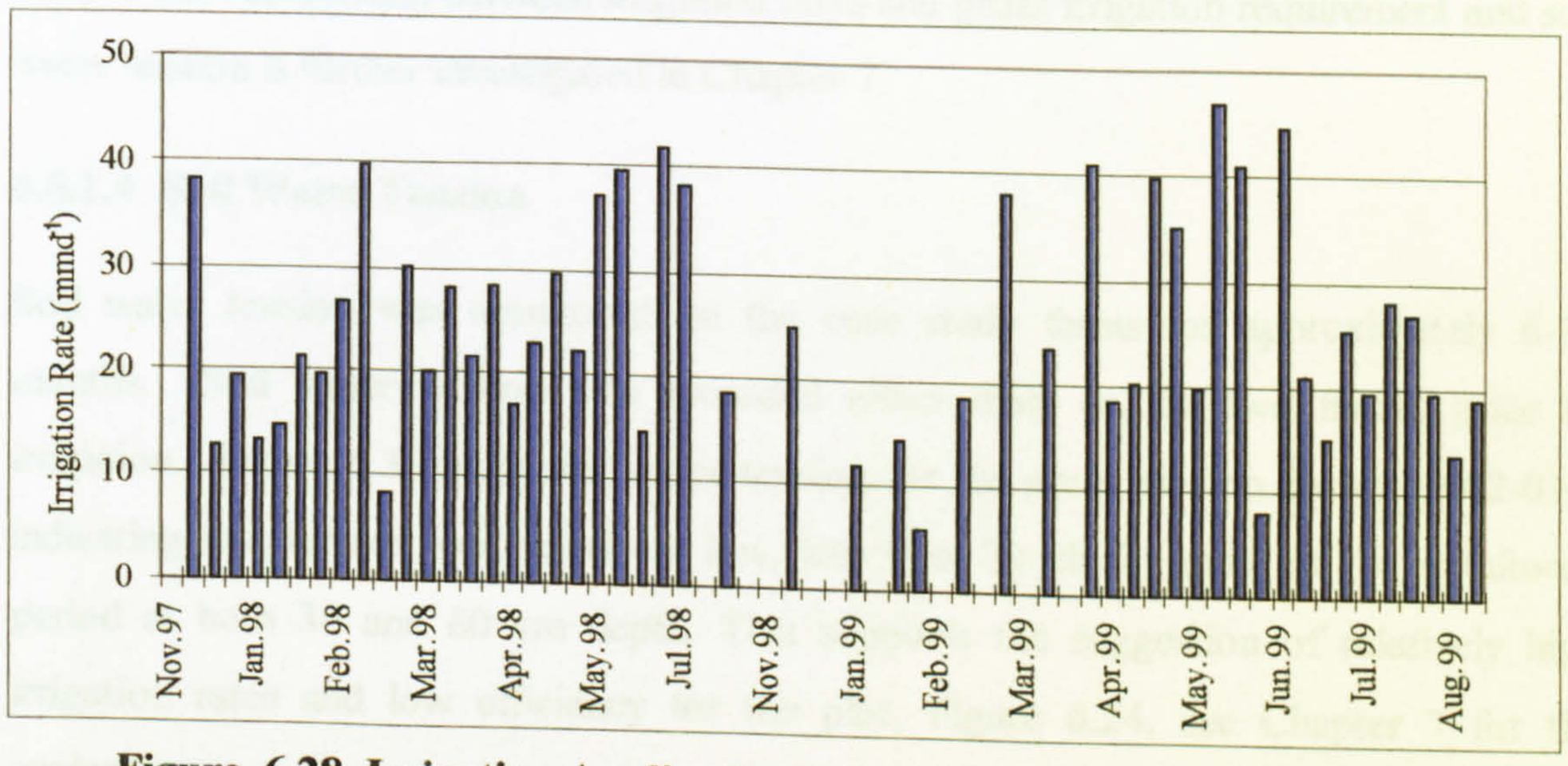

Figure 6.28 Irrigation Application - Farm 002-010- Alfalfa Plot - Flood

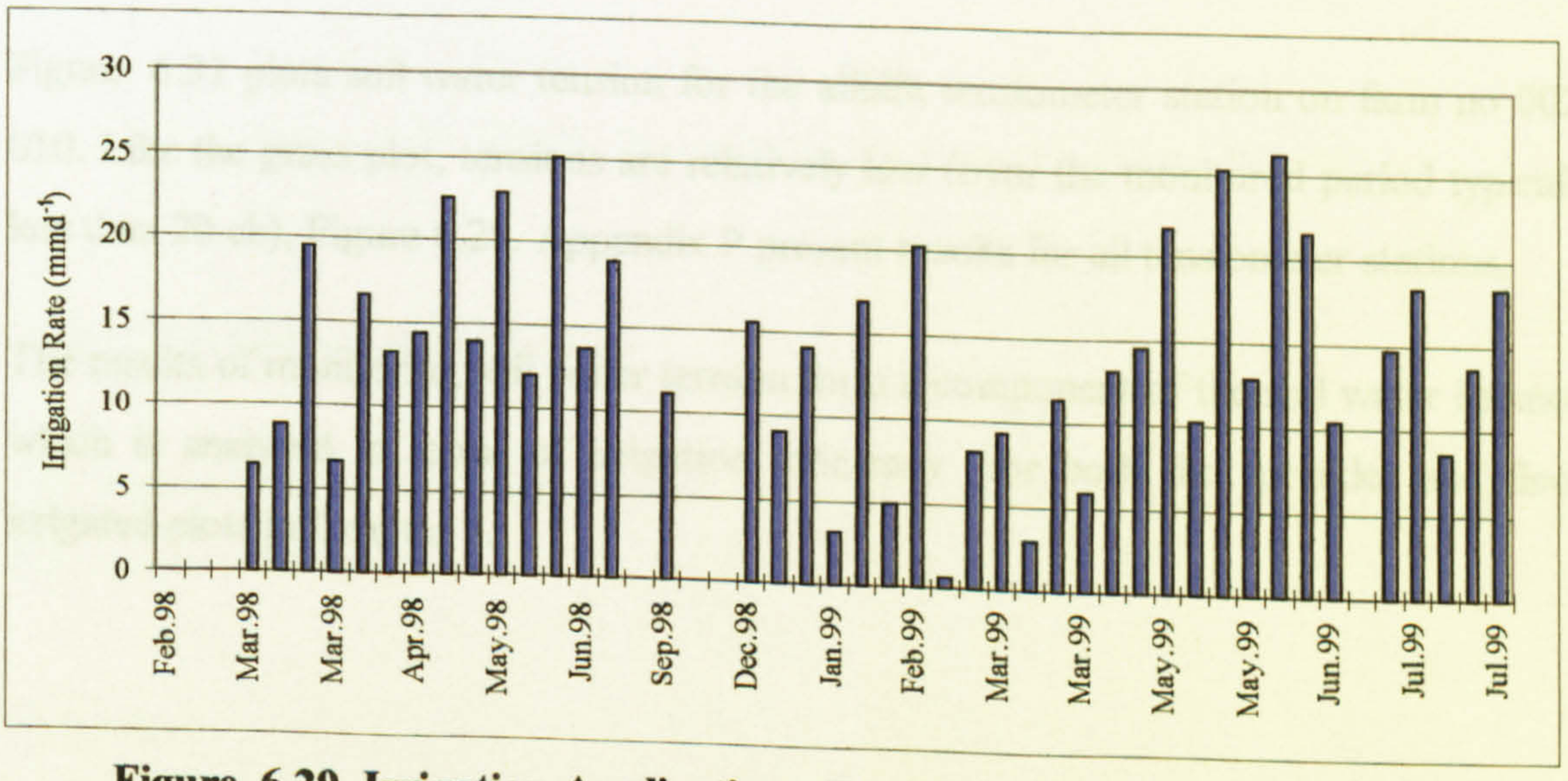

Figure 6.29 Irrigation Application - Farm 001-011- Alfalfa Plot - Flood

Table 6.17 Alfalfa Plots - Mean Irrigation Rates (mmd^{-1})

Farm No	Average	Maximum	Minimum
002-006	27.57	59.35	4.82
001-007	11.72	21.05	2.52
002-009	24.21	55.56	6.56
002-010	24.82	46.84	5.85
001-011	14.05	26.23	2.99

The average irrigation rate varied between a low of 11.72 mmd^{-1} for farm 001-007 to a maximum of more than 27 mmd^{-1} for farm 002-006, Table 6.17. There was also a considerable range between maximum and minimum rates which ranged from 21 to 60 mmd^{-1}. The relationship between irrigation rates and gross irrigation requirement and soil water tension is further investigated in Chapter 7.

6.8.1.4 Soil Water Tension

Soil water tension was monitored on the case study farms for approximately 6-12 months. Soil water tension was recorded either daily or, on two farms, prior to irrigation. Figure 6.30 plots soil water tension for the grass plot on farm no 002-010, indicating that tension was relatively low, less than 20 cb for most of the monitored period at both 30 and 60 cm depth. This supports the suggestion of relatively high irrigation rates and low efficiency for the plot, Figure 6.24, see Chapter 7 for the analysis.

Figure 6.31 plots soil water tension for the alfalfa tensiometer station on farm no 002-010. Like the grass plot, tensions are relatively low (over the monitored period typically less than 20 cb), Figure 6.28. Appendix P present results for all tensiometer stations.

The results of monitoring soil water tension form a component of the soil water balance, which is analysed in terms of irrigation efficiency for both the sprinkler and flood irrigated plots in Chapter 7.

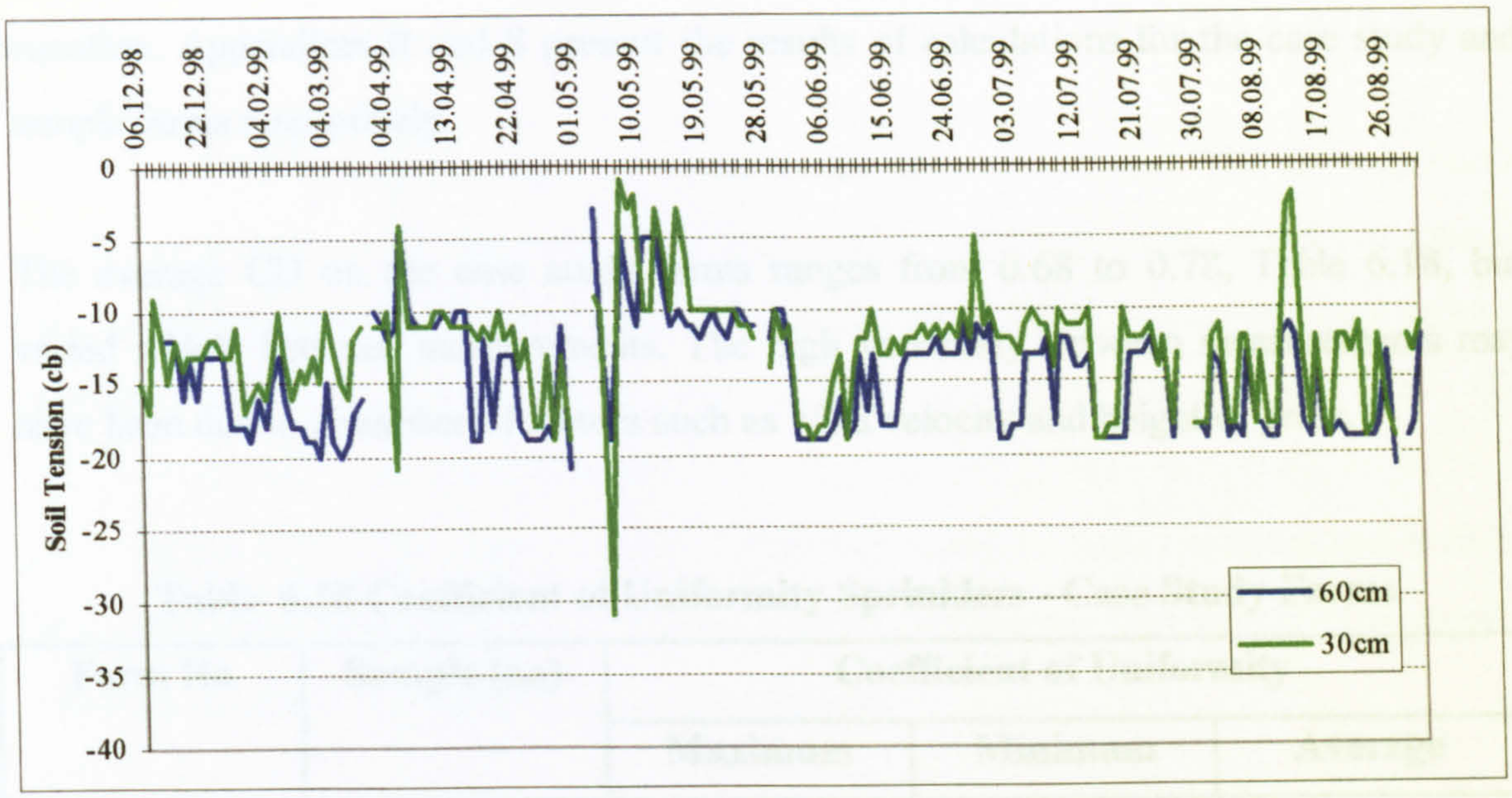

Figure 6.30 Grass Plot Soil Water Tension - Farm 002-010

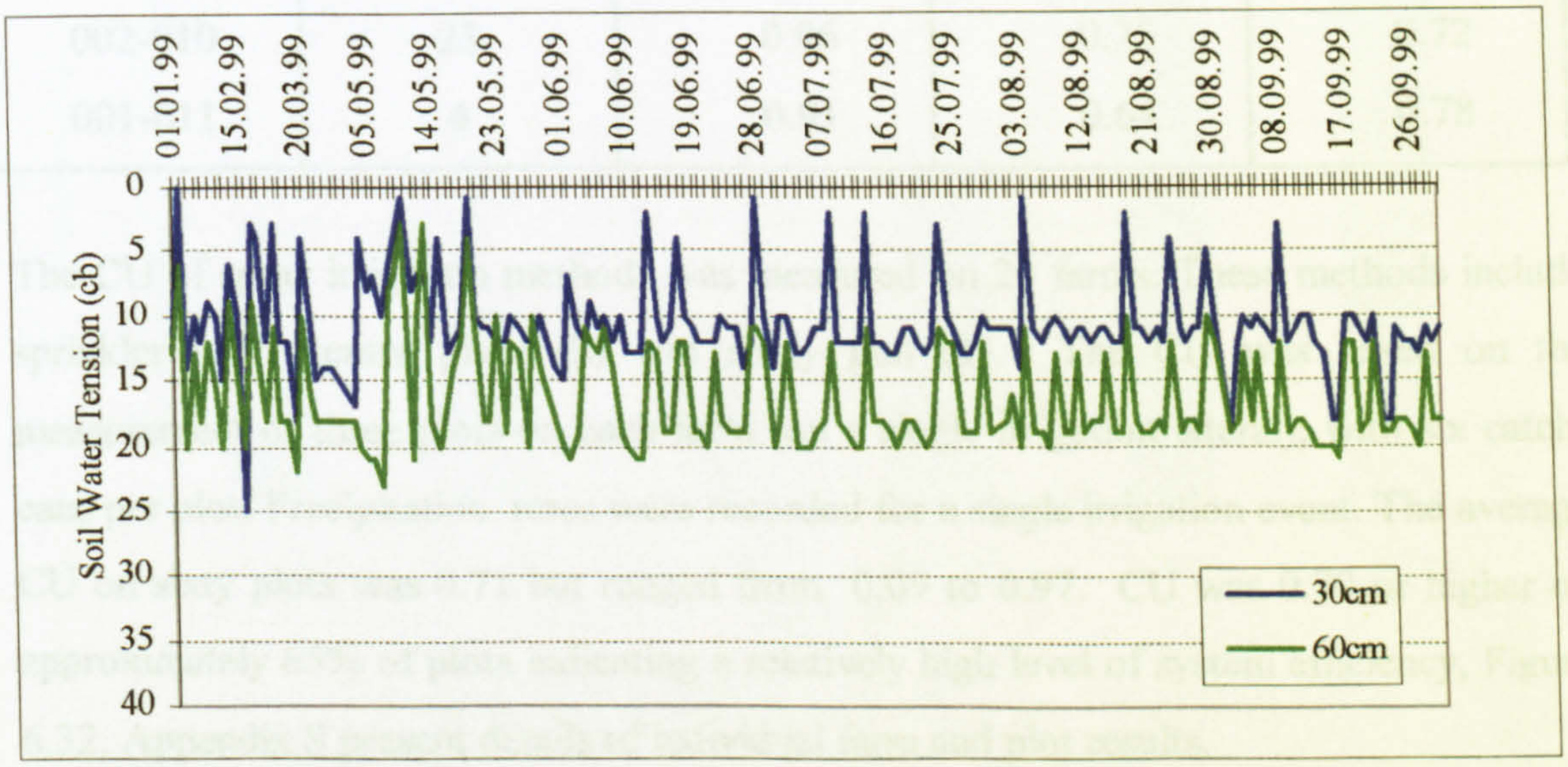

Figure 6.31 Alfalfa Plot Soil Water Tension - Farm 002-010

6.8.1.5 Coefficient of Uniformity

The uniformity of water distribution was measured on both the five case study farms and the sample of 20 farms.

Sprinklers

As outlined in Chapter 5 distribution was measured with catch-cans spaced around the sprinklers, and the coefficient of uniformity (CU) calculated using the Christainsen

equation. Appendices R and S present the results of calculations for the case study and sample farms respectively.

The average CU on the case study farms ranges from 0.68 to 0.78, Table 6.18, but varied widely between measurements. The high variability between measurements may have been due to a number of factors such as wind velocity and height of grass.

Table 6.18 Coefficient of Uniformity Sprinklers - Case Study Farms

Farm No	Sample (no)	Coefficient of Uniformity		
		Maximum	Minimum	Average
002-006	14	0.94	0.15	0.68
001-007	15	0.95	0.48	0.76
002-009	35	0.93	0.27	0.76
002-010	23	0.96	0.25	0.72
001-011	4	0.91	0.64	0.78

The CU of spray irrigation methods was measured on 20 farms. These methods include sprinkler (17), centre pivot (2) and spray gun (1). The CU was based on the measurement of three plots on each farm (on a single irrigation lateral), with six catch-cans per plot. Precipitation rates were recorded for a single irrigation event. The average CU on sixty plots was 0.71 but ranged from 0.09 to 0.97. CU was 0.70 or higher on approximately 65% of plots indicating a relatively high level of system efficiency, Figure 6.32. Appendix S present details of individual farm and plot results.

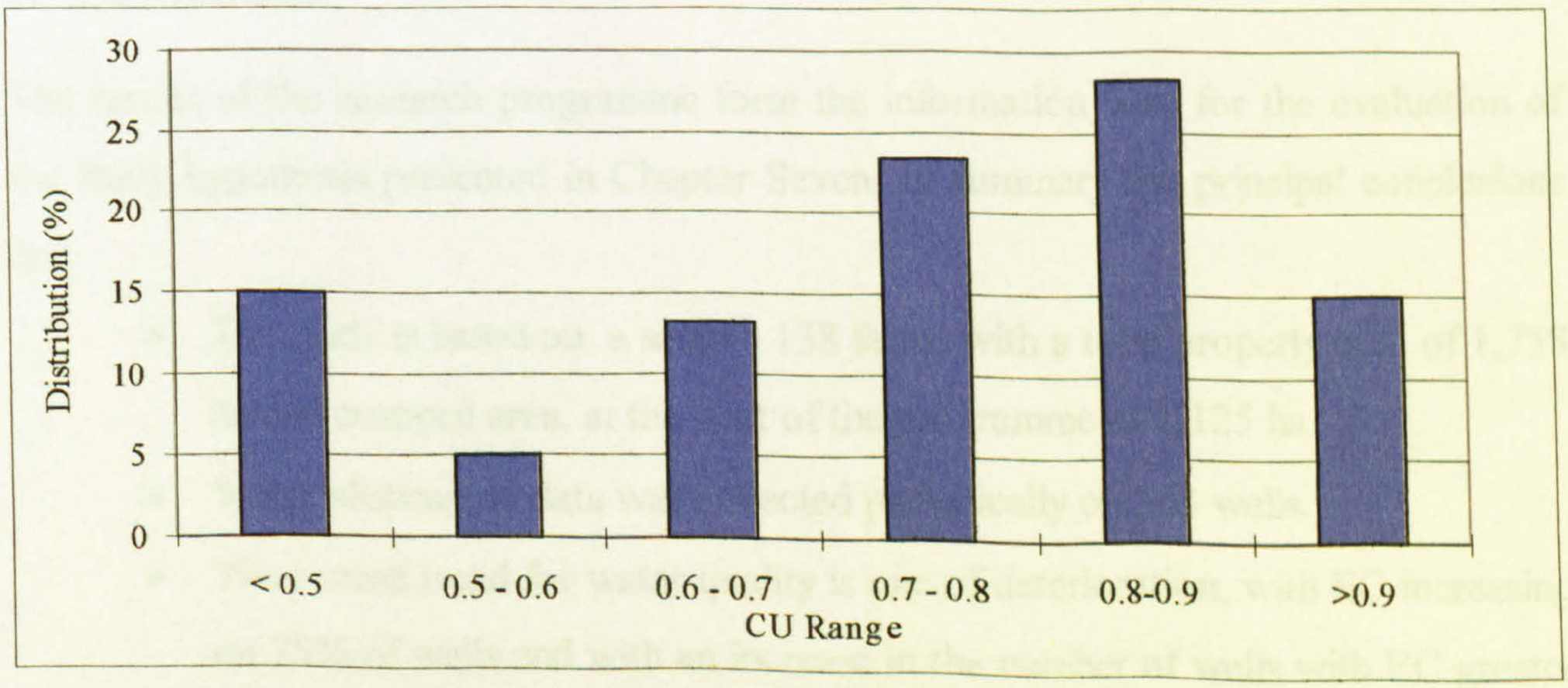

Figure 6.32 Coefficient of Uniformity - Sprinklers

Bubblers

The CU of bubbler irrigation was measured on 88 plots on 20 farms. The CU was based on the measurement of six bubblers within each plot on a single irrigation lateral. Measurements were based on the time required to fill a 5 litre measuring flask at each bubbler. The average CU for the 88 plots was 0.80 but ranged from 0.36 to 0.97. CU was 0.70 or higher on approximately 80% of plots and greater than 0.80 on 60% of plots, Figure 6.33. The results of the CU measurement of both sprinkler and bubbler form part of the methodology for analysis of soil water balances in Chapter 7. Appendix T present details of individual farm and plot results.

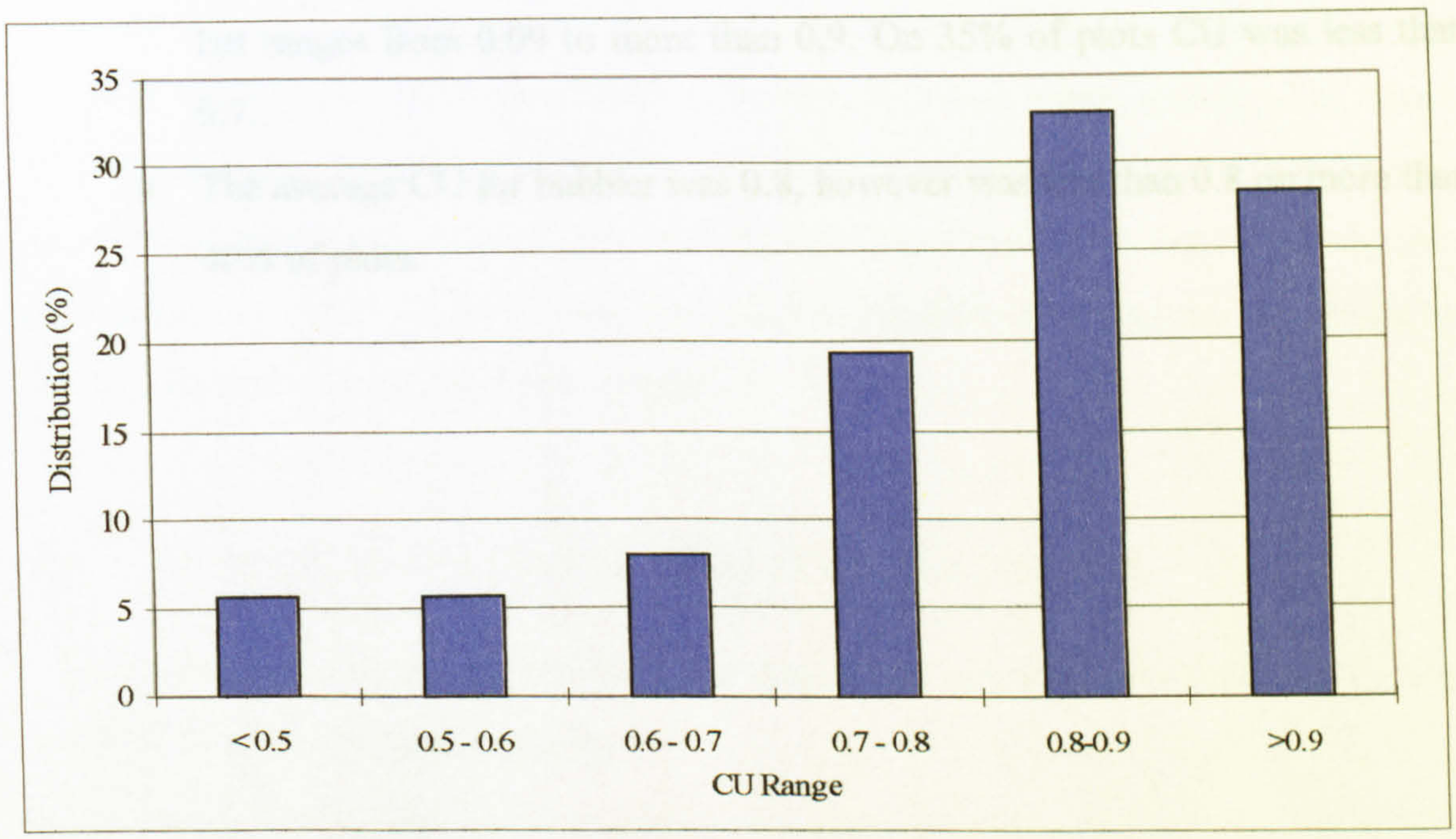

Figure 6.33 Coefficient of Uniformity - Bubblers

6.9 SUMMARY

The results of the research programme form the information base for the evaluation of the study hypothesis presented in Chapter Seven. In summary the principal conclusions are:

- The study is based on a sample 138 farms with a total property area of 1,758 ha and cropped area, at the start of the programme of 1,125 ha
- Water abstraction data was collected periodically on 363 wells.
- The overall trend for water quality is one of deterioration, with EC increasing on 75% of wells and with an increase in the number of wells with EC greater

than 4,000 μScm^{-1}.

- Total abstraction for all farms declined from 22.97 Mm^3 in 1996/7 to 20.69 Mm^3 in 1998/9, a decline of 10%.
- Cropped area declined by 9% between 1995/6 and 1998.
- Irrigation rates for sprinkler irrigated grass, on the five case study farms, indicates highly variable application rates and frequency. Depth of irrigation varied from a few millimetres to over 100 mm per application.
- Average daily irrigation rates on surface irrigated aflalfa ranges between less than 5 to 60 mmd^{-1}.
- Coefficient of uniformity (CU) for sprinklers in the field on average was 0.7, but ranges from 0.09 to more than 0.9. On 35% of plots CU was less than 0.7.
- The average CU for bubbler was 0.8, however was less than 0.8 on more than 40% of plots.

CHAPTER SEVEN

ANALYSIS

7.1. INTRODUCTION

This chapter presents the analysis of the study objectives and results. As listed in Chapter Five the objectives are related to the relationship between water abstraction and water quality, irrigation management and the relative benefits of demand management actions in reducing the of impact of saline intrusion on the South Batinah (Chapter One).

The analysis is presented in three sections, the first examines the spatial relationship between changes in water abstraction (Chapter Six) and water quality. The second section evaluates irrigation management and efficiency of sprinkler and surface irrigation on the five case study farms. The third section investigates the impact of declining abstraction on saline intrusion and the relative benefits of reductions in abstraction through demand management intervention.

7.2. ABSTRACTION - WATER QUALITY RELATIONSHIP

This section presents an evaluation of the spatial and temporal relationship(s) between water abstraction and water quality.

7.2.1. Analytical Methods

The research programme has provided a wealth of time series data on groundwater abstraction, water quality, abstraction, crops and irrigation methods for the study farms. This information forms the basis of the evaluation of the relationship between abstraction and irrigation water quality.

The farm as the fundamental management unit is adopted as the basis for examination of these relationships. Water quality is calculated as the mean irrigation water quality, based on the average water quality of all the wells on the farm, weighted according to proportion of total farm abstraction.

Farm water use is measured as the total abstraction from all wells. Water demand was

calculated as gross irrigation requirements, based on crop type, area, leaching requirements and irrigation methods. It is based on empirical formulae for the calculation of leaching fraction, leaching requirements and irrigation water requirements, with coefficients for crop type and growth stage and maximum salt tolerance.

Where relevant the results of the comparative analyses are presented in charts and/or maps to illustrate trends and correlation, and in some cases spatial distribution and proximity to the coast.

7.2.2. Trends in Irrigation Water Quality

As previously indicated (Section 6.4.2) EC increased for 75% of wells during the research period. There was also an increase in the number of wells with an EC greater than 4,000 μScm^{-1}. But while EC is an indicator of well water quality, on farms using more than one well for irrigation, EC can differ between wells. These difference can be due to a number of factors, in some cases related to well location, for example on large farms wells nearer the coast are the first to be impacted by saline intrusion. Well depth and abstraction rates are also factors, deep wells with high abstraction rates are more likely to cause upconing of saline water and therefore have a higher EC.

On some farms, particularly those with wide EC differences between wells, there was often preferential abstraction from wells with better water quality. In some cases better quality water was used for irrigation of the more salt sensitive crops, while on others it was discharged to central distribution mainlines or channels where water was blended. However, for the purpose of this analysis it is not possible to differentiate between the two groups of farms, therefore for the investigation of the relationship between water salinity and water use and demand, irrigation water EC is calculated and termed "weighted average EC" or ECav. The ECav is the average EC of irrigation water per farm per year, it is calculated from the average annual EC per well, weighted according to the proportion of total abstraction for the farm during that year. Appendix U presents the farm ECav values for all farms over the research period. The ECav forms the basis for the analysis of the relationship between water salinity and water use and demand. It is also used as the irrigation water quality for computation of leaching fraction and leaching requirements, in the calculation of Gross Irrigation Requirement (GIR) per

farm.

Analysis of average ECav values indicated that they increased by 34%, 1994/5-98/9, on Phase 1 farms, and by 24%, 1996/7-98/9, on Phase 2 farms, Table 7.1. In both phases the relative rate of increase of ECav appears to have decreased with time, though the absolute rate of increase remained relatively constant at between 200 to 400 μScm^{-1} per year.

Table 7.1 Summary of ECav

Years	Phase 1		Phase 2		Overall	
	ECav μScm^{-1}	Change %	ECav μScm^{-1}	Change %	ECav μScm^{-1}	Change %
1994/5	2,651					
1995/6	2,965	12				
1996/7	3,137	6	4,215		4,020	
1997/8	3,417	9	4,805	14	4,554	13
1998/9	3,549	4	5,244	9	4,937	8
Total		34		24		23

Figure 7.1 plots the distribution of final ECav, within five water salinity categories. It illustrates the spatial distribution between ECav and distance from the coast, showing that a high proportion of farms with ECav greater than 6,000 μScm^{-1} lie within four km of the coast, whilst farms with lower salinity lie further inland.

An evaluation of farm ECav for the three year period, 1996/7-98/9, indicates, Figure 7.2, a decrease in the number of farms with values of less than 4,000 μScm^{-1} and an increase above this value, particularly above 10,000 μScm^{-1}.

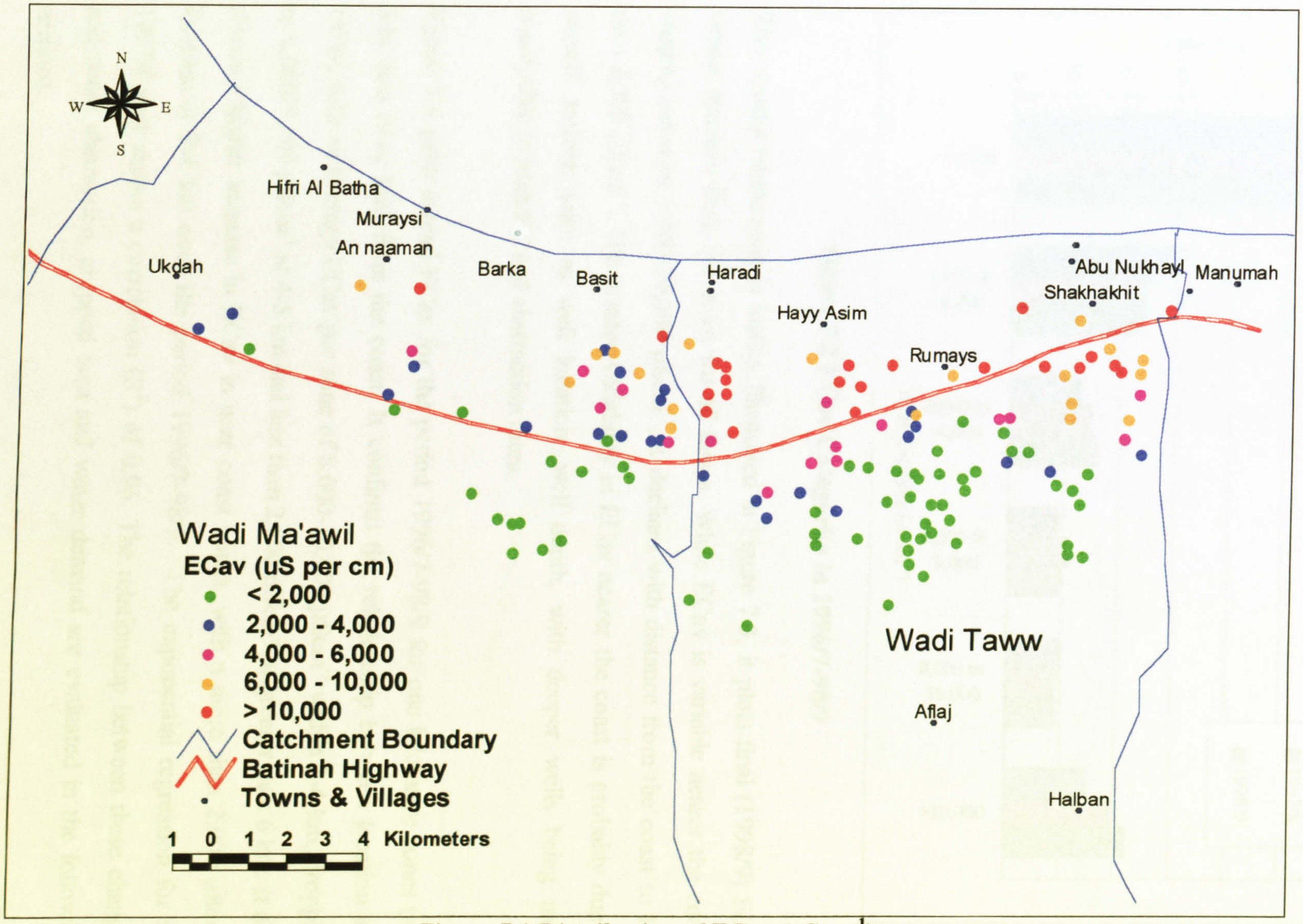

Figure 7.1 Distribution of ECav (uScm^{-1})

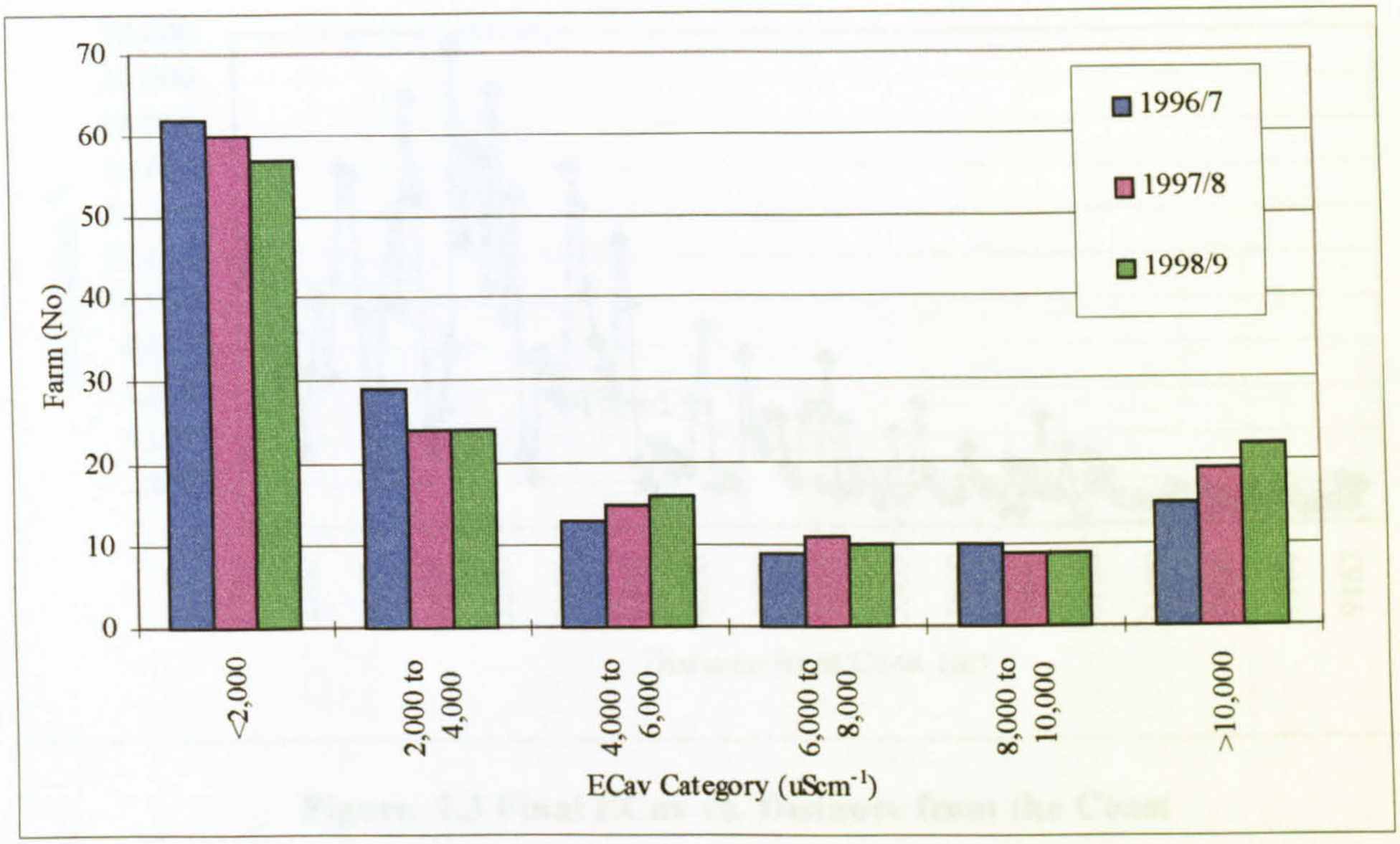

Figure 7.2 ECav Categories in 1996/7-98/9

The spatial relationship is further illustrated in Figure 7.3, it plots final (1998/9) ECav versus distance from the coast for all farms. While ECav is variable nearer the coast, ranging between 5,000-20,000 μScm^{-1}, it declines with distance from the coast to less than 2,000 μScm^{-1}. The greater variability in ECav nearer the coast is probably due to several factors, such as well location, well depth, with deeper wells being more susceptible to high EC and abstraction rates.

Figure 7.4 plots annual ECav for the period 1996/7-98/9 for one kilometre zones (and less than three km) from the coast. It confirms the relationship between location and ECav, with an average ECav per zone of 8,000-10,000 μScm^{-1} within 3-4 km, dropping to 4,000-5,000 μScm^{-1} at 4-5 km and less than 2,000 μScm^{-1} at greater than 6 km. It also shows a higher increase in ECav in near coast zones, with a more than 2,000 μScm^{-1} increase at 3-4 km over the period 1996/7-98/9. The exponential regression for the 1997/8 year shows a correlation (R^2) of 0.96. The relationship between these changes and water abstraction, cropped area and water demand are evaluated in the following sections.

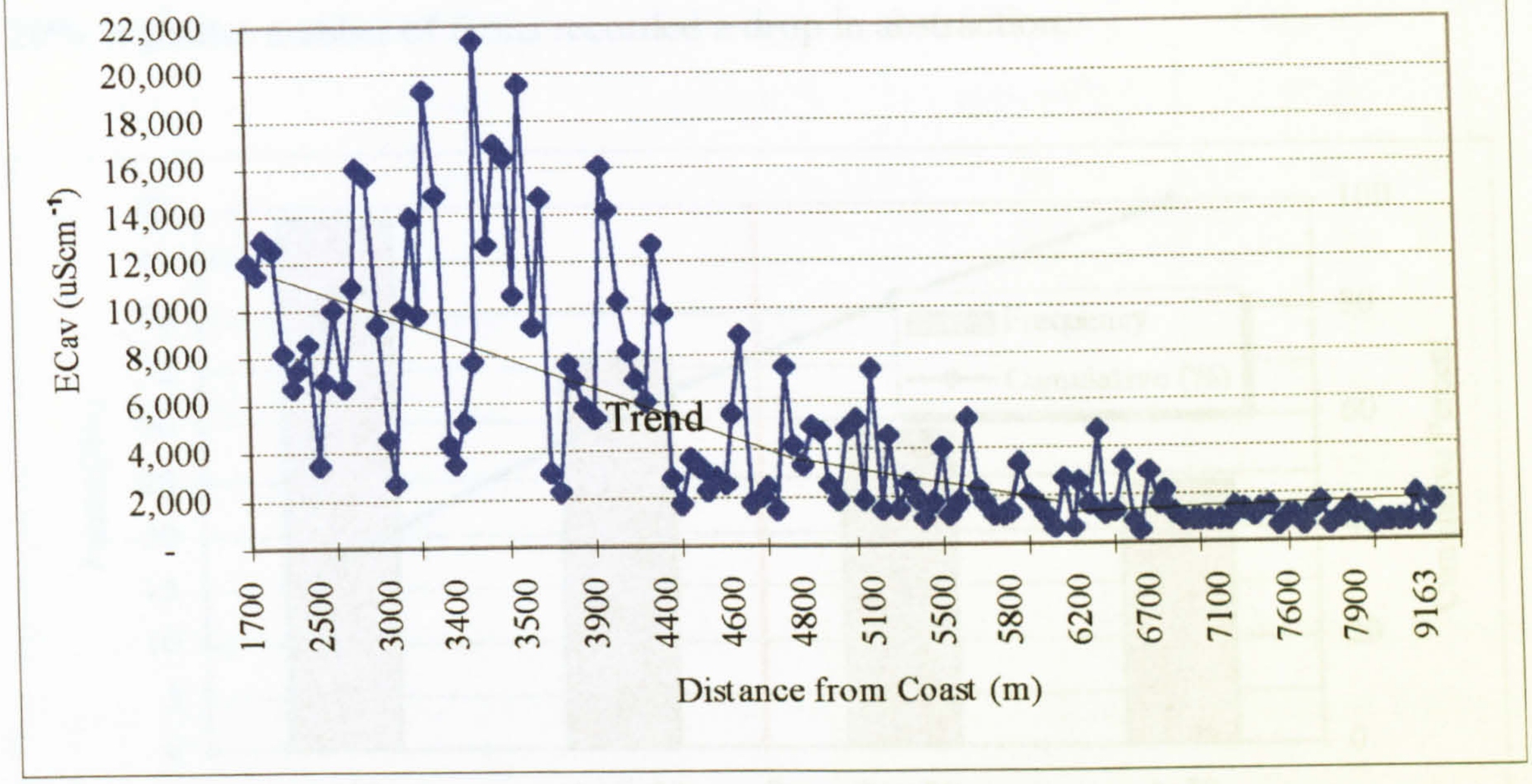

Figure 7.3 Final ECav vs. Distance from the Coast

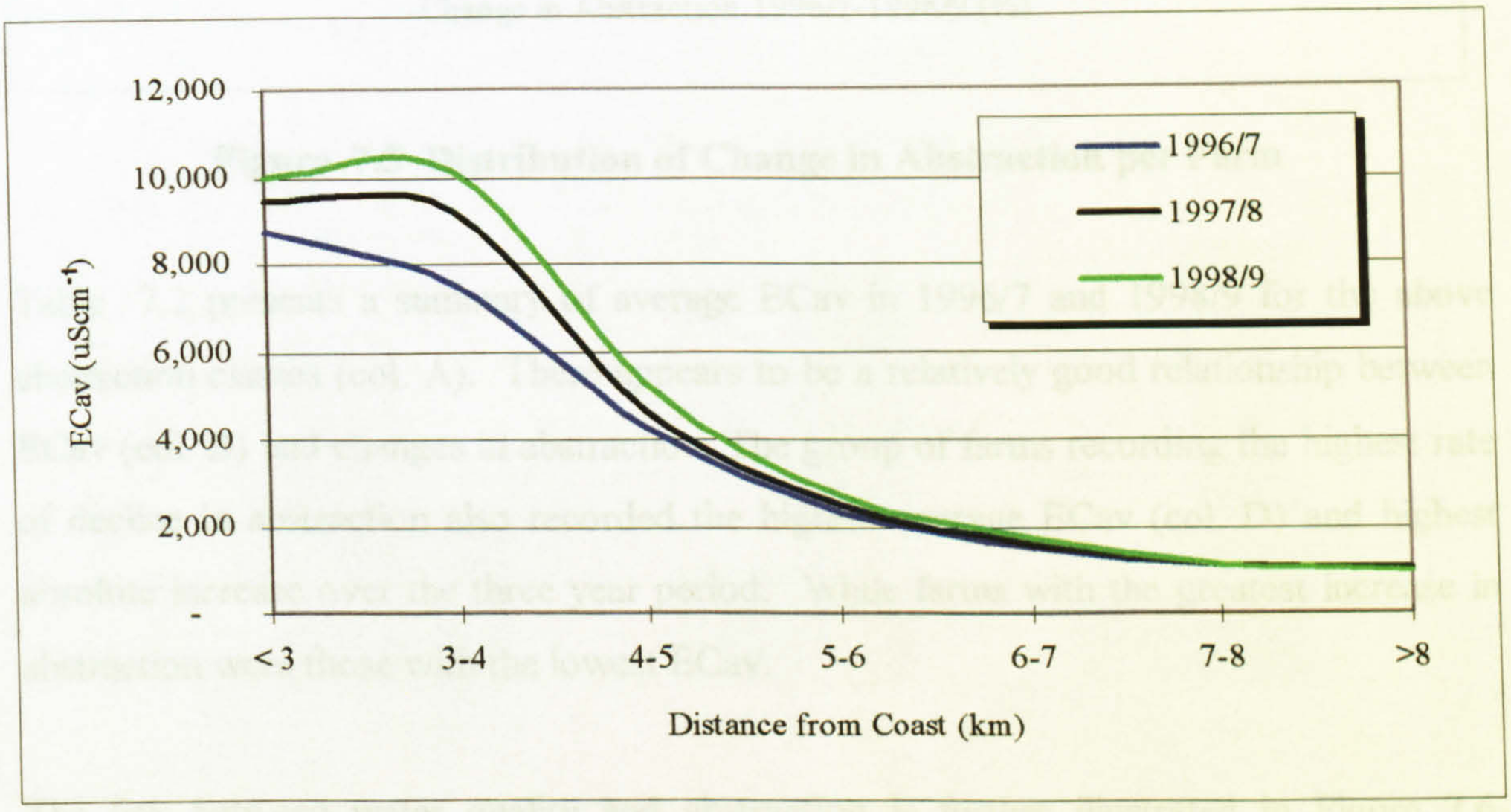

Figure 7.4 Annual ECav versus Distance from Coast

7.2.3. Abstraction Trends and Relationships

As indicated in Chapter 6 (Section 6.5.6) there was an overall trend of decreasing water abstraction over the research period. Total annual abstraction for all farms decreased by 10% in the period 1996/7-98/9. Over this period abstraction declined on 62% of farms and increased on 38%. Figure 7.5 presents the distribution of farms within four classes of change in abstraction. On 49 farms (35%) it decreased by more than 20%, whilst on 26

farms (26%) it declined by up to 20%. While within the two groups of plus and minus 20%, a greater number of farms recorded a drop in abstraction.

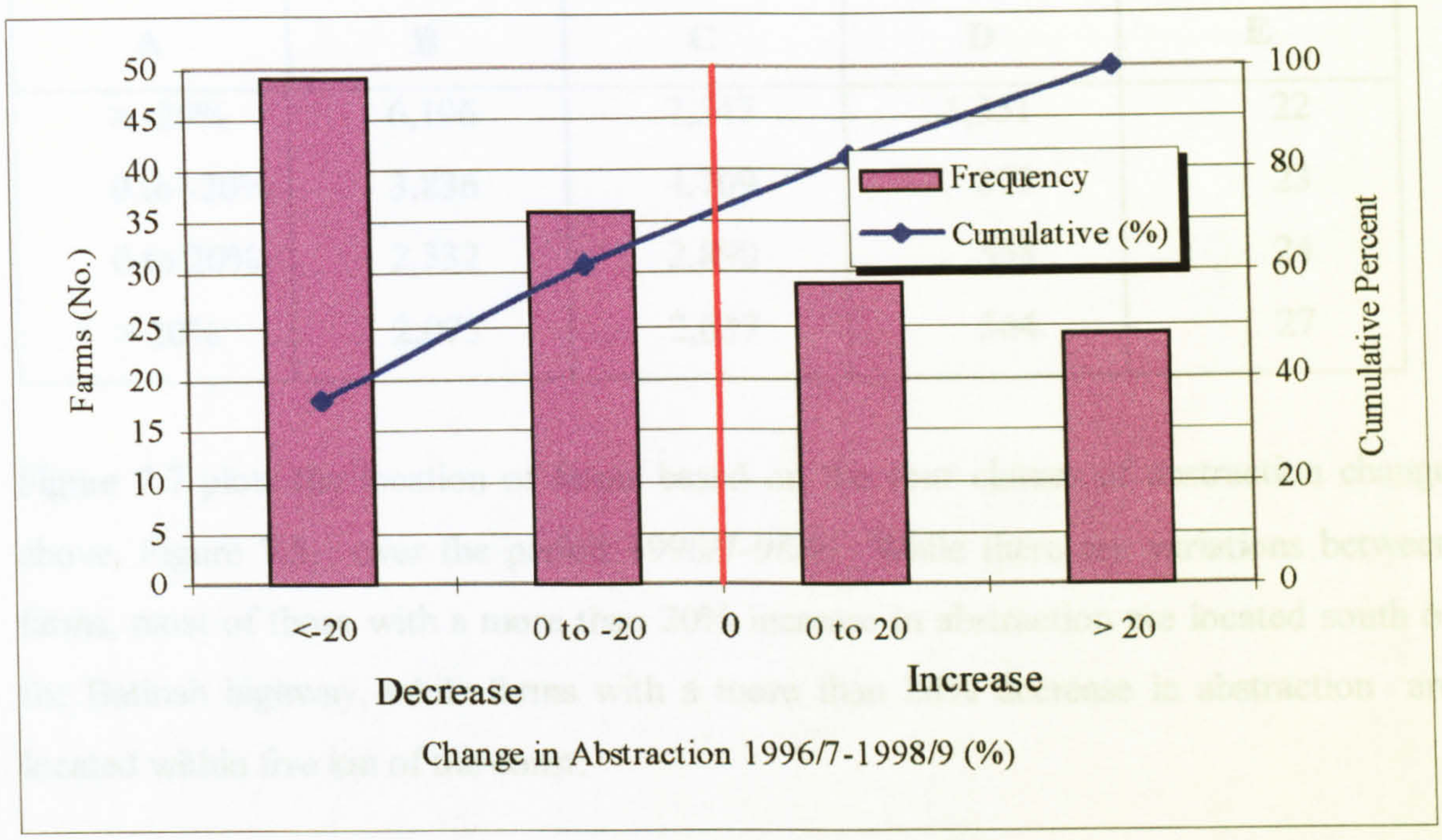

Figure 7.5 Distribution of Change in Abstraction per Farm

Table 7.2 presents a summary of average ECav in 1996/7 and 1998/9 for the above abstraction classes (col. A). There appears to be a relatively good relationship between ECav (col. B) and changes in abstraction. The group of farms recording the highest rate of decline in abstraction also recorded the highest average ECav (col. D) and highest absolute increase over the three year period. While farms with the greatest increase in abstraction were those with the lowest ECav.

The link between water quality and abstraction is further illustrated in Figure 7.6. Analysis of abstraction changes based on three ECav categories, shows that on farms with a final ECav of less than 2,000 μScm^{-1}, abstraction increased on 66% of farms. However, on farms with final ECav values of 2,000 to 6,000 μScm^{-1} and greater than 6,000 μScm^{-1}, abstraction decreased on 78% and 83% of farms respectively. Appendix V presents annual abstraction and ECav for all farms.

Table 7.2 Relationship between Abstraction Trends & ECav

Abstraction Trend (%) A	1996/7 ECav (μScm^{-1}) B	1998/9 ECav (μScm^{-1}) C	Difference (μScm^{-1}) D	Difference (%) E
> -20%	6,196	7,547	1,351	22
0 to -20%	3,836	4,709	873	23
0 to 20%	2,332	2,890	558	24
> 20%	2,073	2,637	564	27

Figure 7.7 plots the location of farms based on the four classes of abstraction change above, Figure 7.5, over the period 1996/7-98/9. While there are variations between farms, most of those with a more than 20% increase in abstraction are located south of the Batinah highway, while farms with a more than 20% decrease in abstraction are located within five km of the coast.

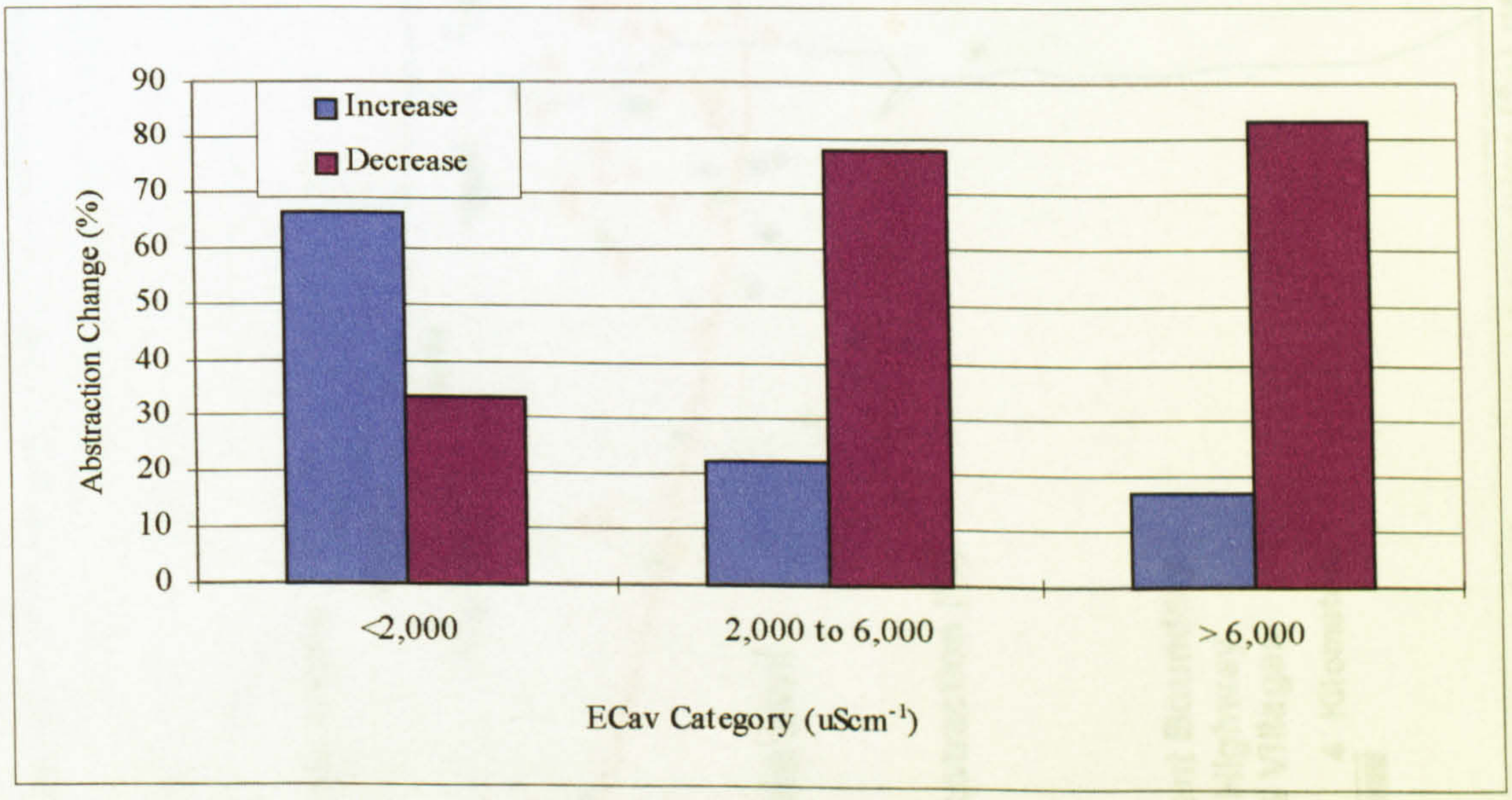

Figure 7.6 Changes in Abstraction (%) versus Final ECav (μScm^{-1})

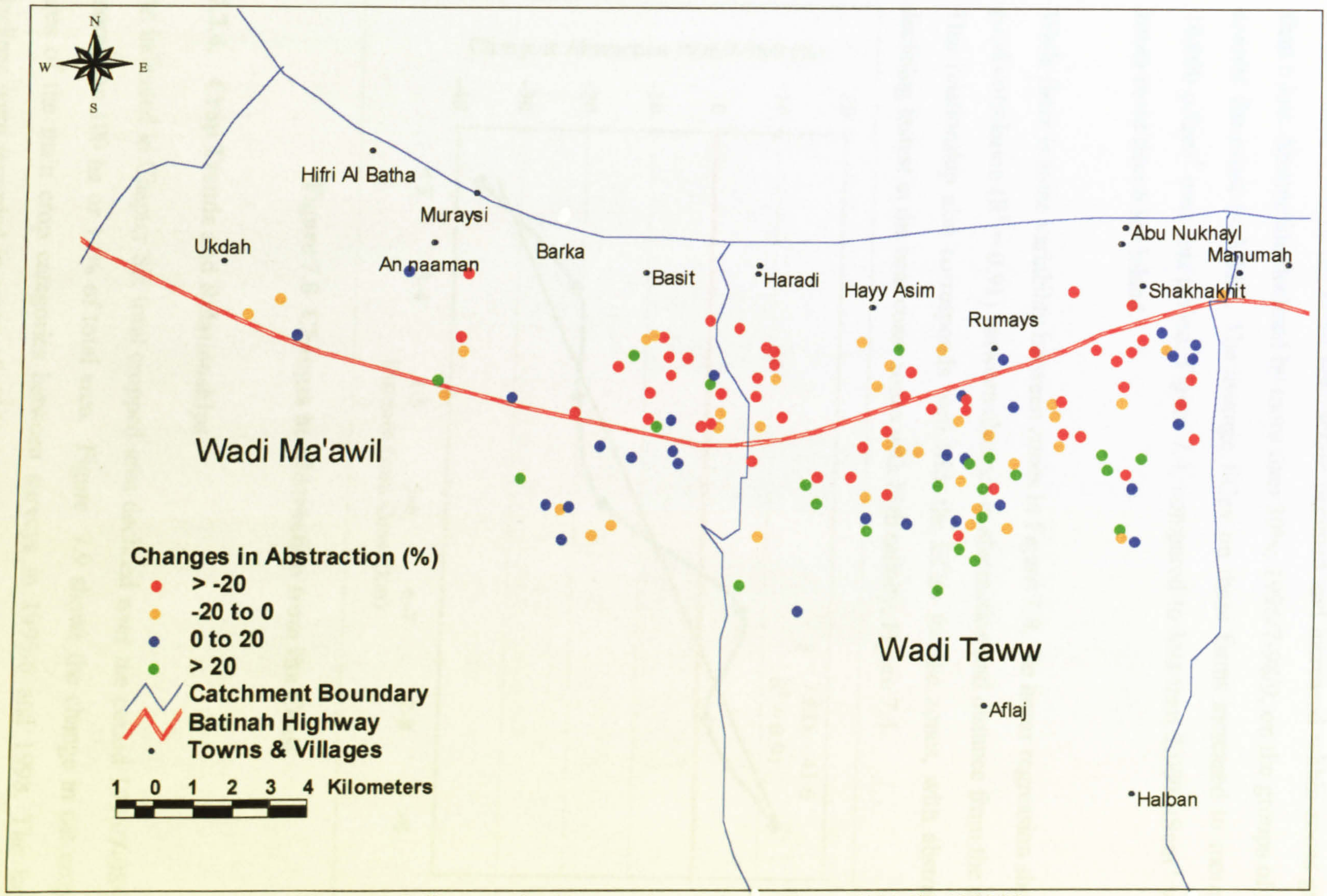

Figure 7.7 Changes in Abstraction (%) per Farm (1996/7-1998/9)

Figure 7.8 shows the relationship between farm location and changes in abstraction. It plots the rate of abstraction change (%) over the period 1996/7-98/9 for farms within seven zones from the coast (< 3, 3-4, 4-5, 5-6, 6-7, 7-8 and > 8 km). It shows that in the zones within 6 km of the coast abstraction declined and increased within zones greater than 6 km. Abstraction declined by more than 30%, 1996/7-98/9, on the groups of farms nearest the coast (< 3 km). The average ECav on these farms increased to more than 10,000 μScm^{-1} over this period, Figure 7.4, compared to less than 2,000 μScm^{-1} within zones more than 6 km inland.

While there is some variability between zones in Figure 7.8, the linear regression shows a good correlation ($R^2 = 0.91$) between changes in abstraction and distance from the coast. This relationship also corresponds well with the ECav for the zones, with abstraction declining fastest in the near coast zones with high salinity, Figure 7.4.

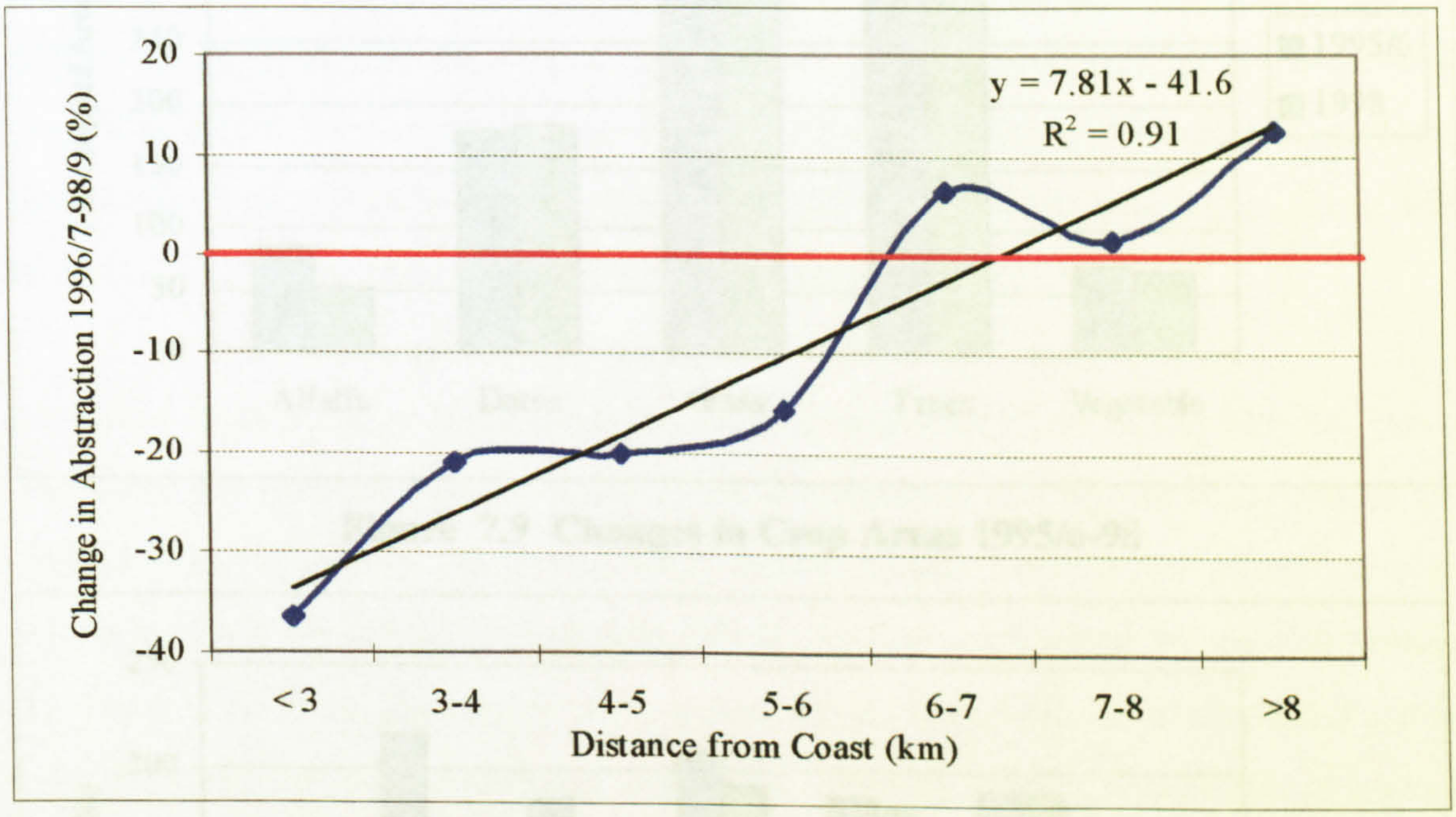

Figure 7.8 Changes in Abstraction from the Coast

7.2.4. Crop Trends and Relationships

As indicated in Chapter Six total cropped area declined over the period 1996/7-98/9 by more than 100 ha or 10% of total area. Figure 7.9 shows the change in net cropped area of the main crop categories between surveys in 1995/6 and 1998. The largest declines were recorded in areas of alfalfa and grass, (34 and 38 ha respectively), with smaller losses for trees (excluding datepalms) (23 ha) and vegetables (6 ha). There was a

small increase in the area of dates (3 ha).

The relationship between changes in cropped area and distance from the coast are presented in Figure 7.10. They indicate that the greatest decline in area occurred within 6 km of the coast; this is also the zone of farms that experienced the greatest increases in ECav (Section 7.2.4). Smaller rates of decline occurred further inland as illustrated in Figure 7.11. The changes in cropped area appear to reflect changes in ECav and changes in abstraction rates reported in Section 7.2.4 and 7.2.5 respectively.

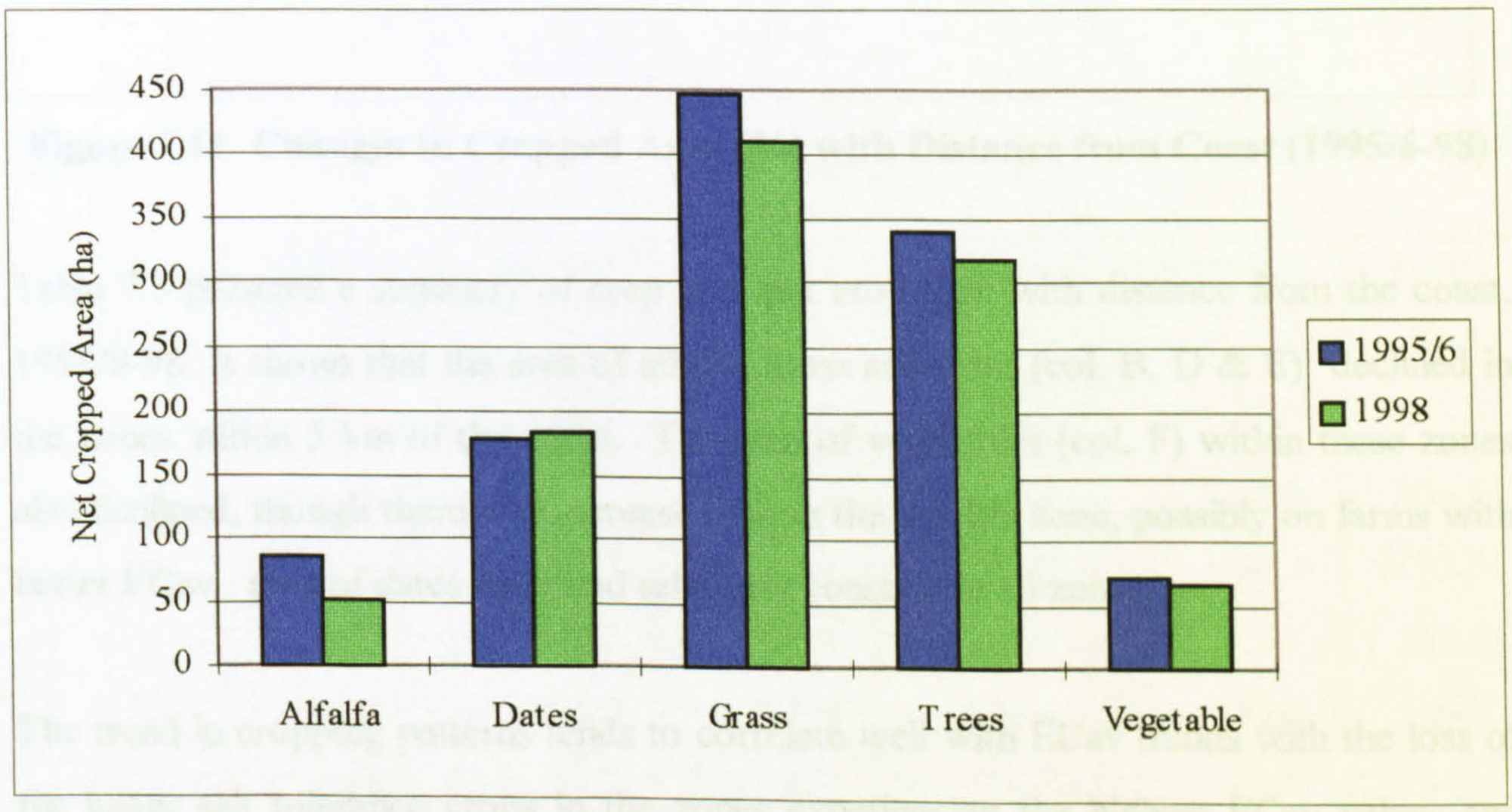

Figure 7.9 Changes in Crop Areas 1995/6-98

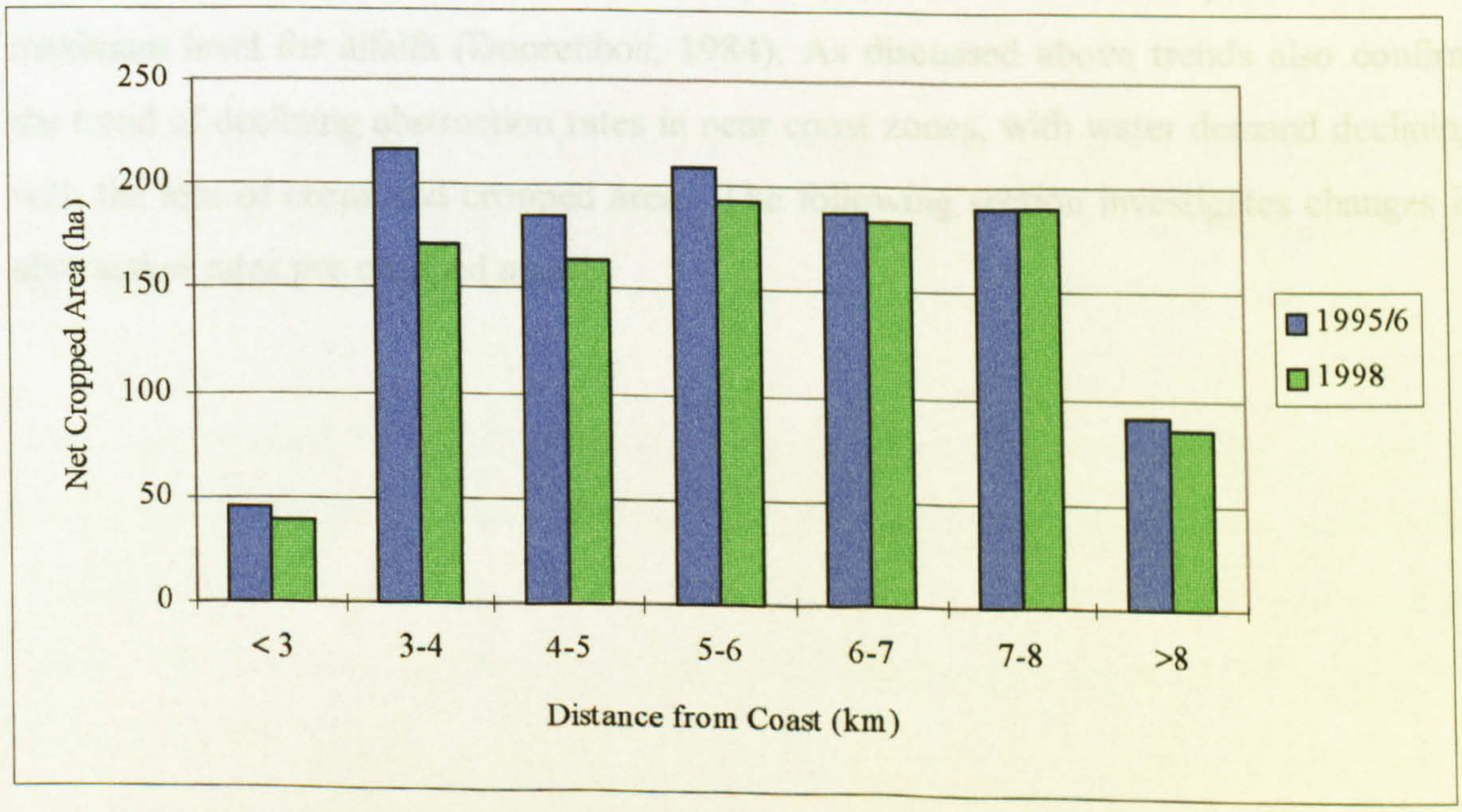

Figure 7.10 Changes in Cropped Area (ha) with Distance from Coast

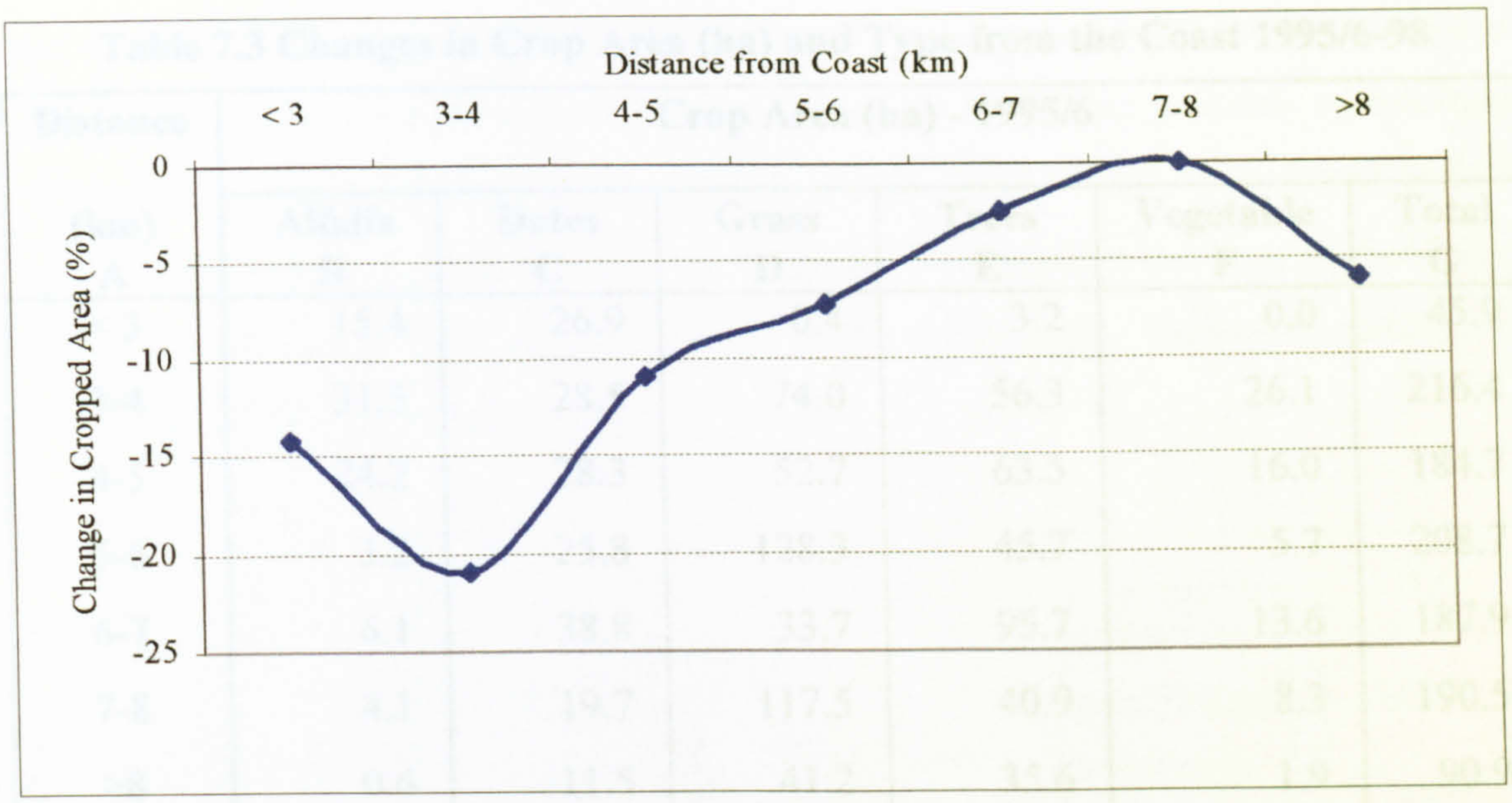

Figure 7.11 Changes in Cropped Area (%) with Distance from Coast (1995/6-98)

Table 7.3 presents a summary of crop area per crop type with distance from the coast, 1995/6-98. It shows that the area of alfalfa, grass and trees (col. B, D & E) declined in the zones within 5 km of the coast. The area of vegetables (col. F) within these zones also declined, though there was increase with in the 4-5 km zone, possibly on farms with better ECav. area of dates remained relatively constant in all zones.

The trend in cropping patterns tends to correlate well with ECav trends with the loss of the lower salt tolerance crops in the zones experiencing the highest ECav values and highest rising in salinity. Irrigation water quality greater than 10,000 μScm^{-1} near the maximum level for alfalfa (Doorenbos, 1984). As discussed above trends also confirm the trend of declining abstraction rates in near coast zones, with water demand declining with the loss of crops and cropped area. The following section investigates changes in abstraction rates per cropped area.

Table 7.3 Changes in Crop Area (ha) and Type from the Coast 1995/6-98

Distance (km) A	Crop Area (ha) - 1995/6					
	Alfalfa B	Dates C	Grass D	Trees E	Vegetable F	Total G
< 3	15.4	26.9	0.4	3.2	0.0	45.9
3-4	31.5	28.5	74.0	56.3	26.1	216.4
4-5	24.2	28.3	52.7	63.5	16.0	184.7
5-6	3.2	25.8	128.3	45.7	5.7	208.7
6-7	6.1	38.8	33.7	95.7	13.6	187.9
7-8	4.1	19.7	117.5	40.9	8.3	190.5
>8	0.6	11.5	41.2	35.6	1.9	90.9
Distance	**Crop Area (ha) - 1998**					
(km)	**Alfalfa**	**Dates**	**Grass**	**Trees**	**Vegetable**	**Total**
< 3	9.0	26.6	0.7	3.0	0.0	39.4
3-4	13.7	30.5	65.0	51.8	9.9	171.0
4-5	14.1	28.3	46.2	52.4	23.6	164.5
5-6	4.8	26.7	110.7	40.9	10.3	193.5
6-7	5.5	37.2	39.4	92.0	9.0	183.2
7-8	3.1	21.7	113.0	41.4	11.3	190.5
>8	0.9	11.3	34.9	36.5	1.8	85.4

7.2.5. Changes in Farm Irrigation Rates

Figure 7.12 shows a comparison of gross irrigation rates ($m^3ha^{-1}y^{-1}$) within the seven zones (as listed above) as well as the average ECav in 1999 per zone. It illustrates the variations in irrigation rates between the zones, and between 1995/6 and 1998.

Based on the need for higher leaching with deterioration of water quality, it would be anticipated that rates of irrigation would be greatest the near coast zones, and decline further inland. While this is generally true for the zones more than four km from the coast, with more than 22,000 $m^3ha^{-1}y^{-1}$ at 4-5 km declining to about 17,000 $m^3ha^{-1}y^{-1}$ at more than 8 km.

For the farms within 3 km of the coast irrigation rates were 18,000 $m^3ha^{-1}y^{-1}$ in 1995/6

and declined to less than 12,000 $m^3ha^{-1}y^{-1}$ by 1998. These are relatively low irrigation rates given, the poor water quality within the zone, and are most probably symptomatic of the advance stage of degradation of many of the farms. Field observations indicate that for many farms within the zone, that irrigation is reduced as the farm is abandoned. Often the datepalm will continue to survive, albeit under highly stressed conditions, on even very low irrigation rates.

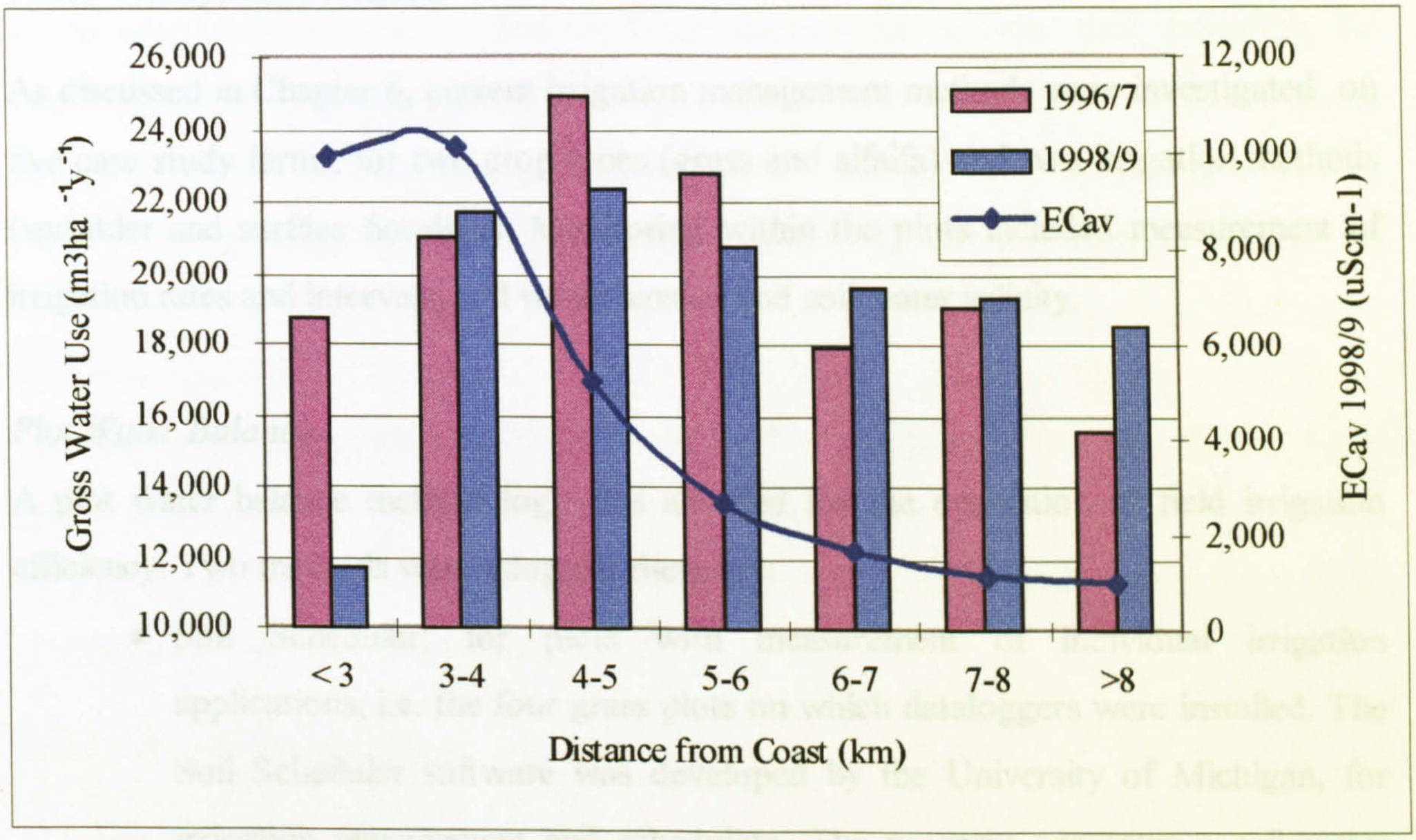

Figure 7.12 Gross Water Use vs. Spatial Distribution

7.2.5.1. Conclusion

In conclusion the analysis in Section 7.2 demonstrated the link between water quality and abstraction. While there may be variations between farms, there appears to be a reasonably good spatial relationship between abstraction rates and farm location. As shown in Figure 7.8 the rate of decline in abstraction is highest on farms nearest the coast. The decline in abstraction rates on farms nearer the coast also corresponds with the trends in water quality (Sections 7.2.2 and 7.2.3). There is a link between a rise in ECav, leading to a loss of cropped area and resultant decline in abstraction. The low rates of irrigation on farms near the coast is likely to compound the impact of high ECav, as a reduction of leaching will lead to greater crop losses.

7.3. IRRIGATION MANAGEMENT

This section presents the analysis of irrigation methods and management on plots on the five case study farms. The objective was the evaluation of current irrigation management practices on a sample of farms to determine current levels of irrigation efficiency and potential improvements.

7.3.1. Analytical Methods

As discussed in Chapter 6, current irrigation management methods were investigated on five case study farms, for two crop types (grass and alfalfa) and two irrigation methods (sprinkler and surface flooding). Monitoring within the plots included measurement of irrigation rates and intervals, soil water tension and soil water salinity.

Plot Water Balance

A plot water balance methodology was adopted for the evaluation of field irrigation efficiency. Two methods were adopted, these are:

- Soil Scheduler; for plots with measurement of individual irrigation applications, i.e. the four grass plots on which dataloggers were installed. The Soil Scheduler software was developed by the University of Michigan, for irrigation management and scheduling. The program generates a soil water balance based on soil water content and calculated crop water requirements (ETc). The ETc was calculated from the ETo for Mudallah met station, based on mean monthly climate data (Chapter 3), and crop coefficients as described in Appendix W. Plot soil water content at field capacity were those measured by TDR and presented in Appendix Z. The full results of the analysis on a daily basis is listed in Appendix AB.
- Empirical Plot Water Balance; for the plots on which irrigation was recorded as periodic meter readings, five alfalfa and one grass plot, the calculation water balance, ETc was calculated from empirical formula and coefficients as listed in Appendix W.

Soil Water Content

The available water content of plots was measured by TDR along with soil moisture tension. Appendix Z presents the plot TDR and soil moisture tension readings. The soil

water content was assumed to be at field capacity at the start of the balance. Depletion occurred due to cropwater extraction, leaching and percolation losses, while irrigation and rainfall events increased soil water content. Whenever irrigation and/or rainfall plus the existing water content exceeded the soil waterholding capacity, water was lost to deep percolation.

Irrigation Interval and Rates

In the case of the four grass plots on which dataloggers recorded daily irrigation, the interval between irrigation's and daily irrigation rates were evaluated. On the remaining grass plot, as well as the alfalfa plots water meter readings were collected periodically, usually weekly. These were used to calculate average daily irrigation rates.

Soil Water Salinity

The measurement of soil salinity levels from Soil Moisture Extraction (SME) tubes provided a control on irrigation leaching levels for comparison with assumed values in the plot water balance. Appendix AA lists the results of the records for plots on which soil moisture extracts were collected.

7.3.2. Plot Water Balances

The following subsections present the results of the analysis of plot water balances for sprinkler and surface irrigated grass and alfalfa plots respectively.

7.3.2.1. Grass Plots

Figures 7.13-7.19 plot the results of the plot soil water balance and soil moisture tension for the four grass plots, with daily records of irrigation applications. The periods of monitoring of irrigation vary between plots with the shortest set of records, 4 months for farm 6 to nearly 2 years for farms 9 and 10. The difference in duration between plots was due to the abandonment of the plots on farms 6 and 7 in April 1998 and June 1999 respectively. In both cases the plots were retired from cultivation.

Soil moisture tension was monitored for part of 1998/9 in four plots (farms 7, 9, 10 and 11). The monitored period varied between farms from four to nine months, Figures 7.15, 7.17, 7.19 and 7.21, and in all cases was less than the plot water balance period. The records of soil moisture tension provide a comparison with the plot water balances, of

the levels of water depletion, and trends over the monitored period. While soil moisture tension should generally reflect the plot water balance, there are likely to be some variations due to site conditions, associated with variability of irrigation uniformity within the plot, due to sprinkler uniformity, wind and grass height. There are also likely to be variations due to the plot water balance methodology, which is calculated as the water content within the rooting depth (75 cm), however tensiometers monitored tension at specific depths of 30 and 60 cm.

On farm 6 the soil water balance follows a trend of progressive decline, Figure 7.13, from Dec. 1997 to the cessation of irrigation in Apr. 1998. Irrigation rates were low, virtually all events were less than 20 mm (with two exceptions). The impact of the low rates were also visible in the field with uneven crop height and bare patches. The ECav for the farm is more than 7,000 μScm^{-1} therefore these low rates would have compounded the affect of high water salinity, due to inadequate leaching, as discussed below. Due to the abandonment of the plot prior to the installation of tensiometers there are no soil moisture tension records for comparison with the plot water balance.

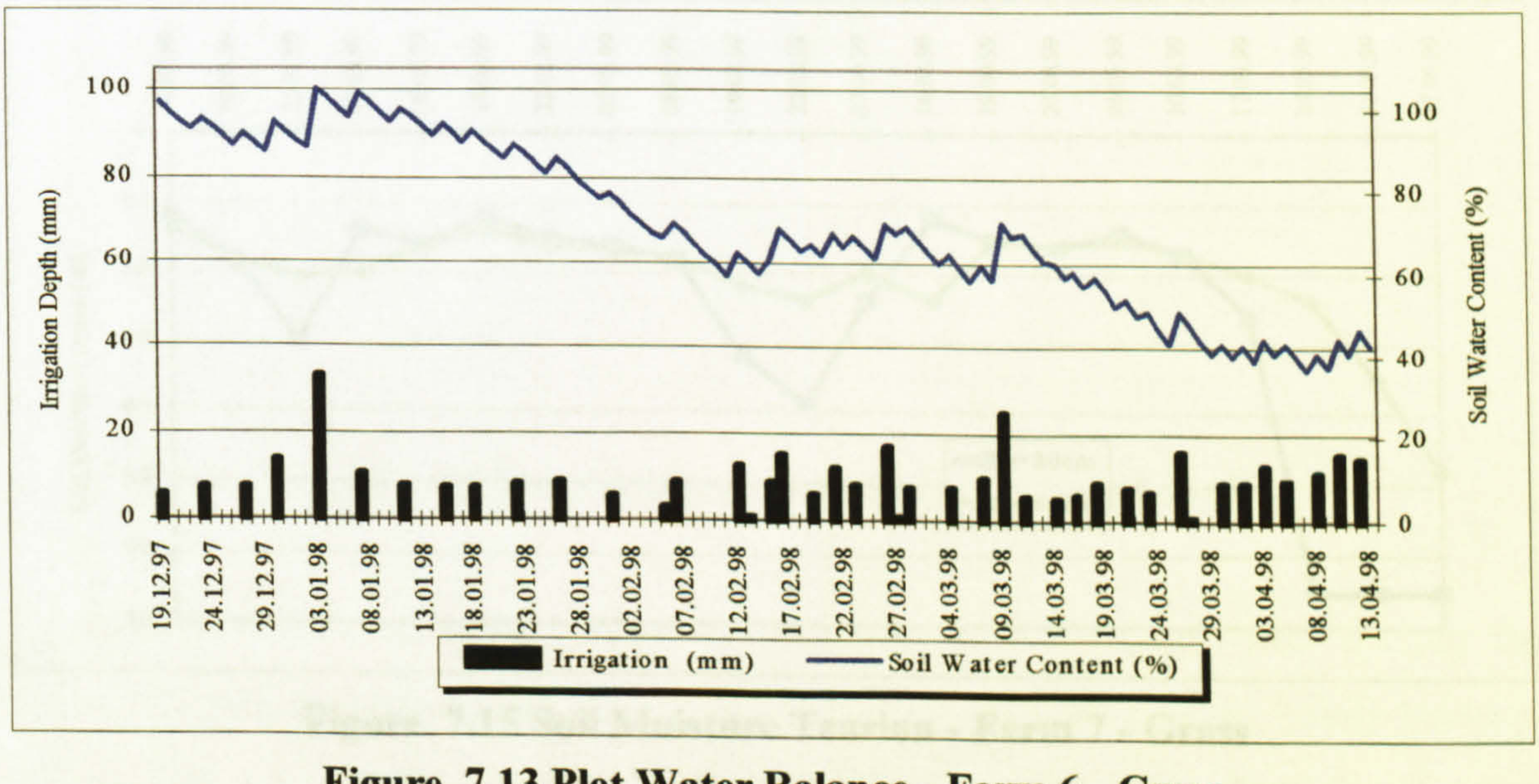

Figure 7.13 Plot Water Balance - Farm 6 - Grass

The soil water balance for farm 7 shows wide variations with occasional peaks, at or near, field capacity interspersed with periods of less than 50% soil water content, Figure 7.14. The decline in water content is due to frequent, but low, irrigation rates of less than 20 mm over the March-July period in both 1998 and 1999. Water levels declined in June 1999 as irrigation rates were reduced, with abandonment of the plot. Soil moisture

tension was monitored for five months (Jan.-May 1999), Figure 7.15. At 30 cm depth it shows similar trends to the plot water balance, with a raise in tension of 30-40 cb in early Mar. and Apr. as soil water content declined, Figure 7.14. At 60 cm tensions showed a similar, though less marked response. Soil moisture tension increased at both depths from late May onwards as irrigation ceased and soil water content was depleted.

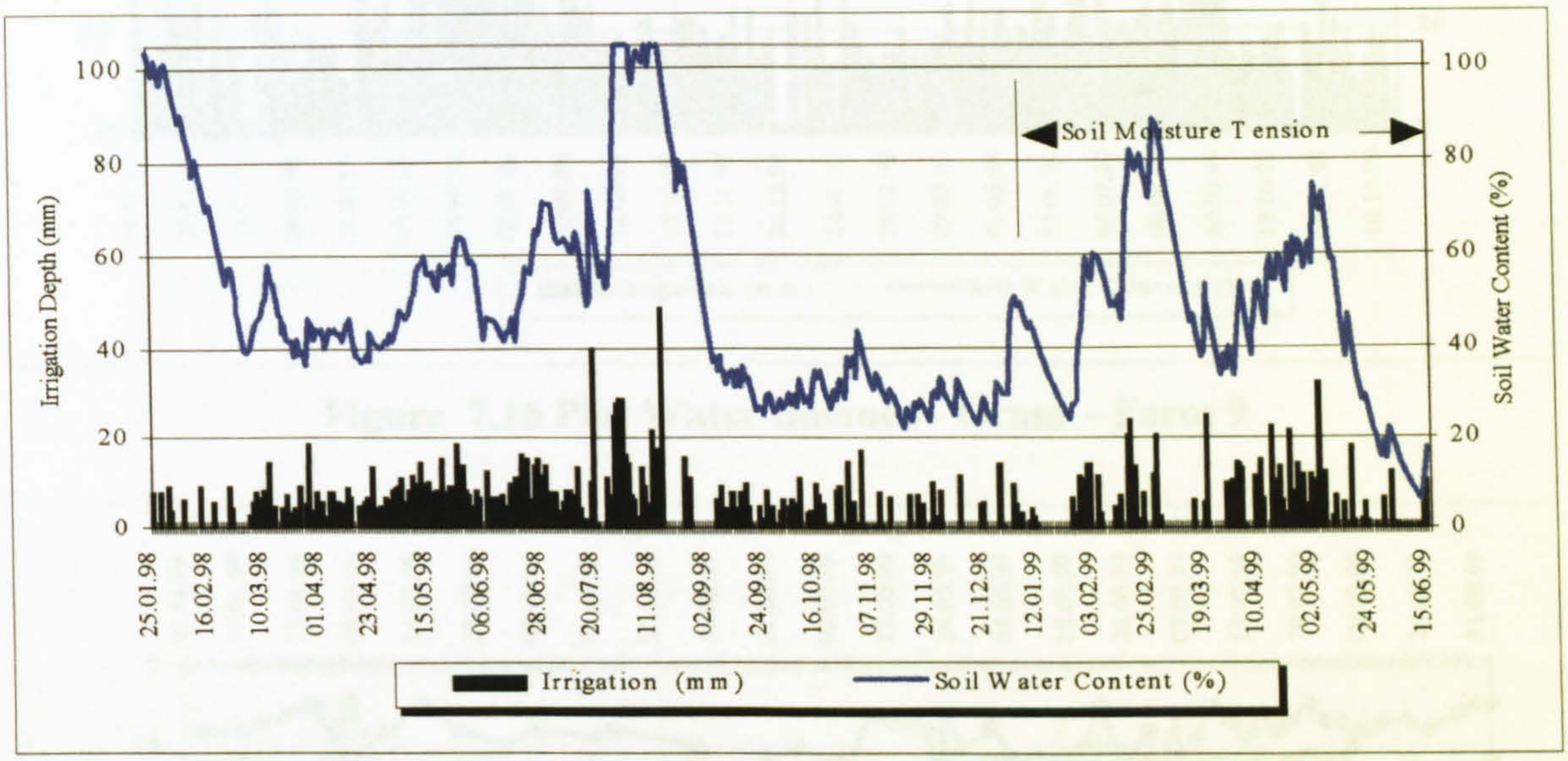

Figure 7.14 Plot Water Balance - Farm 7 - Grass

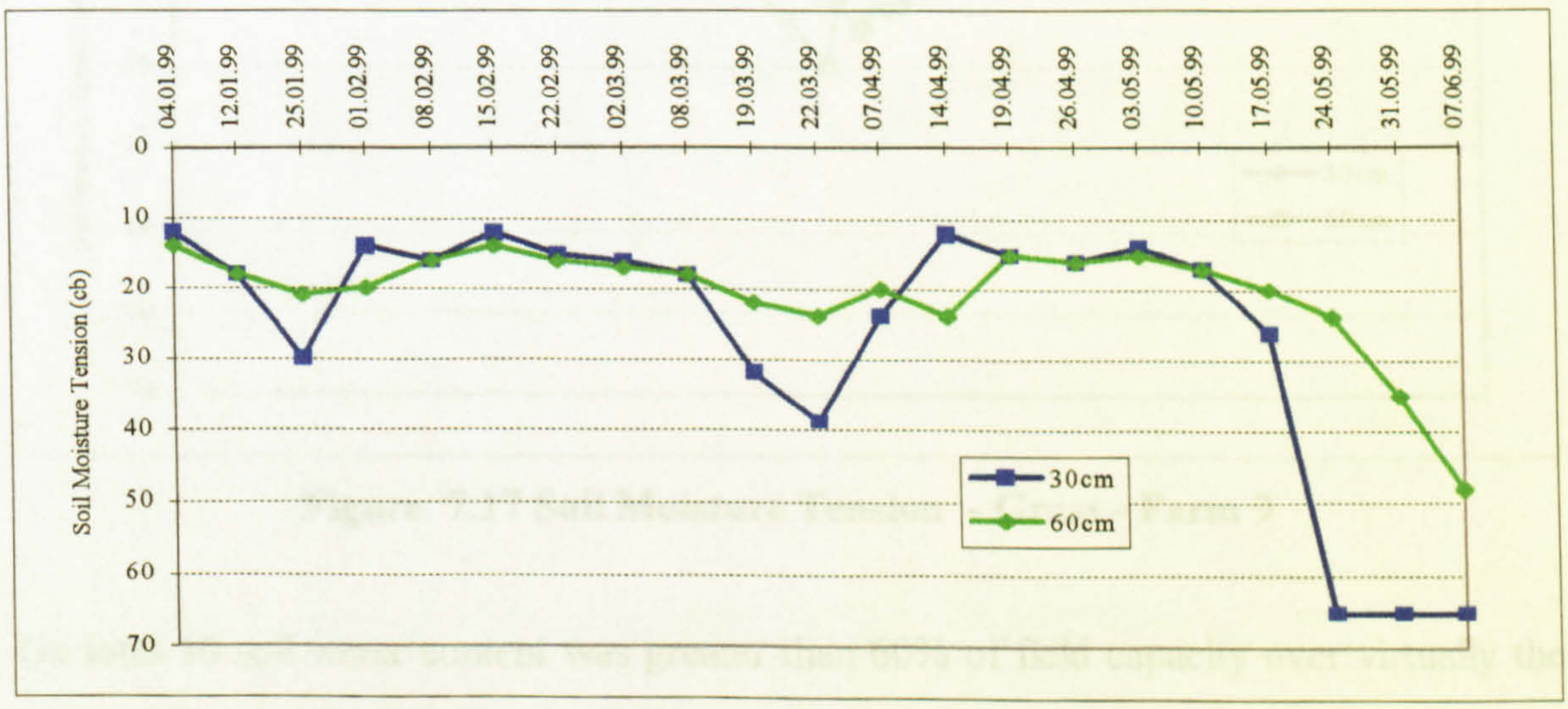

Figure 7.15 Soil Moisture Tension - Farm 7 - Grass

Apart from two periods (March and September 1998), soil water content on farm 9 was within 75% of field capacity, Figure 7.16. Irrigation rates were higher than those recorded on farms 6 and 7, with many individual events of greater than 20 mm. The generally high soil water content is reflected in soil moisture tension, over the period Jan.-Aug. 1999, Figure 7.17, with tensions of less than 20 cb at 30 cm and less 30 cb at 60 cm.

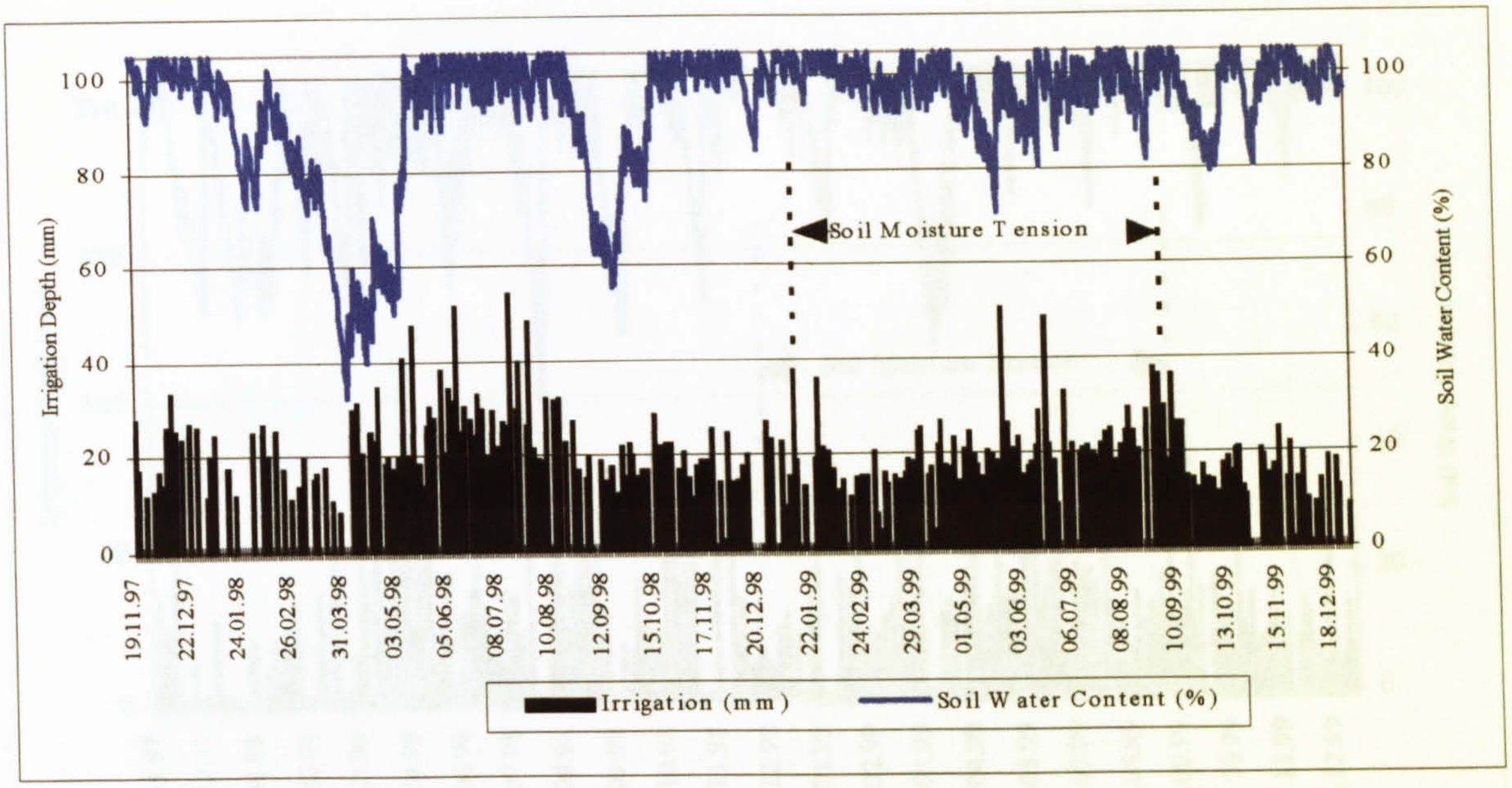

Figure 7.16 Plot Water Balance - Grass - Farm 9

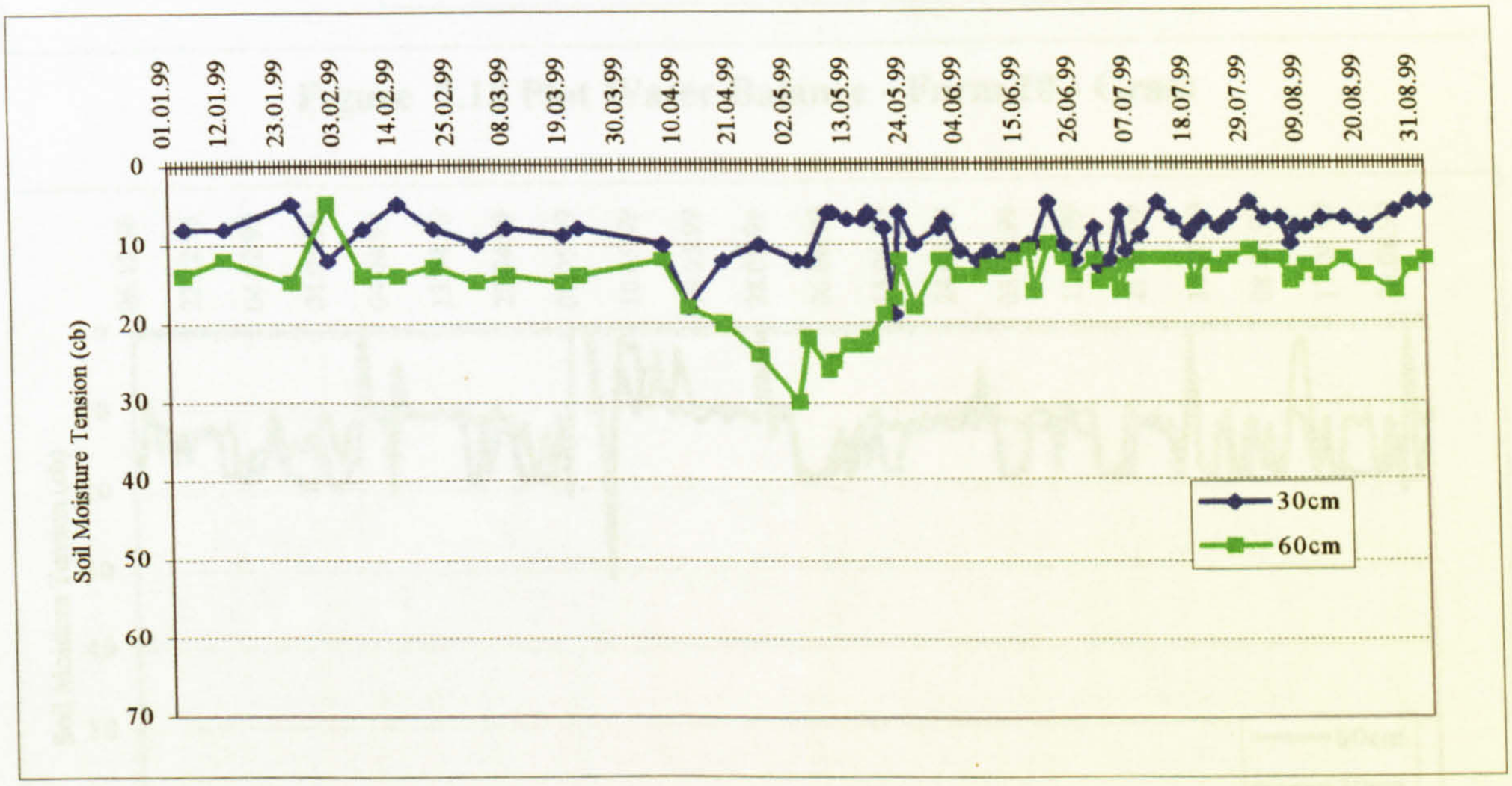

Figure 7.17 Soil Moisture Tension - Grass - Farm 9

On farm 10 soil water content was greater than 60% of field capacity over virtually the entire two year monitoring period, Figure 7.18. Irrigation rates varied widely between events from a less than 20 mm to more than 100 mm. The generally high soil water content is reflected in low soil moisture tensions, over the period Jan.-Aug 1999, with tensions of less than 20 cb at both 30 and 60 cm depth, Figure 7.19.

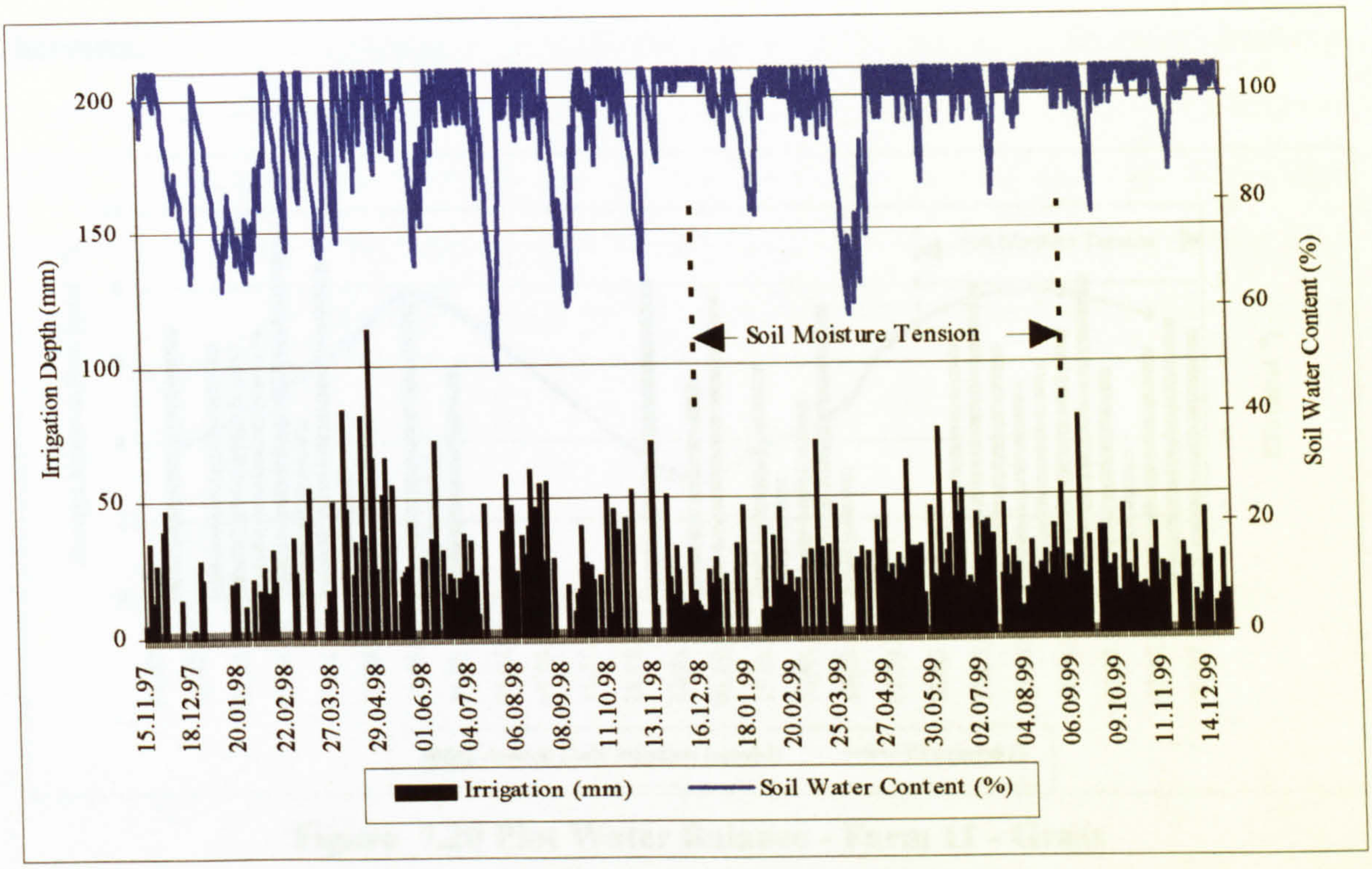

Figure 7.18 Plot Water Balance - Farm 10 - Grass

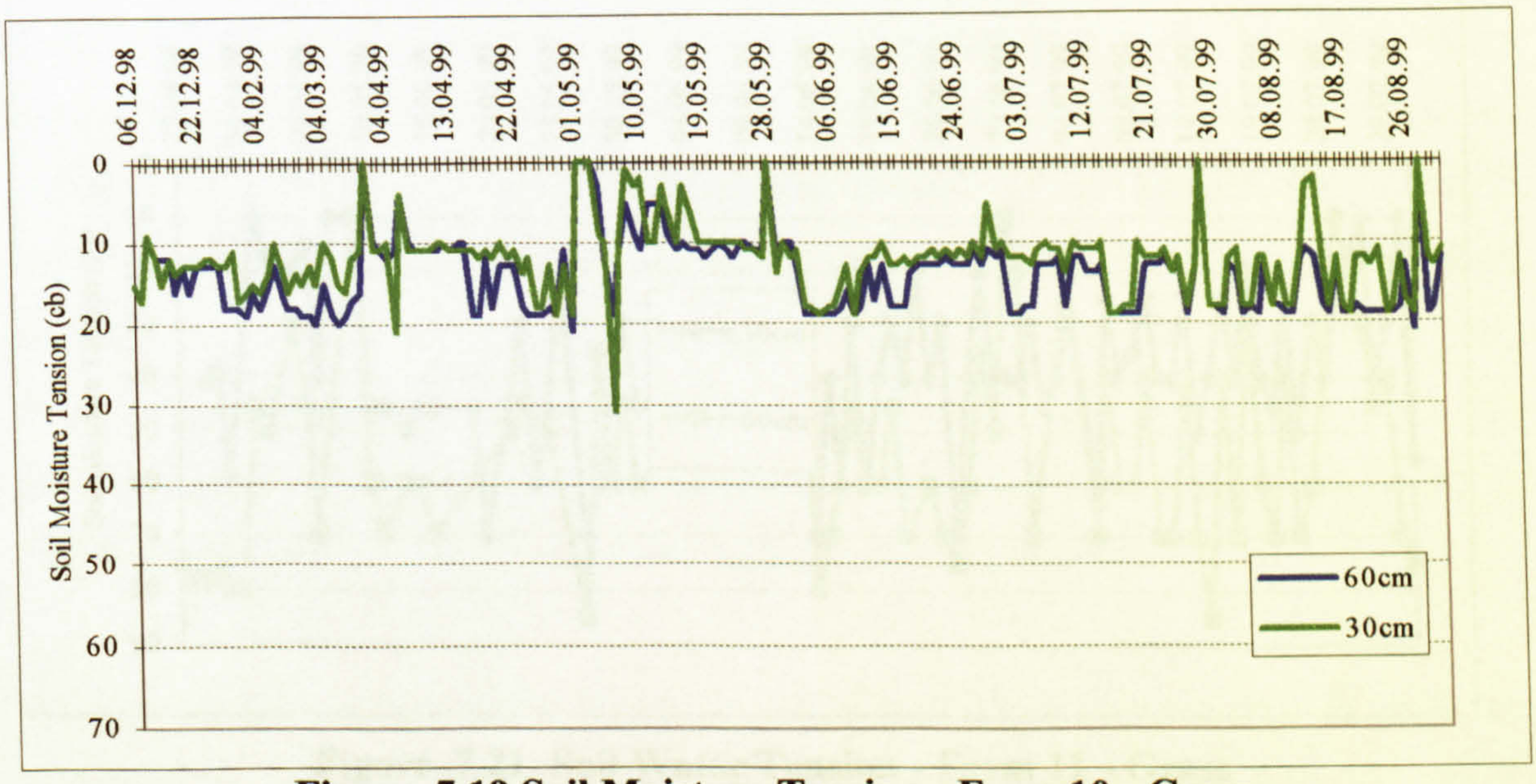

Figure 7.19 Soil Moisture Tension - Farm 10 - Grass

The water balance for the plot on farm 11, Figure 7.20, was derived from the calculation of ETc (mmd^{-1}). It indicates that irrigation rates were below crop water requirements for most of the monitored period. The results of the monitoring of soil moisture tension over the period Apr.-Aug. 1999, Figure 7.21, reflect the low irrigation rates and indicate high soil moisture tensions at both 30 and 60 cm depth. In particular tensions at 60 cm were frequently above 60 cb, indicating frequent under-irrigation. These high levels of tension were evident in the field with slow grass growth and long intervals between harvests.

harvests.

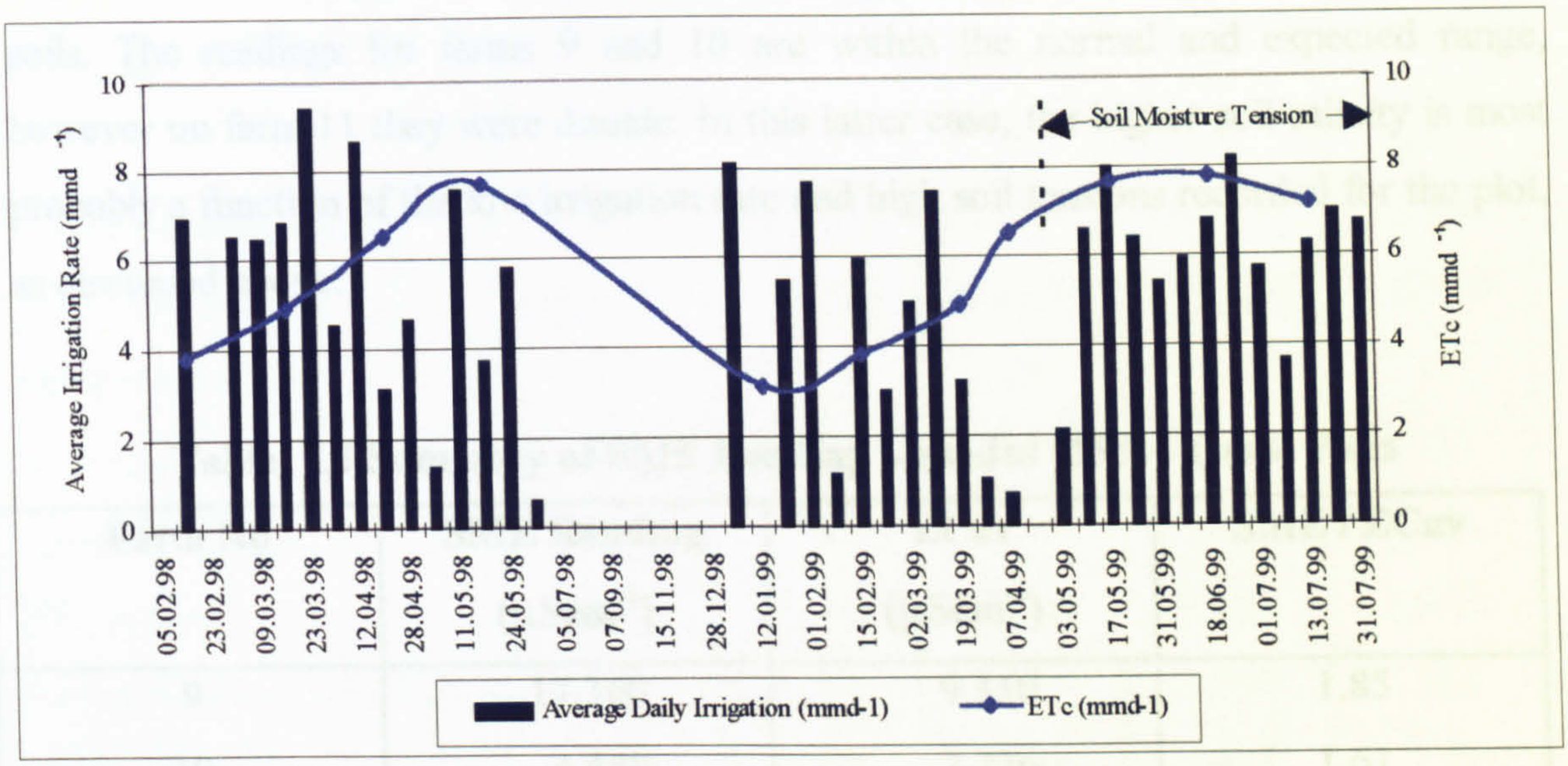

Figure 7.20 Plot Water Balance - Farm 11 - Grass

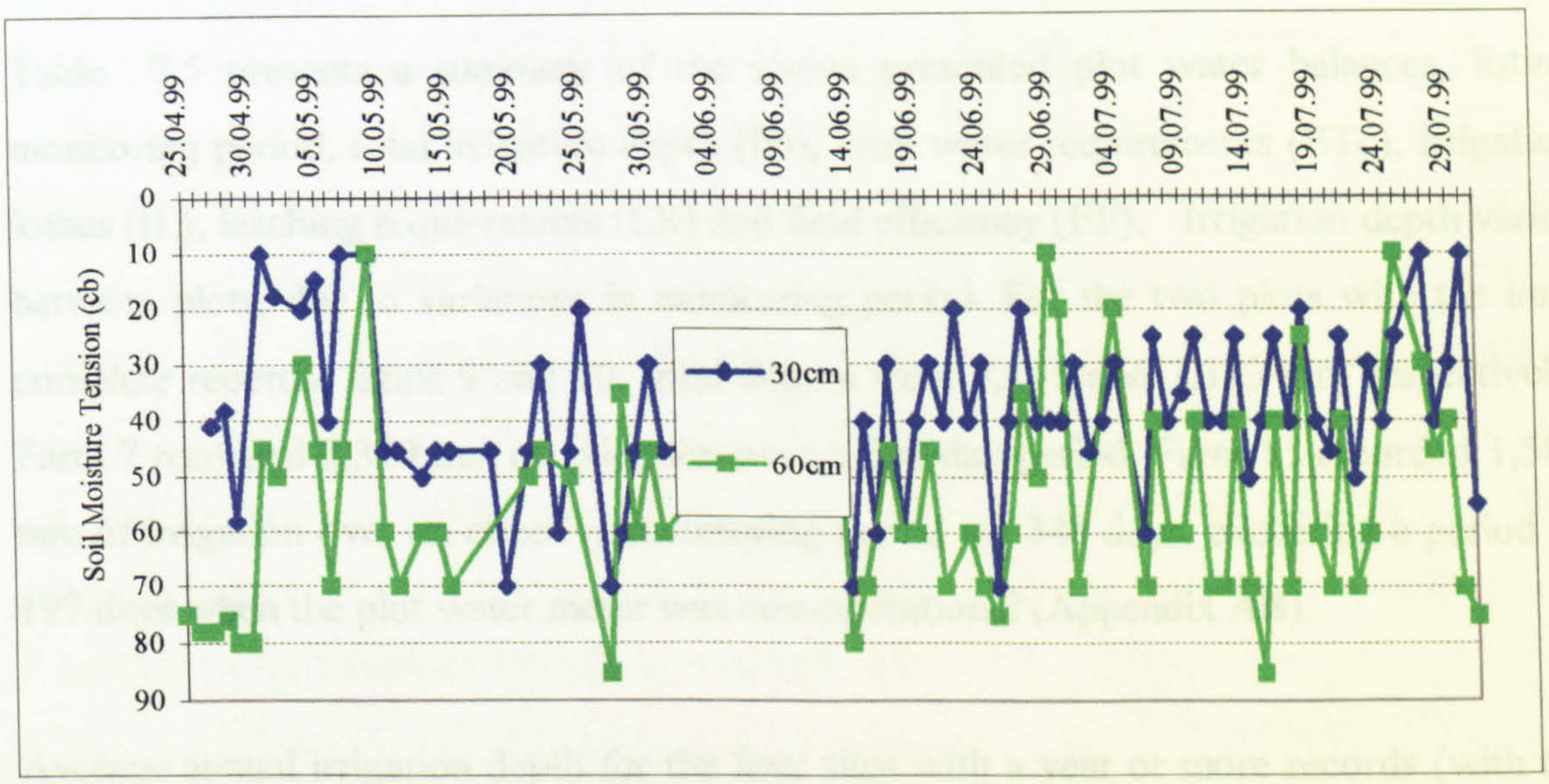

Figure 7.21 Soil Water Tension - Farm 11 - Grass

In general, and within the limits of field measurements, the soil moisture tension records compare well with the plot water balances. They reflect the trends in soil water content in response to irrigation and crop water use. They also confirm that the plot water balance methodology provides a good indicator of actual water use in the field.

The measurement of soil water salinity provided another indicator of the relationship between irrigation rates and crop water use. Soil moisture extractions were taken during Jun.-Jul. 1999 on three plots (Farm Nos. 9, 10 and 11), Table 7.4. The ratio of SME

readings to ECav provides a general indication of the status of irrigation leaching. Typically soil extractions are 1.5 times greater than irrigation water EC for well irrigated soils. The readings for farms 9 and 10 are within the normal and expected range, however on farm 11 they were double. In this latter case, the higher soil salinity is most probably a function of the low irrigation rate and high soil tensions recorded for the plot, as discussed above.

Table 7.4 Summary of SME Reading (Jun-Jul 1999) - Grass Plots

Farm No	SME Reading (μScm^{-1})	ECav (μScm^{-1})	SME / ECav
9	17,300	9,310	1.85
10	4,480	2,776	1.61
11	2,900	941	3.08

Table 7.5 presents a summary of the above presented plot water balances, listing monitoring period, total irrigation depth (ID), crop water requirements (ETc), irrigation losses (IL), leaching requirements (LR) and field efficiency (EF). Irrigation depth varied between plots, due to variations in monitoring period. For the two plots with the long complete records, farms 9 and 10, total depths were 5,131 and 7,323 mm respectively. Farm 7 recorded 2,329 mm of irrigation over a 508 day period. Farm 11 recorded 1,587 mm of irrigation over an effective monitoring period of 345 days, excluding a period of 197 days when the plot water meter was non-operational (Appendix AB).

Average annual irrigation depth for the four sites with a year or more records (with the exception of farm 11, for which records were extrapolated from 345 to 365 days), ranged from less than 1,700 mm on farm 11, to more than 3,600 mm on farm 10, Table 7.4. These rates are similar to those previous reported on the Batinah (Stephens, 1993 & Al Shukairi, 1995).

A comparison of ID and ETc, Table 7.4 (Deficit/Surplus), indicates that irrigation depth was greater than crop water requirements on farms 9 and 10, and lower on farms 6, 7 and 11. This corresponds with the observed soil moisture tensions for the plots, and indicate that water stress occurred to a limited extent on farm 7 and to greater degree on

farm 11 and, possibly, farm 6.

Table 7.5 Summary of Plot Water Balances - Grass

Element	Farm No.				
	6	7	9	10	11*
Start Date (dd.mm.yy)	16.12.97	25.01.98	19.11.97	15.11.97	5.02.98
Stop Date (dd.mm.yy)	14.04.98	17.06.99	29.12.99	27.12.99	1.06.99
Period (days)	119	508	770	772	345
ID (mm)	391	2,329	5,131	7,323	1,587
Annual ID (mmy^{-1})	NA	1,765	2,479	3622	1,680
ETc (mm)	464	2,364	4,120	3,324	1,952
Deficit/Surplus (ID-ETc)	-73	-35	1,011	3,999	-365
LR (mm)	139	213	1,236	439	58
IL (mm)	9	102	1,021	3,324	
Field Efficiency (%)	>100	>100	> 100	51	>100

* Farm 11 Meter non operational between 1.06.98 - 14.12.98

The plot water balance indicates that losses occurred due to high application rates and/or high frequency irrigation. Some, or all, of these losses can contribute to the leaching of soil salts. The highest irrigation losses were recorded on farm 10, with lower levels on farm 9, 7 and 6. A comparison of IL and LR in Table 7.5, indicates IL was greater than LR only on farm 10, while on farms 6,7 and 9 IL was lower than LR. On this latter group of farms lack of leaching is likely to lead to a build up of soil salinity and ultimately to the deterioration of crop productivity.

The field efficiency, (i.e. ratio of water demand (ETc and LR) to ID) of the five grass plots varied from 50 to more than 100%, Table 7.5. Efficiency levels of more than 100% were recorded on the three under-irrigated plots of farms 6,7, 9 and 11. On farm 10 efficiency was 50%.

Efficiency levels in excess of 100% tend to indicate under-irrigation, that is insufficient irrigation to meet crop and leaching requirements. Based on the soil moisture tension records, this appear to have been the case on farm 11 with long period of high tension Figure 7.21. It is also supported by the comparison of the plot water balance, Table 7.5, with deficit of 365 mm over the monitored period.

The soil moisture and water balance records tend to indicate a moderate amount of under-irrigation occurred on farm 7. However the plot balance is biased by the decline in soil water levels at the end of the monitored period as the crop was abandoned.

Farm 9 appears to have had a genuinely high level of field efficiency, with low soil moisture tensions and a water surplus (1,011 mm) close to LR (1,236) mm). This is further supported by the analysis of irrigation frequency and rates (Section 7.3.3.2), indicating good scheduling practices were followed on the farm.

The relatively low level of efficiency, 50%, on farm 10 appears to be consistent with soil moisture tension, with tensions of less than 20 cb recorded for more than 6 months.

7.3.2.2. Irrigation Frequency and Rates

The analysis of individual irrigation events provides a useful assessment of the frequency of irrigation, and variability of irrigation management. This information was available for the four plots on which dataloggers were installed (Farms 6, 7, 9 and 10).

Figure 7.22 presents the distribution of irrigation rate (mm per application) for the four plots. It illustrates the high frequency of low irrigation rates on farms 6 and 7, with 70% of applications of 10 millimetres or less. Farm 9 had the most consistent irrigation rate with 90% of applications within the range of 20-40 mm, while on farm 10 there was a wide range of rates with some in excess of 80 mm .

The high frequency of low application rates and the wide range of rates, both indicate that there is potential to improve irrigation efficiency through better scheduling of irrigation, to attain consistent irrigation depth. Ideally for soils within the area, the irrigation depth should be 30 - 40 mm. Low application rates are likely to increase evaporative losses, while high application rates will increase percolation losses, both of which reduce system efficiency.

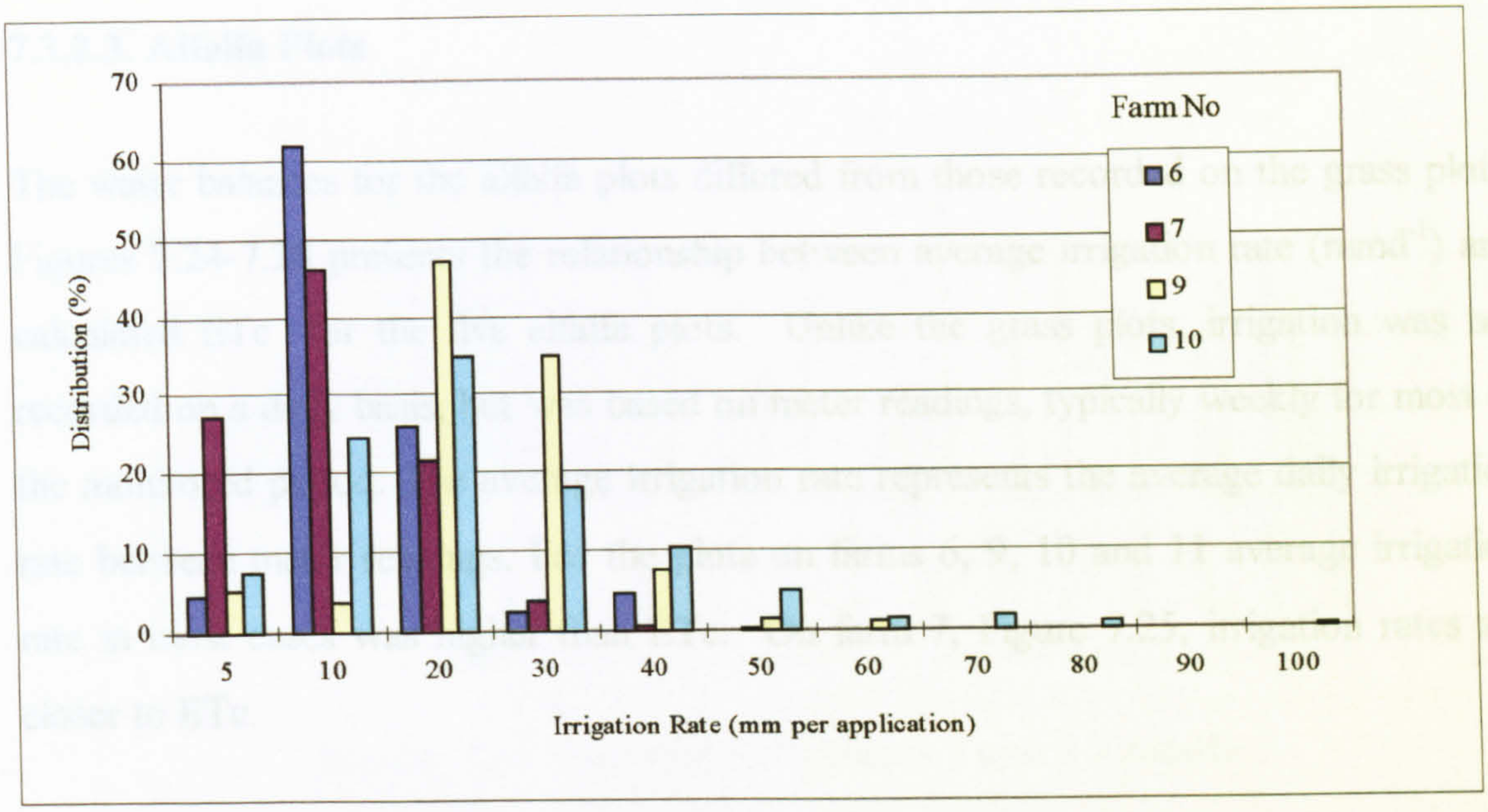

Figure 7.22 Distribution of Irrigation Rate (Farm Nos. 6,7,9 and 10)

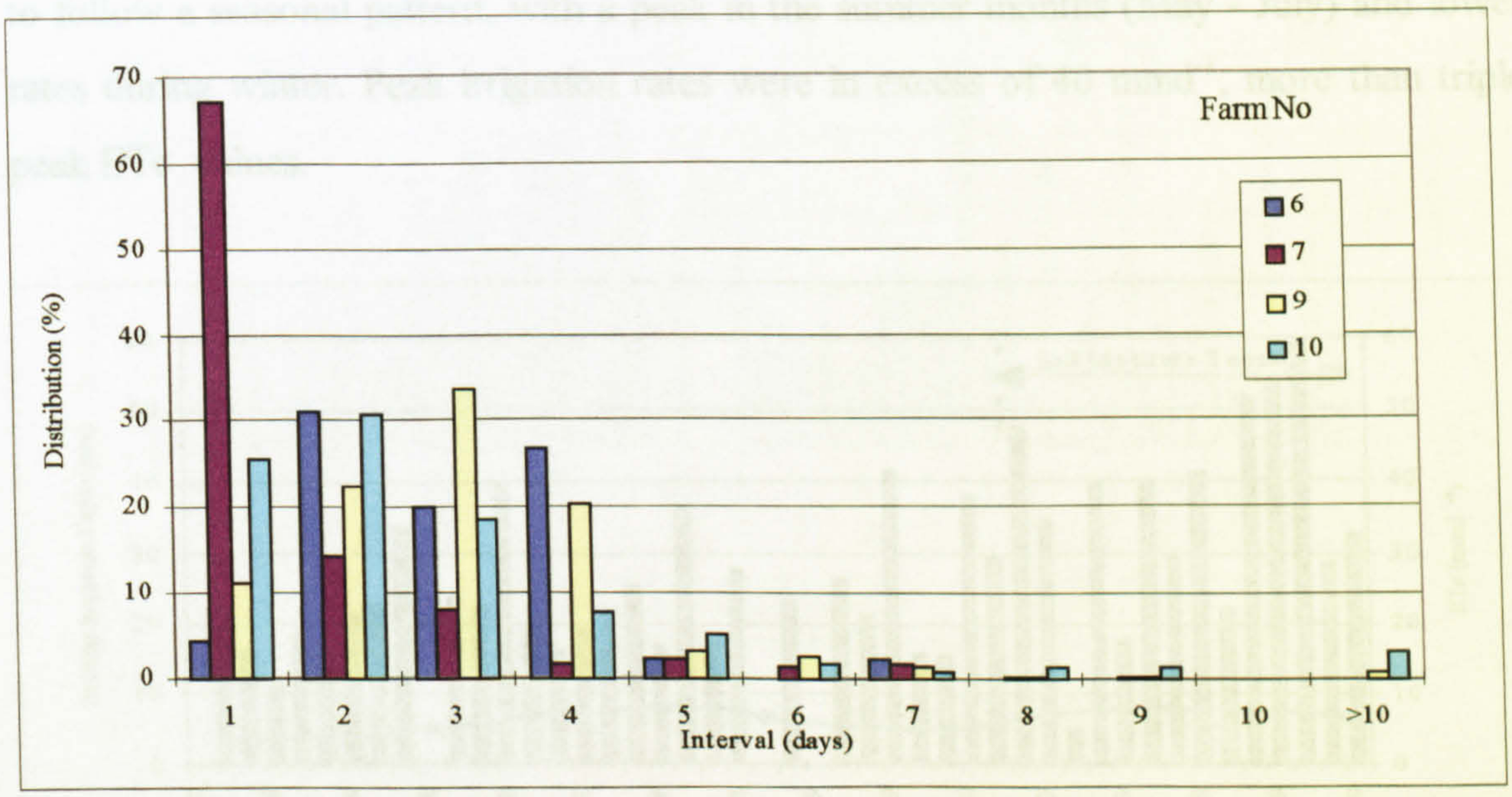

Figure 7.23 Distribution of Irrigation Interval (Farm Nos. 6,7,9 and 10)

Figure 7.23 presents the frequency of irrigation intervals, that is interval (day) between irrigations for the four above-mentioned grass plots. It illustrates wide variations within, and between, plots. Nearly 70% of intervals on farm 7 were daily, while on farm 6 they mostly ranged from 2 to 4 days. The short interval combined with low irrigation rates, Figure 7.22, on both farms would reduce overall irrigation efficiency.

7.3.2.3. Alfalfa Plots

The water balances for the alfalfa plots differed from those recorded on the grass plots. Figures 7.24-7.28 presents the relationship between average irrigation rate (mmd^{-1}) and calculated ETc for the five alfalfa plots. Unlike the grass plots, irrigation was not recorded on a daily basis, but was based on meter readings, typically weekly for most of the monitored period. The average irrigation rate represents the average daily irrigation rate between meter readings. For the plots on farms 6, 9, 10 and 11 average irrigation rate in most cases was higher than ETc. On farm 7, Figure 7.25, irrigation rates are closer to ETc.

While there are wide variations between average irrigation rates, on all plots, they appear to follow a seasonal pattern, with a peak in the summer months (May - July) and lower rates during winter. Peak irrigation rates were in excess of 40 mmd^{-1}, more than triple peak ETc values.

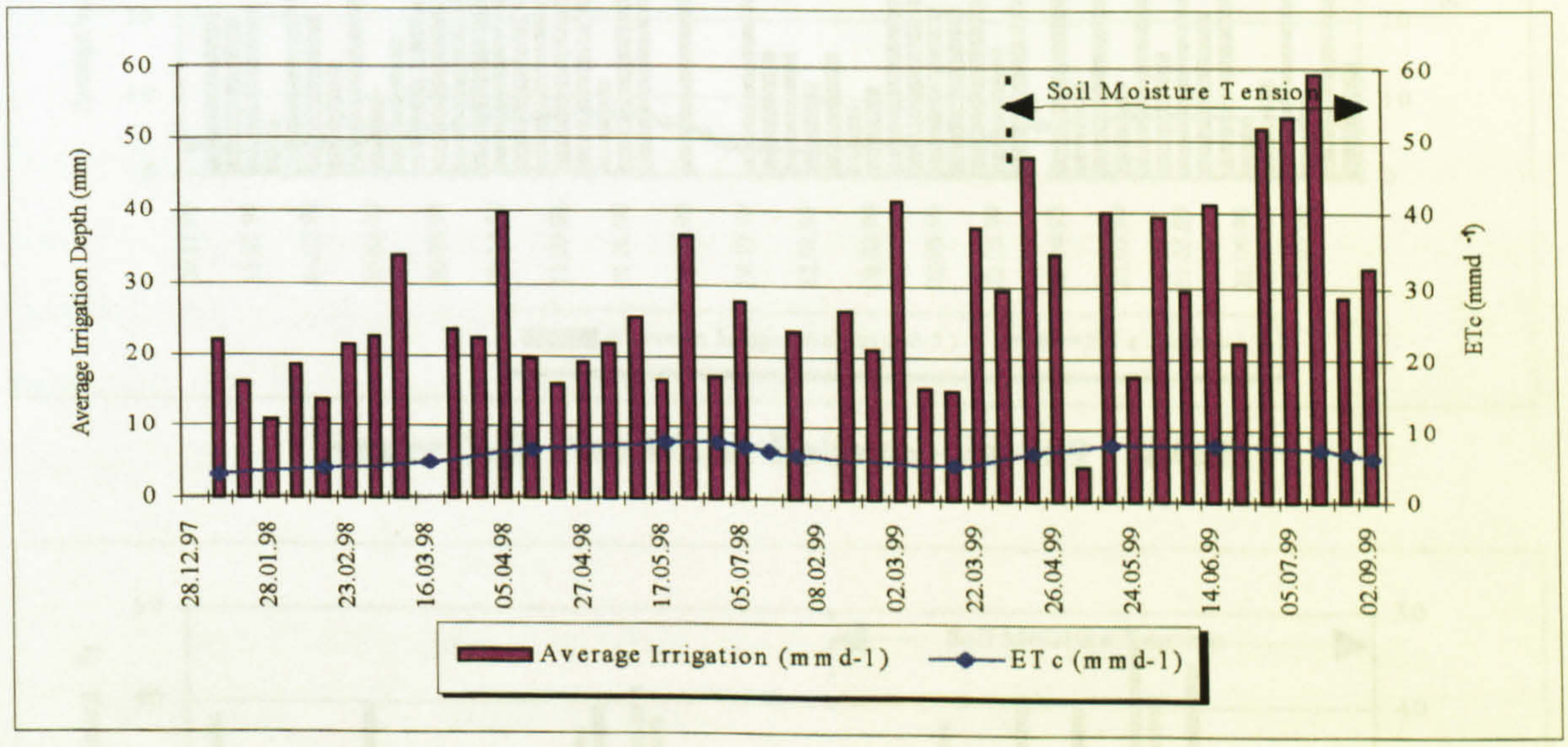

Figure 7.24 Plot Water Balance - Farm 6 - Alfalfa

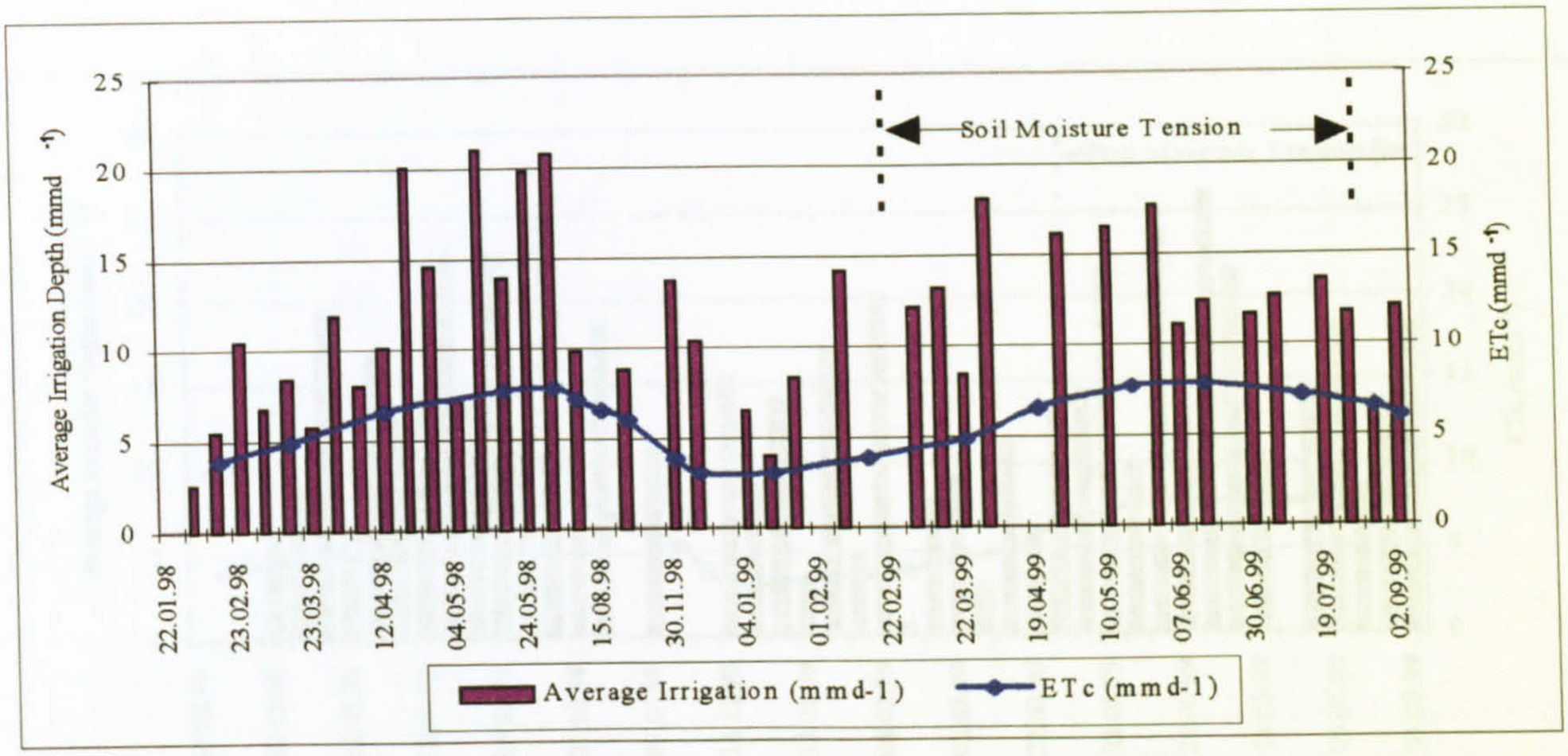

Figure 7.25 Plot Water Balance - Farm 7 - Alfalfa

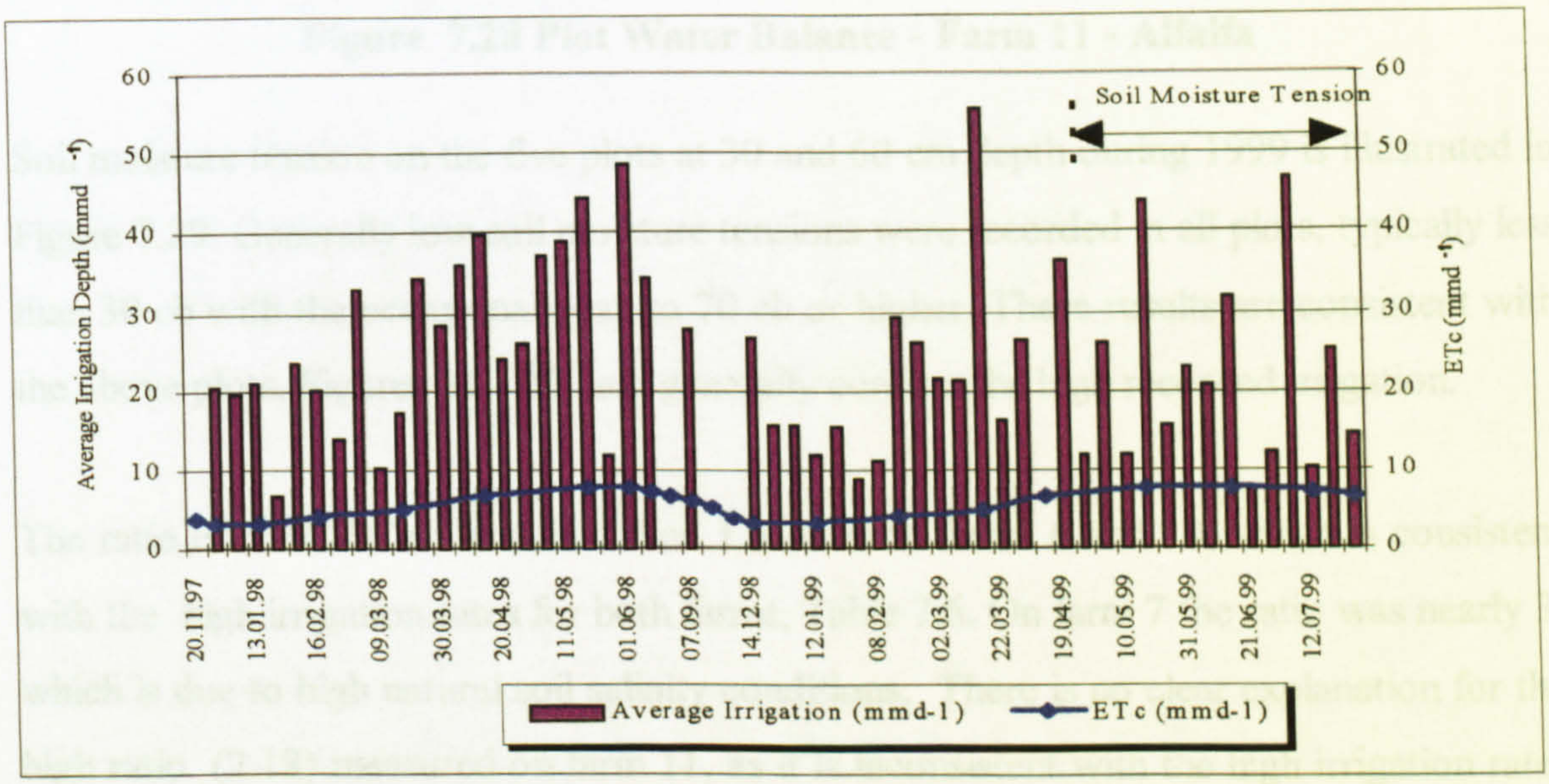

Figure 7.26 Plot Water Balance - Farm 9 - Alfalfa

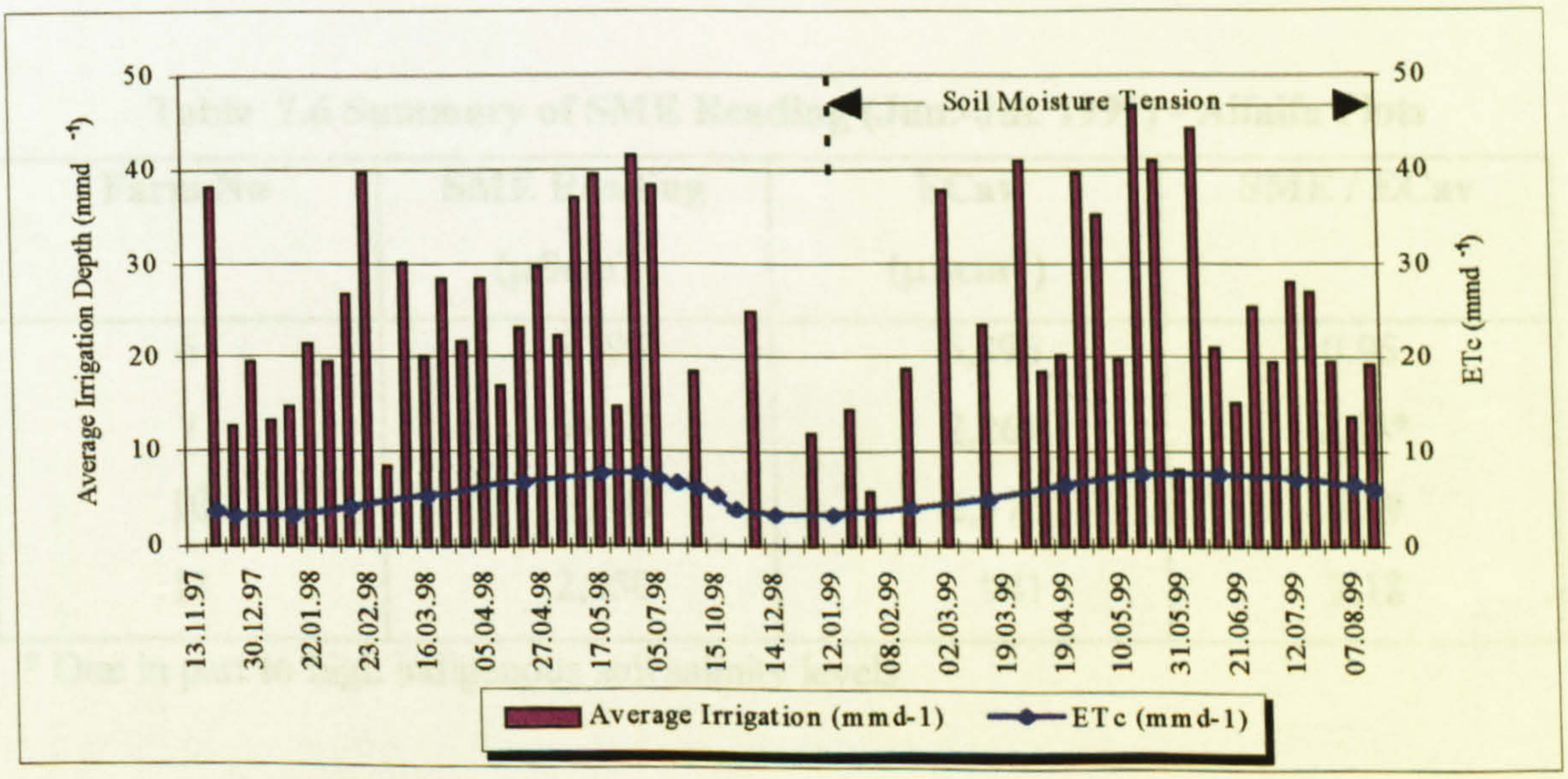

Figure 7.27 Plot Water Balance - Farm 10 - Alfalfa

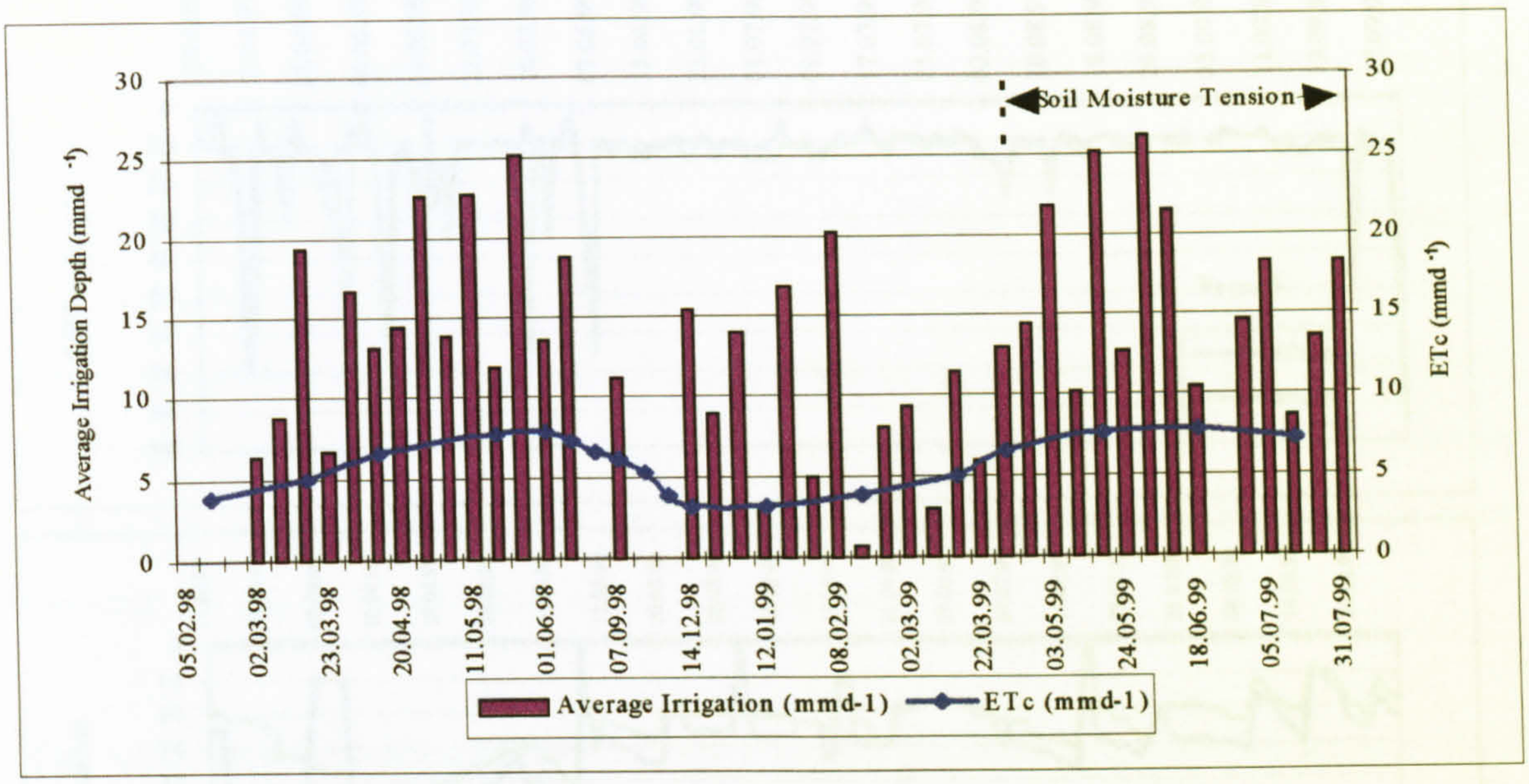

Figure 7.28 Plot Water Balance - Farm 11 - Alfalfa

Soil moisture tension on the five plots at 30 and 60 cm depth during 1999 is illustrated in Figure 7.29. Generally low soil moisture tensions were recorded in all plots, typically less than 30 cb with the occasional peak to 70 cb or higher. These results are consistent with the above plots, Figures 24 - 28, and generally confirm the high recorded irrigation.

The ratio of SME/ECav was less than 1.5 on both farms 6 and 10, which is consistent with the high irrigation rates for both farms, Table 7.6. On farm 7 the ratio was nearly 3, which is due to high natural soil salinity conditions. There is no clear explanation for the high ratio (2.18) measured on farm 11, as it is inconsistent with the high irrigation rates and low EC of irrigation water.

Table 7.6 Summary of SME Reading (Jun.-Jul. 1999) - Alfalfa Plots

Farm No	SME Reading (μScm^{-1})	ECav (μScm^{-1})	SME / ECav
6	6,593	6,896	0.95
7	6,450	2,264	2.84*
10	2,200	2,776	0.79
11	2,050	941	2.18

* Due in part to high indigenous soil salinity levels

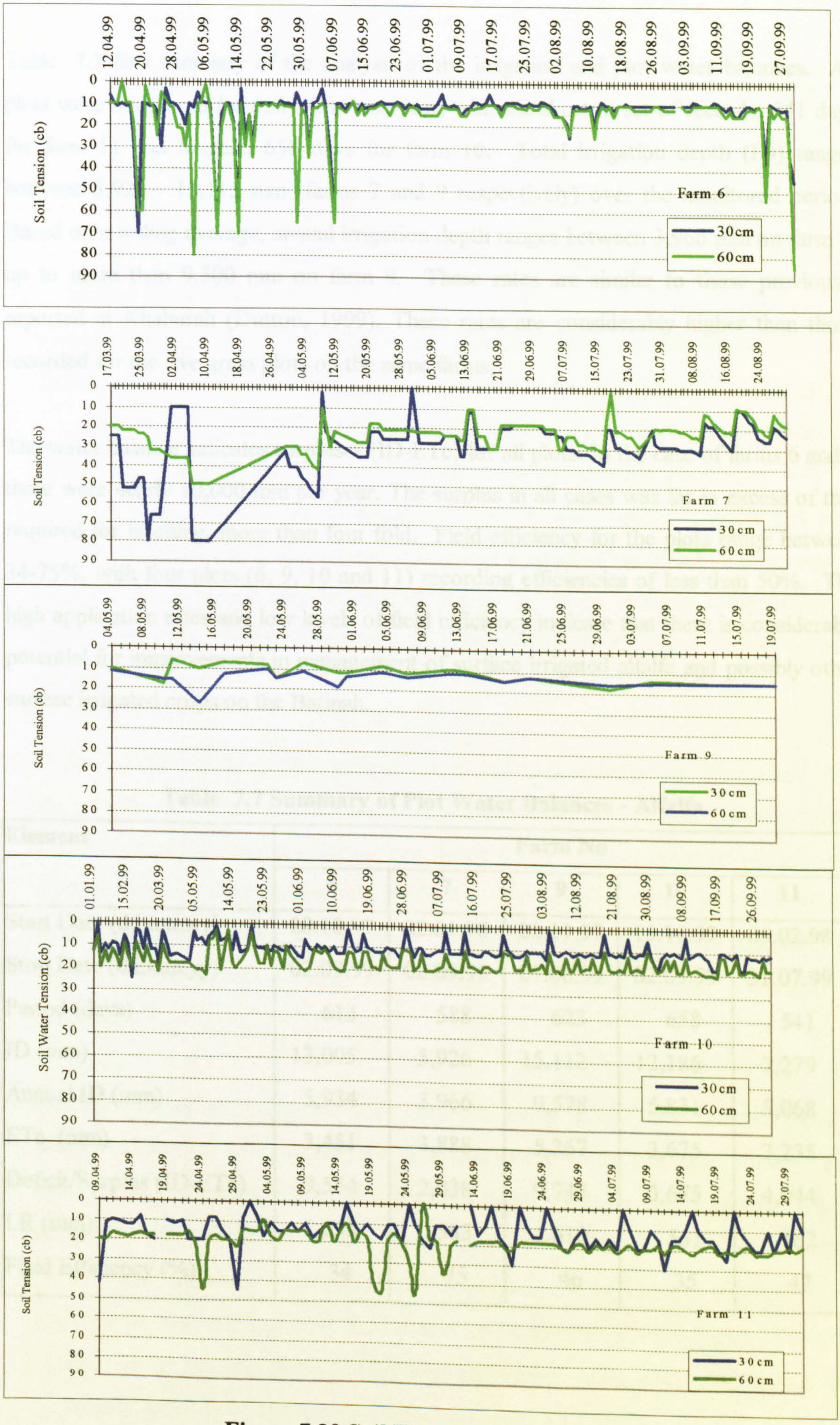

Figure 7.29 Soil Tension on Alfalfa Plots

Table 7.7 lists summary of the analysis of the irrigation and plot water balances. All plots were monitored for more than one year, with the shortest set of records, 541 days for farm 11 and longest, 658 days for farm 10. Total irrigation depth (ID) ranges between 5,926 - 15,115 mm (farms 7 and 9 respectively) over the monitored period. Based on a rolling average, annual irrigation depth ranges between 3,966 mm on farm 7, up to more than 9,500 mm on farm 9. These rates are similar to those previously reported at Khaburah (Dutton, 1999). These rates are considerably higher than those recorded for the five grass plots on the same farms.

The water balance indicates surpluses (ID-ETc) for all plots. In the case of farms 6 and 9 these were nearly 10,000 mm per year. The surplus in all cases was far in excess of that required for leaching, more than four fold. Field efficiency for the plots range between 34-75%, with four plots (6, 9, 10 and 11) recording efficiencies of less than 50%. The high application rates and low levels of field efficiency indicate that there is considerable potential for improvements in management of surface irrigated alfalfa and possibly other surface irrigated crops on the Batinah.

Table 7.7 Summary of Plot Water Balances - Alfalfa

Element	Farm No				
	6	7	9	10	11
Start Date (dd.mm.yy)	28.12.97	22.01.98	22.11.97	13.11.97	05.02.98
Stop Date (dd.mm.yy)	02.09.99	02.09.99	07.08.99	02.09.99	31.07.99
Period (days)	613	588	623	658	541
ID (mm)	13,005	5,926	15,112	12,186	7,279
Annual ID (mm)	5,934	3,966	9,578	5,831	5,068
ETc (mm)	3,451	3,888	5,367	3,675	3,235
Deficit/Surplus (ID-ETc)	9,554	2,038	9,745	3,675	4,044
LR (mm)	1,035	583	1,610	551	162
Field Efficiency (%)	34	75	46	35	47

7.3.3. Conclusions

Section 7.3 confirms that current irrigation management practices on some farms within the study area are inefficient and can be improved. Such improvement in irrigation management if adopted would contribute to reducing water demand within the catchments and to attaining sustainable water use. This conclusion is also supported by the results of the evaluation of sprinkler and bubbler coefficient of uniformity in Chapter Six. Specific conclusions are:

- **Sprinkler Irrigation;** the plot water balance results indicate that there was considerable variability in irrigation rates between farms. Equivalent annual irrigation rates range from 1,700-3,600 mm. While the results are similar to those previously reported on the Batinah, they confirm that for some systems the current level of irrigation management could be improved. They indicate that both under and over irrigation is occurring. Under-irrigation could be a result of limitation of water supply on some farms, which may be exacerbated by increased leaching requirements as water quality deteriorates. It may also be related to the limitation of current on-farm management practices.

- **Irrigation Scheduling;** the analysis of irrigation scheduling for four grass plots shows wide variations in irrigation rates and frequency within, and between, farms. This variability indicates that for the case study farms, at least, irrigation management practices are less than optimum. In particular, high frequency (daily) low application rates will increase evaporative losses. These findings highlight the potential for improved management through the adoption of more systematic scheduling of irrigation.

- **Surface irrigation;** irrigation rates ranged between 3,500-9,500 mm per year, or two to three times those for the sprinkler irrigated grass on the some farms. These rates are well in excess of crop and leaching requirement for alfalfa on the southern Batinah. Field efficiencies for the plots were 34-75%, and less than 50% for four plots. While the results are consistent with previous studies (Dutton, 1999), they also highlight the need for improved management of surface irrigation systems. Part of the explanation for the low levels of efficiency may be associated with *gelba* design, high permeable soils and on-farm irrigation management.

7.4. MANAGEMENT EVALUATION

The objective of this section is to evaluate the relationship between reductions in abstraction due to saline intrusion and the potential effectiveness of options for sustainable water management in Wadis Taww and Ma'awil. This section utilizes the findings of Section 7.2 which confirmed the spatial and temporal relationships between reductions in abstraction and water quality. It uses a calibrated groundwater flow model, of a representative 'slice' of the catchments to evaluate and compare, the status quo that is the 'non-intervention' case, and demand and supply management interventions. It also presents a zero abstraction option, though an unrealistic management option, this provides a reference point for comparison of the non-intervention and intervention options.

7.4.1. Barka Profile Model

The Barka Profile Model was utilised to evaluate the impact of changes in water abstraction and demand management on saline intrusion and groundwater depletion. The model was developed in 1994-95 by Mr. Richard Lakey (Lakey, 1996). It is a groundwater flow model based on MODFLOW 3D flow model software, calibrated for the central Wadi Ma'awil catchment.

The Barka Profile Model is the most accurate tool currently available to predict the future impact of changes in water abstraction within the study area as well as the impact of potential management actions. It is based on a comprehensive study of the hydrogeological features of the southern Batinah, utilizing information and data from drilling programmes and geophysical logging. The model is located to provide a representative slice of the hydrogeological and agricultural characteristics of the area, as well as to take best advantage of data from drilling and well monitoring records. It is based on cells of 1,250 metre squares, transecting the Wadi Ma'awil catchment, from the sea to the upper catchment. It is three layers deep, according to the primary hydrostatigraphic units, these are:

- Layer 1 Sub Recent and Recent alluvium; unconfined
- Layer 2 Ancient alluvium; semi confined
- Layer 3 Various bedrock units; ranging from unconfined to confined

A cross section of the layers is shown in Figure 7.30.

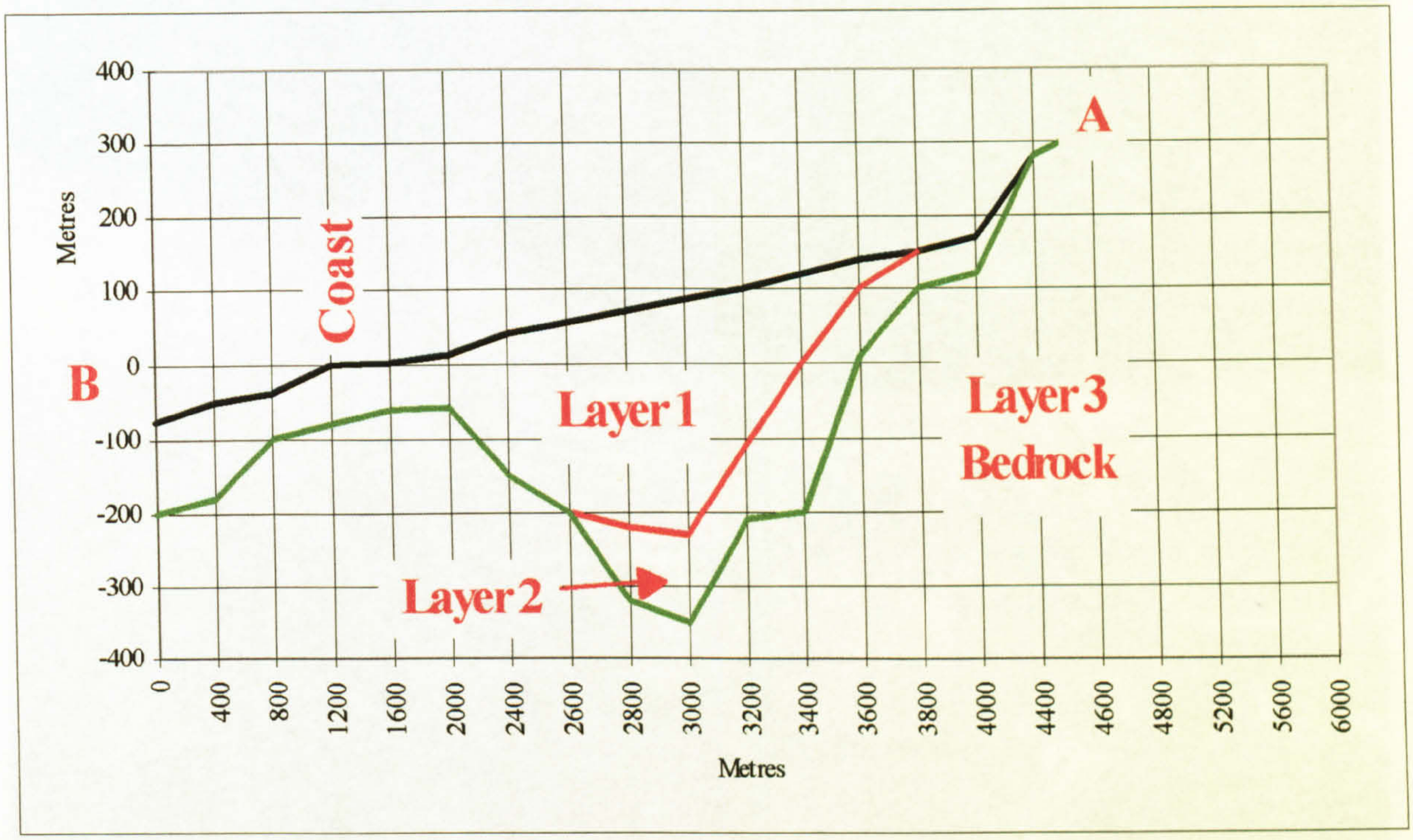

Figure 7.30 Cross Section of Barka Profile Model

The model incorporates water flow and storage characteristics for the three layers, based on well lithology and pumping tests results. It also integrates data on water demand from the NWIP for all the farms located within each cell. Water demand is based on the combined net water demand within the cell abstracted at a node at the centre of the cell.

The model 'slice' is located approximately in the centre of Wadi Ma'awil, Figure 7.31, and runs inland, perpendicular to the coast across the alluvial plain, and into the mountainous upper catchment.

The model was calibrated using the historical records of groundwater levels of eight monitoring wells located within the slice. Four of these wells JT-72, BM-1, RE-4 and RE-3; Figure 7.31, are selected to present the response and trends (under different conditions) in groundwater levels. The analysis of water inflows, outflows and storage depletion is based on the central cell and guard cell either side. Appendix AE provides details of the model parameters, calibration process and sensitivity analysis.

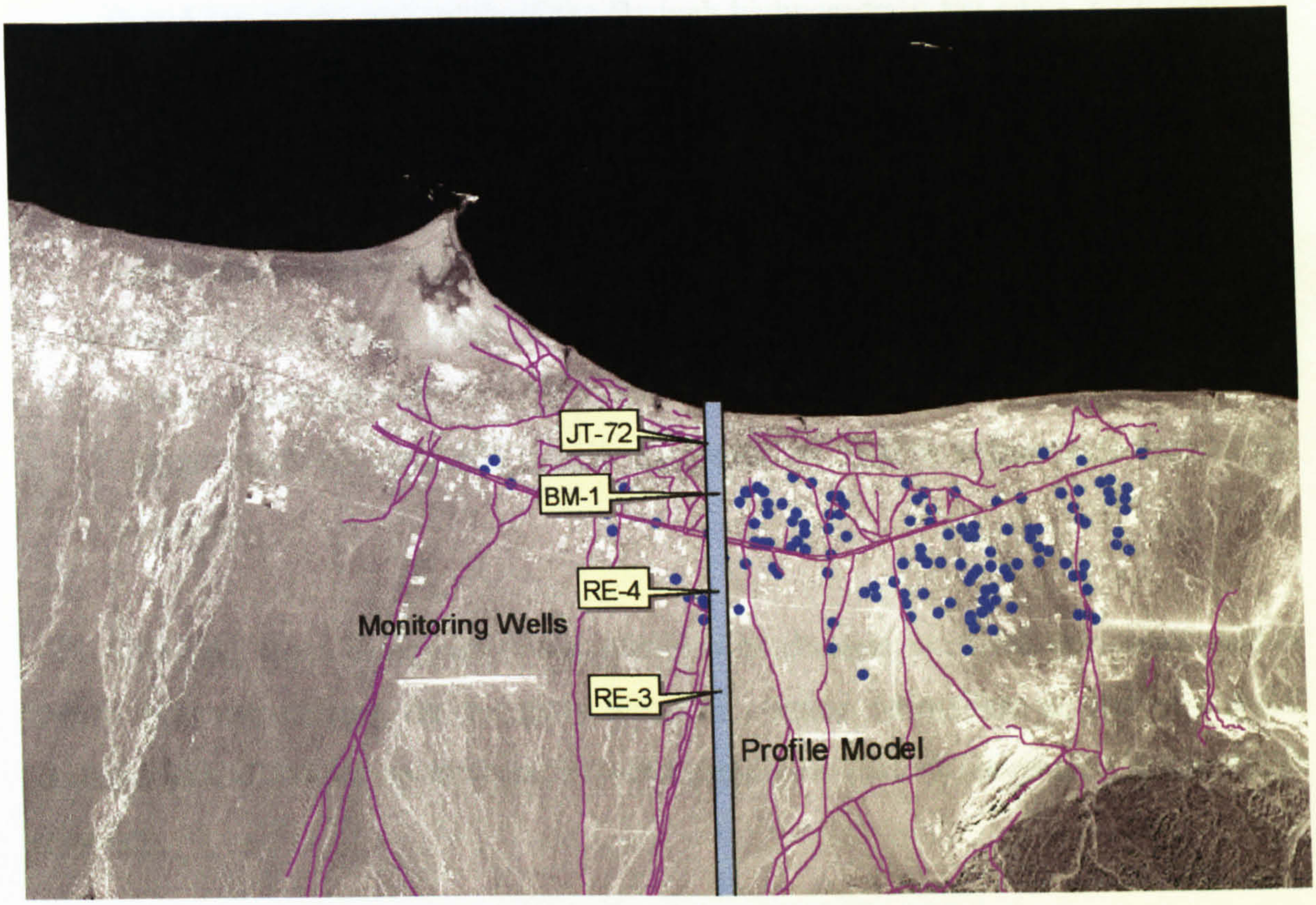

Figure 7.31 Barka Profile Model

7.4.2. Abstraction Options Investigated

The calibrated model provides a tool for the prediction of future trends in groundwater levels within each cell for the evaluation of trends in groundwater levels, saline intrusion and aquifer storage depletion.

The model was used to investigate five scenarios; the non-intervention case, and two demand management, one supply management and zero abstraction options as listed below. The two demand management scenarios were also evaluated at two commencement dates (2000 and 2008).

The scenarios investigated were:

a) Non Intervention (Non-Int.): the impact of current trends in abstraction reductions (Section 7.7.2).

b) Demand Management: an enforced 30% reduction in abstraction on farms more than 4 km inland and south of the Batinah highway from the years 2000 (DM30-2000) and 2008 (DM30-2008) respectively.

c) Demand Management: an enforced 50% reduction in abstraction on farms more than 4 km inland and south of the Batinah highway from the years 2000 (DM50-2000) and 2008 (DM50-2008) onwards.

d) Zero Abstraction (Zero-2008): a total reduction in abstraction from the year onwards. Though this is not likely to be an acceptable or feasible management option it provides a bench mark for comparison with other options.

e) Supply Management (SM-2008): the transfer of treated waste water from the Muscat Municipal area, for the irrigation of tree and fodder crops, as per current Omani standards (MRME, 1993) for reuse of treated wastewater from 2008 onwards.

The following subsections outline the selection of changes in abstraction rates, due to either observed changes on the study farms or nominal reductions as part of demand management strategies or increase in water supply as part of the supply management strategy.

7.4.2.1. Non-Intervention (Non-Int)

The non-intervention case is based on the observed spatial trends in abstraction for the study farms (Section 7.2). For application of these in the Profile Model, annual abstraction records were evaluated based on the model cell dimension (1250 m) and location of rows 12-19, that is for a section from the coast to 10.5 km inland. This evaluation included abstraction records for all farms for the period 1996-99, as reported in Chapters Six and Seven, as well as more recently, processed records for the 1999-00 year (Appendix H). The additional year of data further supports observed spatial trends in abstraction (Section 7.2).

Table 7.8 presents a summary of the analysis of abstraction rates for the study farms based on the Profile Model cell locations (col. A) and distance from the coast (col. B). Total abstraction declined by more than 35% over the period 1996-99, with annual rate nearly 12%. The total and annual rates of decline, decreased with distance from the sea.

Table 7.8 Changes in Abstraction Rate vs. Distance from Sea

Model Rows (A)	Distance (km) (B)	% Change Abstraction		Abstraction (m^3ha^{-1})
		1996-99	Annual Average	
12-14	< 2.8	-35.5	-11.8	11,695
15	2.8 - 4.1	-35.3	-11.8	23,559
16	4.1 - 5.3	-15.3	-5.1	22,417
17	5.3 - 6.1	-13.1	-4.4	20,249
18	6.1 - 7.8	-4.8	-1.6	18,957
19	7.8 - 9.3	6.1	2.0	19,174

The observed trends and spatial distribution of changes in abstraction rates form the basis for analysis of the non-intervention case (Section 7.2). This is based on the assumption that the study farms provide a representative sample of the spatial distribution of farms on the lower catchment as a whole, and, therefore, are indicative of general trends within the area. This assumption is based on the scatter distribution of study farms, and confined nature of the aquifer from which water is being abstracted.

The analysis also makes several assumptions about future trends in abstraction. The first of these relates to farms located within 4 km of the sea; as indicated above, abstraction rates are declining by around 12% a year. This decline, as shown in Section 7.2, is due to the impact of increasing water salinity, with a resultant decline in cropped area. There are no indications from this study, or the longer term groundwater monitoring programmes (MWR, 1999a), that water quality will improve in the foreseeable future, therefore abstraction will continue to decline as further crops are abandoned.

The second assumption is regarding the group of farms furthermost inland (row 19), more than 8 km, where a small increase in abstraction is occurring. It is assumed that abstraction will increase to the year 2008, with an accumulative increase over 1996-09 of approximately 20%, after which abstraction is assumed to remain constant. The rise in abstraction on these farms is possibly attributable to the later development of these farms. Abstraction increased as tree crops matured and cultivated areas expanded. However, without development of new farms an upper limit of demand must ultimately be reached, which is assumed for this study to be 2008.

Table 7.9 lists the rates of change in abstraction per row of the profile model. As discussed above for the non-intervention case (col. A), in rows 12-15 abstraction declined by 12% per year, with a 5% decrease in rows 16 and 17, no change in row 18 and an increase of 2% in row 19.

In the case of the demand and supply management options (col. B, C and E), the rate of change in abstraction is the same as the non-intervention case, with a 12% per annum decline in rows 12-15. The rate of decline in abstraction in rows 16-19 varies between the options, dependent on the level of intervention. In the case of supply management, abstraction ceases, with the use of treated wastewater for irrigation. For the zero abstraction case, abstraction ceases totally in all rows.

Table 7.9 Profile Model Abstraction Changes (%)

Row	Distance (km) (*)	No-Int. (A)	DM 30 (1) (B)	DM-50 (2) (C)	Zero-2008 (D)	SM-2008 (3) (E)
12	0.30	-12%	-12%	-12%	-100%	-12%
13	1.55	-12%	-12%	-12%	-100%	-12%
14	2.80	-12%	-12%	-12%	-100%	-12%
15	4.05	-12%	-12%	-12%	-100%	-12%
16	5.30	-5%	-30%	-50%	-100%	-100%
17	6.55	-5%	-30%	-50%	-100%	-100%
18	7.80	0%	-30%	-50%	-100%	-100%
19	9.30	2%	-30%	-50%	-100%	-100%

(*) Distance to inland side of row
(1) Demand management options DM30-2000 and DM30-2008
(2) Demand management options DM50-2000 and DM50-2008
(3) Supply management replacement of abstraction with alternative treated wastewater supply on farms within rows 16-19

7.4.2.2. Demand Management Options (DM30-2000, DM30-2008, DM50-2000 & DM50-2008)

For the analysis of the demand management options the following criteria and assumptions were adopted:

- Demand management was implemented from two alternative commencement dates that is 2000 and 2008 onwards (listed as suffix to the option acronym). The year 2008 is assumed to be a feasible start date for such actions as there a number of pre-

requisite conditions to be met. It is also based on the lack of progress during the 1990s, and the likely lead-time for institutional development and implementation of a comprehensive programme. However the date of 2000 was also evaluated to determine the relative benefits earlier intervention.

- Actions would be specifically targeted at farms more than four kilometres inland (rows 16-19 (col. B & C, Table 7.9). The rationale being that based on current trends, most of the near coast farms (less than four km) are in an advanced stage of degradation and will be abandoned as farming units within the near future.
- Demand actions would be single 30% and 50% reductions in abstraction in the targeted group of farms in years 2000 and 2008 (DM30-2000, DM30-2008, DM50-2000 and DM50-2008 respectively). This may be an oversimplification of the process, however for comparative purposes, a more protracted implementation of actions is unlikely to produce significantly better results.
- The rates of reduction of 30% and 50% are selected as nominal rates of reduction which in principle could be implemented through either a single mechanism, such as water quotas, or combination of mechanisms such improved irrigation management, change from perennial tree crops to seasonal cropping and retirement of farms from production. These nominal rates by comparison with the non-intervention provide an indication of the likely scale of reduction required to reduce the future impact of saline intrusion.

7.4.2.3. Zero Abstraction (Zero-2008)

The zero abstraction case is not regarded as a legitimate demand management option, but is used as a reference for comparison of the non-intervention and other options, demand and supply. It is based on the complete cessation of abstraction from the end 2008 onwards (col. D, Table 7.9) in all rows (12-19).

7.4.2.4. Supply Management (SM-2008)

While the primary objective of the study related to demand management, one supply management option was evaluated, that is the reuse of treated wastewater. As mentioned in Chapter 4 (Section 4.4.2.1), a wastewater treatment scheme is currently proposed for

the Greater Muscat area to the south. The scheme may ultimately produce a large volume of water suitable for reuse, possible on the southern Batinah. This water will be treated (tertiary treatment) to the Omani standard for reuse of effluent water (MRME 1993), and will be suitable for irrigation of tree and fodder crops, including grass and alfalfa.

For the purposes of the analysis in the model, it is assumed that this water is supplied directly to the farm gate, as a substitute for well water. Direct reuse was selected over the use of recharge wells, as the water will be of a suitable quality and this would be a more efficient use of the resource. The analysis is based on the reuse on farms within rows 16-19. The model included an allowance for an on-farm recharge rate for leaching and percolation losses. The earliest that this supply could be available is from 2008 onwards, therefore this has been assumed as the commencement date for the option.

7.4.3. Model Results

This section presents the results of the model in three ways, the first as changes in water levels for the four representative monitoring wells (JT-72, BM-1, RE-4 and RE-3), Figures 7.32 to 7.35. The second as changes in daily flow rates (m^3d^{-1}) for water use, saline intrusion and groundwater depletion, Figures 7.36 to 7.38. The flow rates (m^3d^{-1}) are the total flow volume for the profile cells for rows 12-19, this unit is used for comparison of changes with time and between the four options. Note that for saline intrusion, Figure 7.37, positive values indicate inflow to the aquifer and negative values outflows. While for groundwater storage, Figure 7.38, negative values indicate depletion and positive values recharge. The third set of results lists the rate and extent of saline intrusion by 2041, Table 7.10.

The model time period is from 1977 to 2041, with the period 1977-96 being the calibrated and 1997-2041 the predicted periods respectively. Appendix AF lists the model results for monitoring well water levels and rates of water use, saline intrusion and groundwater depletion.

a) Non-Int:

- Water levels progressively recover from 1996 onwards, and in the wells nearer the coast (JT-72 and BM-1) will be back to mid 1970s levels by 2041, Figures 7.32 and 7.33. Water levels further inland recover more slowly, and reach about a third of their 1970s level by 2041 (RE-4 and RE-3), Figures 7.34 and 7.35.
- Rates of water use, Figure 7.36, decline from a peak of nearly 35,000 m^3d^{-1} to less than 30% of this (10,000 m^3d^{-1}) by 2041. This magnitude of change is similar the imbalance between recharge and water use (50 and 123 Mm^3y^{-1} respectively) for the catchments as a whole and suggests that the 10,000 m^3d^{-1} rate is possibly close to the sustainable level of abstraction.
- Saline intrusion rates decrease from a peak of more than 10,000 m^3d^{-1}, Figure 7.37, to less than 4,000 m^3d^{-1} in 2041. While this is a large decline, even by this stage, it is still higher than 1977 levels.
- Depletion of groundwater storage declines rapidly, and ceases soon after 2008, thereafter there is a relatively small recharge component.

b) DM30-2000:

- For the two wells nearer the coast (JT-72 and BM-1) water levels initially recover at a faster rate than non-intervention, but the rate of recovery has slowed by 2041, Figures 7.32 and 7.33. Water levels are lower than Non-Int. by 2041, due to the slower rate of decline in water use in DM30-2000, Figure 7.36.
- The water level response at the two inland wells (RE-4 and RE-3), has higher initial rate of recovery, compared to non-intervention, but ultimately reaching a similar level by 2041, Figures 7.34 and 7.35.
- At intervention in 2000, water use drops from 25,000 to 18,000 m^3d^{-1}, and stabilises to around 14,000 m^3d^{-1} by 2025, and thereafter remains relatively constant.
- The rate of saline intrusion declines from over 10,000 m^3d^{-1} in 2000 to less than 6,000 m^3d^{-1} in 2025, and to nearly 5,000 m^3d^{-1} by 2041.
- At initiation the intervention will reduce groundwater storage depletion from over 5,000 m^3d^{-1} to less than 500 m^3d^{-1}.

c) DM30-2008:

- For the near coast wells (JT-72 and BM-1) water level recovery is similar to Non-Int, Figures 7.32 and 7.33. For wells RE-4 and RE-3, Figures 7.34 and 7.35 water levels recover by 4-5 metres by 2041, however they will still be more than six metres below 1977 levels.
- Water use initially declines to below Non-Int levels with the application of the action in 2008, Figure 7.36, but are similar (10,000 m^3d^{-1}) to Non-Int by 2041, indicating no long-term water saving benefit.
- The rate of saline intrusion initially declines faster than Non-Int, but is the same by 2041, Figure 7.37.
- Depletion of groundwater stops as soon as the action is implemented in 2008, with a recovery of about 4,000 m^3d^{-1}, Figure 7.38.

d) DM50-2000:

- Water levels initially recover in near coast wells (JT-72 and BM-1), Figures 7.32 and 7.33, more rapidly than Non-Int., but by 2041 are only 0.5 m higher. They are also similar to the final water levels attained in the DM50-2008 case.
- Water levels in the inland wells (RE-4 and RE-3) follow a similar trend, Figures 7.34 and 7.35 with a final level in 2041 comparable with the DM50-2008 case.
- Water use declines from over 10,000 m^3d^{-1} in 2008, to approximately 8,000 m^3d^{-1} by 2041, Figure 7.36.
- Saline intrusion decreases by 50% from 6,000 m^3d^{-1} in 2008 to approximately 3,000 m^3d^{-1} in 2041, Figure 7.37.
- The intervention results in an initial recovery of groundwater storage of more than 5,000 m^3d^{-1} which progressively declines to less than 1,000 m^3d^{-1} by 2041, Figure 7.38.

e) DM50-2008:

- Water levels recover markedly in all wells and are back to 1977 levels in JT-72 and BM-1 by 2030, Figures 7.32 and 7.33, while on RE-4 and RE-3 they recover to about half 1977 levels by 2041, Figures 7.34 and 7.35.
- Water use declines from 10,000 m^3d^{-1} in 2008 to approximately 8,000 m^3d^{-1} by 2041, Figure 7.36

- The rate of saline intrusion declines faster than Non-Int and DM30-2000 and DM30-2008, and is reduced to 1977 levels by 2033, Figure 7.37.
- The response for groundwater storage is similar to DM30-20008, with depletion stopping in 2008, thereafter recharge occurs, Figure 7.38.

f) SM-2008:

- As the only supply management options, SM-2008 produces markedly different responses to the non-intervention and demand management options.
- Water levels make a rapid recovery in all four wells. In the near coast wells (JT-72 and BM-1), Figures 7.32 and 7.33, water levels are back to 1977 levels by 2015, and in the inland wells (RE-4 and RE-3) by 2025. In all wells they are 1- 2 metres above 1977 levels by 2041.
- Groundwater use, that is pumping from wells virtual ceases (apart from the few coast wells still operation by 2008), as treated wastewater is the principal water source for irrigation, Figure 7.36.
- The rate of saline intrusion declines rapidly, from more than 8,000 m^3d^{-1} in 2008 to less than 500 m^3d^{-1} in 2025, and with groundwater discharge from 2033 onwards, Figure 7.37.
- The rate of groundwater storage recovery is initially nearly 20,000 m^3d^{-1} in 2008, as leaching and percolation losses recharge the aquifer and decline to less than 4,000 m^3d^{-1} by 2041, Figure 7.38.

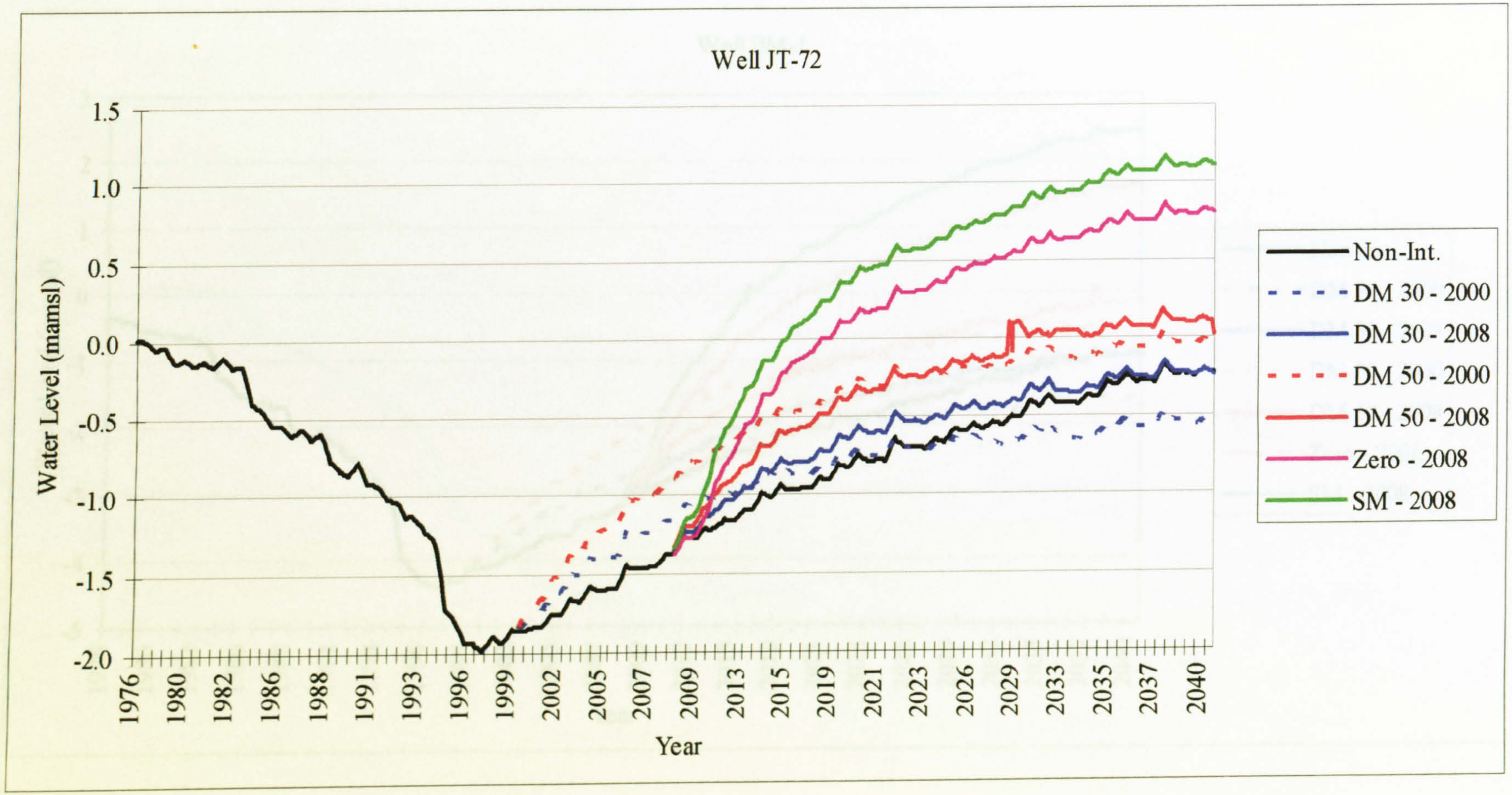

Figure 7.32 Monitoring Well JT-72

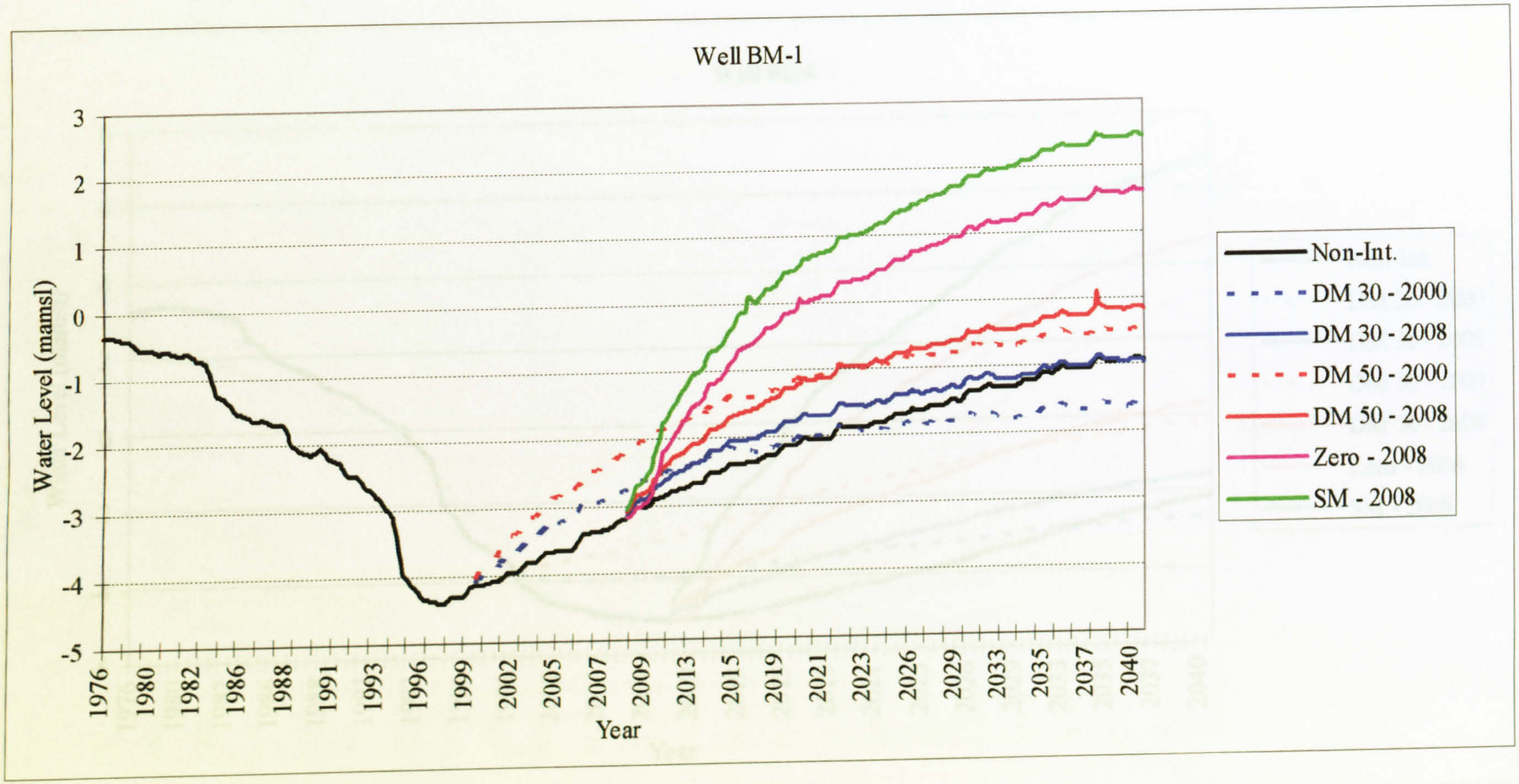

Figure 7.33 Monitoring Well BM-1

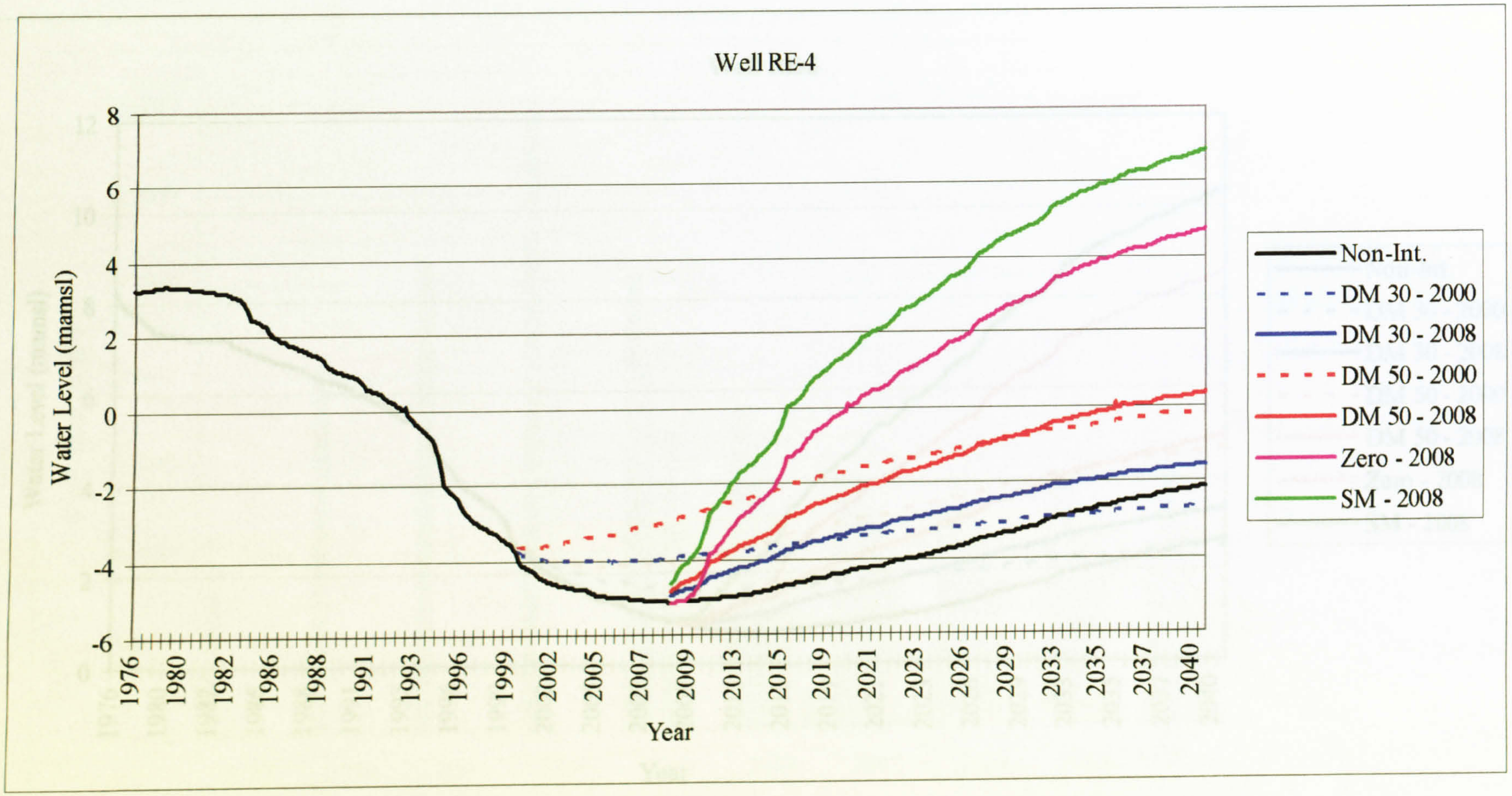

Figure 7.34 Monitoring Well RE-4

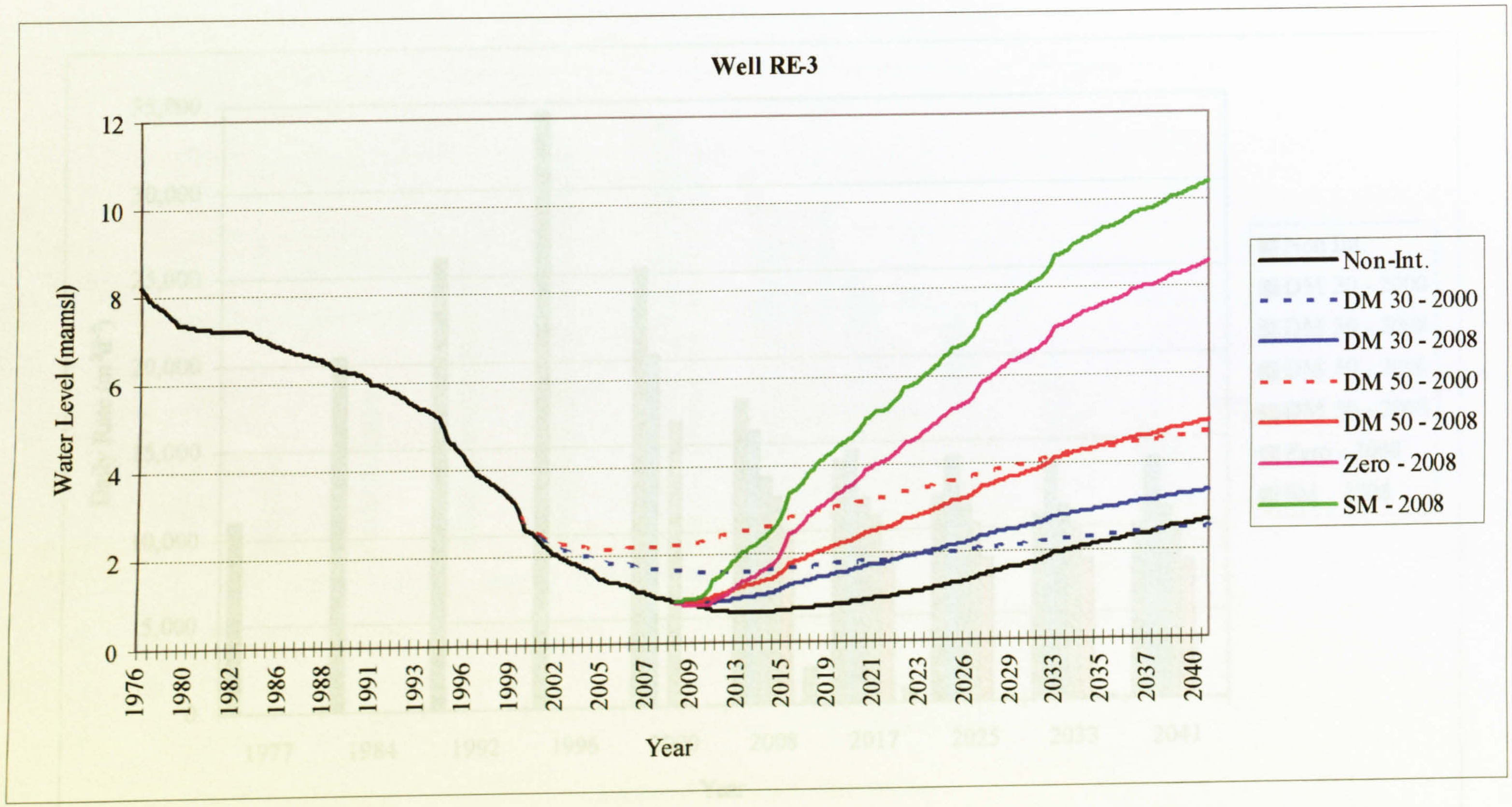

Figure 7.35 Monitoring Well RE-3

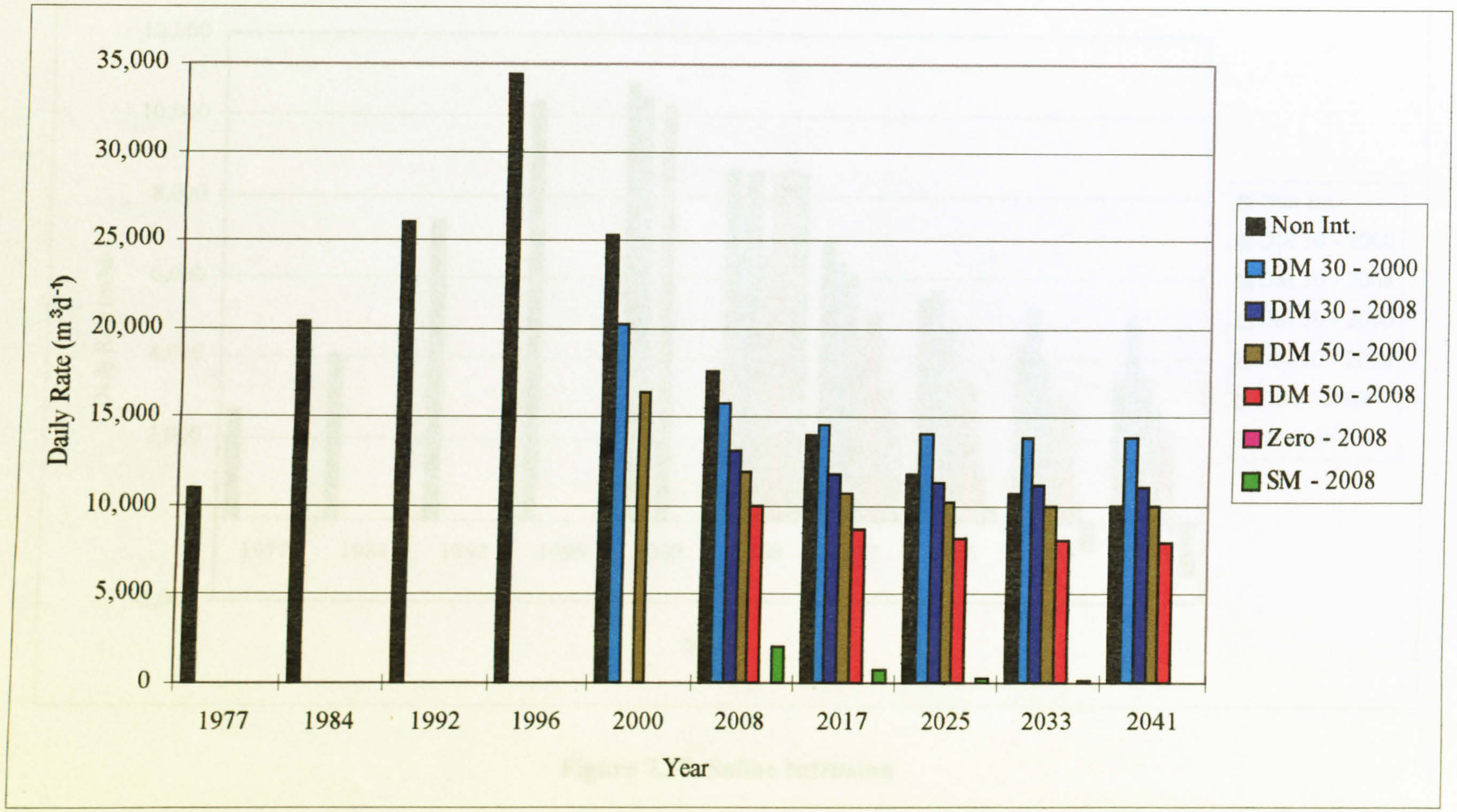

Figure 7.36 Water Use from Wells

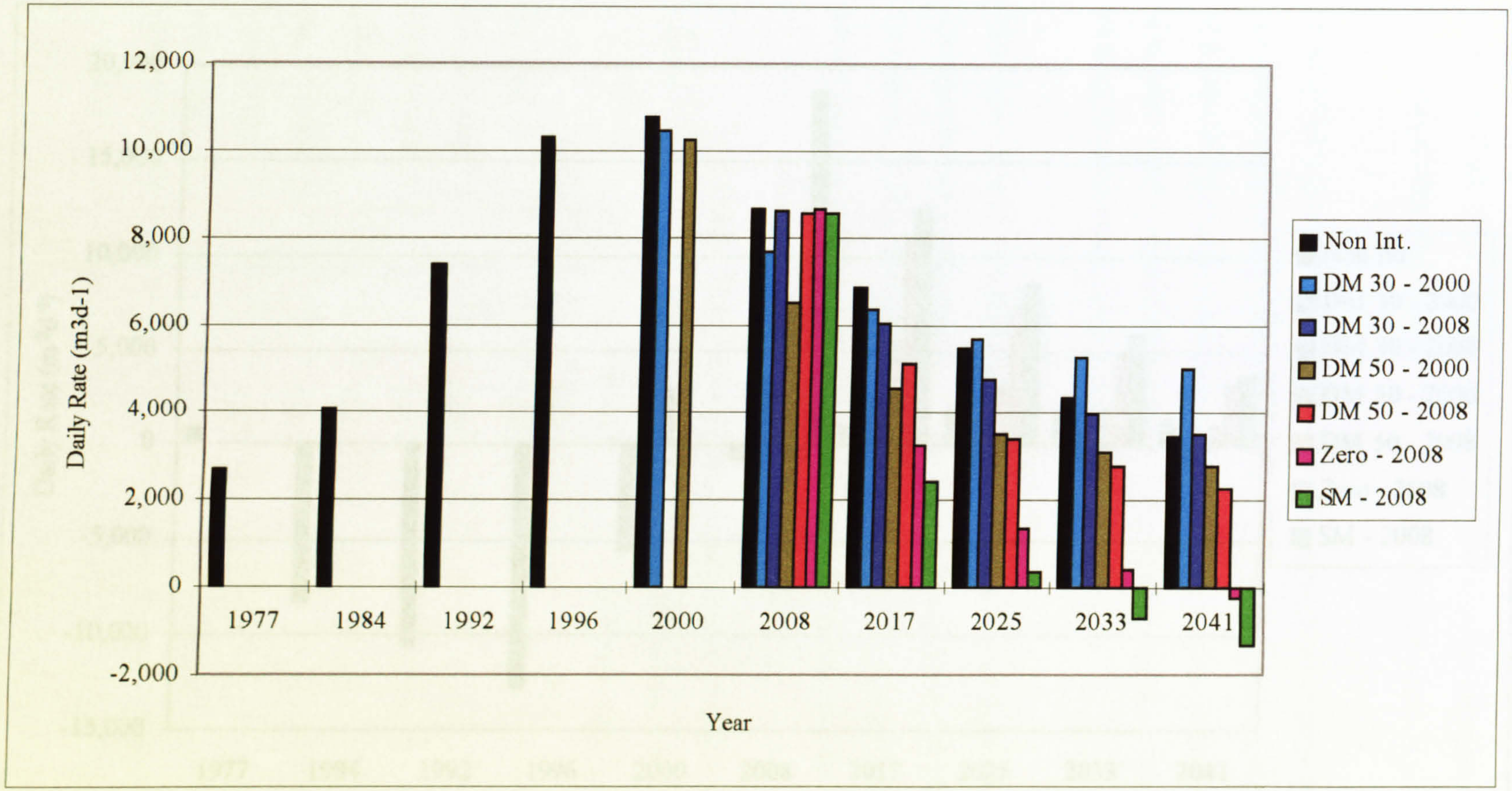

Figure 7.37 Saline Intrusion

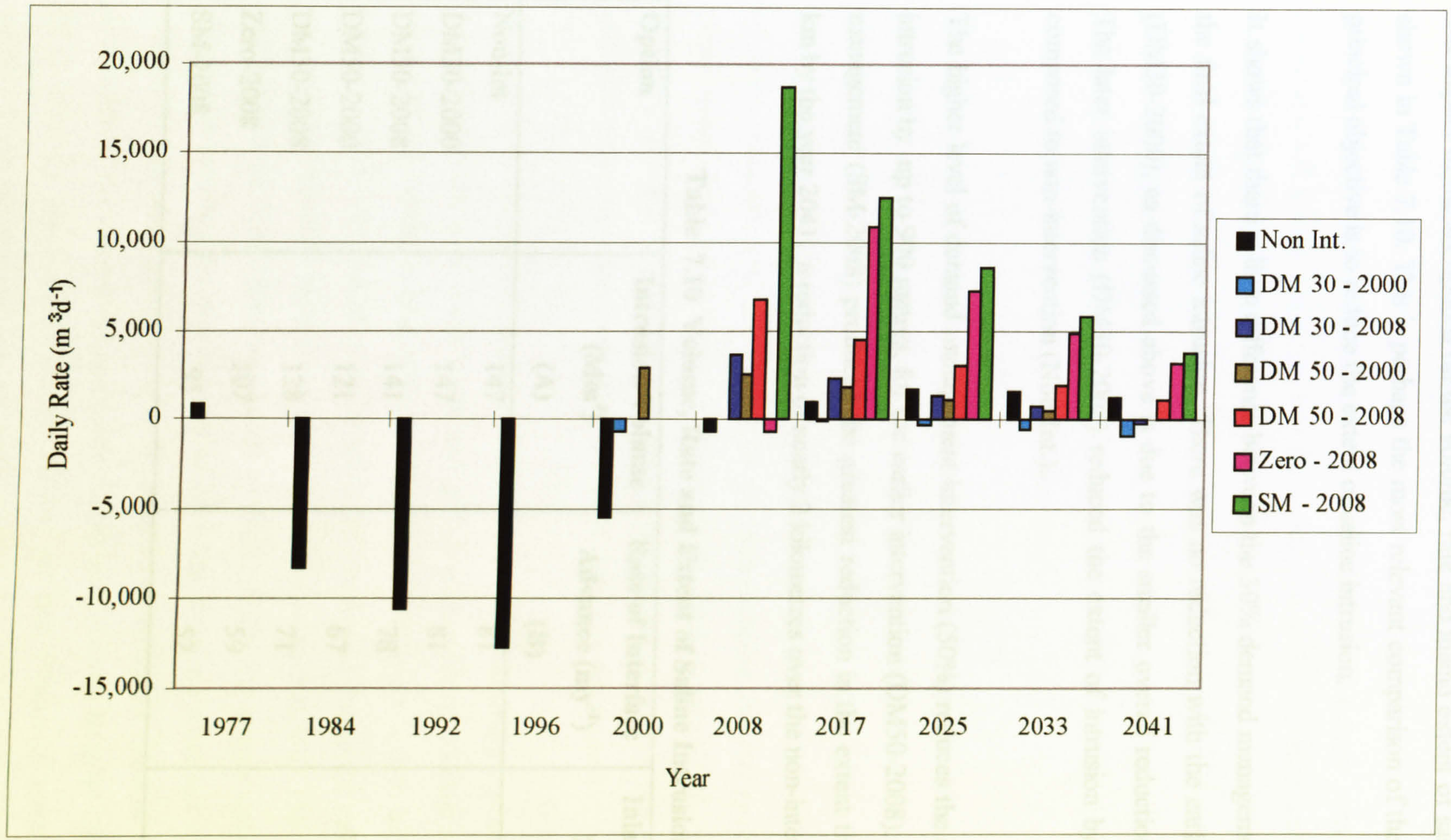

Figure 7.38 Groundwater Storage

7.4.3.1. Extent of Saline Intrusion

The impact of the six options on the volume, rate and inland extent of saline intrusion is shown in Table 7.10. This is perhaps the most relevant comparison of the options as the principal objective is to reduce the extent of saline intrusion.

It shows that there is little difference between the 30% demand management options and the final extent of saline intrusion. There was no reduction with the earlier intervention (DM30-2000), as discussed above is due to the smaller overall reduction in water use. The later intervention (DM30-2008) reduced the extent of intrusion by less than 300 compared to non-intervention (Non-Int.).

The higher level of demand management intervention (50%) reduces the extent of saline intrusion by up to 900 metres, for the earlier intervention (DM50-2008). But the supply management (SM-2008) produced the greatest reduction in the extent the front at 4.40 km by the year 2041, a reduction of nearly 2 kilometres over the non-intervention case.

Table 7.10 Volume, Rate and Extent of Saline Intrusion

Option	Intrusion Volume (Mm^3) (A)	Rate of Interface Advance (my^{-1}) (B)	Inland Extent by 2041 (km) (C)
Non-Int	147	81	6.24
DM30-2000	147	81	6.24
DM30-2008	141	78	6.03
DM50-2000	121	67	5.34
DM50-2008	128	71	5.56
Zero-2008	107	59	4.82
SM-2008	95	52	4.40

7.4.4. Conclusion

The above analysis shows the impact of non-intervention and the relative benefits of demand and supply management options within the study area.

As illustrated by the non-intervention case the impact of current trends in declining abstraction will lead to a recovery in water levels and decline in saline intrusion rates and reduction in groundwater depletion. In this case saline intrusion in itself is in effect acting as an ad hoc demand management mechanism. Water demand is effectively being reduced through the destruction of farms nearer the coast. As indicated by the model results this process is predicted to continue for another 30-40 years, and will culminate with the saline front more than 6 kilometres inland.

The analysis of the demand management options indicates that the higher levels of intervention will produce greater benefits in terms of water level recovery and reductions in saline intrusion. However, the final results are not much greater than the non-intervention case by the year 2041, due to the continued degradation of farms as a result of saline intrusion, and the impact of the accumulative (in the period 1976-2000) groundwater depletion. Earlier intervention in 2000 compared to 2008, does not ultimately produce greater benefits, this is primarily due to the impact of declining abstraction over the interventing years (2000 to 2008) on water use.

By contrast the supply management of reuse of treated wastewater produces the greatest benefits in recovery of water levels and groundwater storage. Groundwater levels are predicted to recovery to mid 1970s levels within 10-20 years, and to be up to 2 metres higher by 2041. The rate of saline intrusion will be slowed due to the reduction in water use and the positive recharge from irrigation and percolation. The saline front is predicted to be 4.40 kilometres inland at 2041. While the supply option is the most effective in reducing the impact of saline intrusion, there are a number of questions that need to be addressed before it would be feasible, including the financial costs and social acceptability. Provisional estimates indicate the unit cost will be more than 0.200 RO/m^3 ($US 0.52/$m^3$), ten times the current returns per unit volume of water, therefore any supply scheme will require high levels of subsidy.

CHAPTER EIGHT
DISCUSSION AND CONCLUSIONS

8.1. INTRODUCTION

This chapter discusses the implications for the findings for the future of water resource management on the south Batinah and presents the conclusions of the study. It concludes with a list of recommendations for improvements in water management and for future studies.

8.2. DISCUSSION

The study findings are relevant to water resource management, both on the South Batinah and within the broader context of the arid zone as discussed below.

8.2.1. South Batinah

The Batinah region is the principal agricultural area of Oman. The presence of suitable soils and groundwater, along with agricultural development policies over the period 1970-90, led to a rapid expansion of irrigated land. This development has resulted in the expansion of water demand beyond the renewable resources of the region, leading to depletion of groundwater and saline intrusion. Though the catchments of the southern Batinah have been the most severely affected to date, intrusion is also occurring, to a lesser extent, in catchments of northern Batinah (MWR, 1999). In the early 1990s, in recognition of the threat to farming by saline intrusion and the need to limit demand for water, restrictions were established on the allocation of new lands and construction of new wells. Though these restrictions may have limited the expansion of demand, monitoring of groundwater indicates that depletion of groundwater and saline intrusion has continued through the 1990s.

Water balance studies of the southern Batinah indicate that the catchments of Wadis Taww and Ma'awil are severely over-developed. Water demand in the mid-1990s was estimated to be more than double the annual freshwater recharge. Over pumping of the aquifer for more than 20 years, apart from the problem of saline intrusion has resulted in depletion of water storage, with the resultant and progressive decline in aquifer water levels. As indicated in Chapter Four water levels within 10 km of the coast were below

sea level by 1994, and have continued to decline. This, in essence, has provided the hydraulic gradient for continued saline intrusion.

One of the objectives of this study was to investigate the relationship between saline intrusion and water demand and the impact of this relationship on regulation of water demand. The study confirmed that within the catchments of Wadis Taww and Ma'awil there is a spatial relationship between water demand and saline intrusion. It was demonstrated that while overall abstraction is declining as water quality deteriorates, the rate of decline is highest near the coast, and decreases further inland. However, there was also a small increase in abstraction on the group of farms furthest inland.

Field observations and comparison of aerial photographs for 1989 and 1999 indicate that there has been very limited expansion of new farms within the catchments during the 1990s. This possibly confirms the effectiveness of the above mentioned restrictions on development of new land and construction of wells. The increase in abstraction on the group of farms furthest inland is probably due to crop maturity and to additional on-farm (existing) development.

The results of the Barka profile model indicate that under all demand management scenarios, including the 'zero' abstraction option, saline intrusion will continue for at least another 30-40 years. This is due to accumulative loss of groundwater storage over the past 30 years, so that even if pumping could be totally stopped, an unrealistic scenario, it would take a considerable time for groundwater levels to recover. Over this period the saline front will have advanced at least 5 km inland from the coast.

The current rate of saline intrusion and trends in abstraction indicate that there would be few water saving benefits from targeting demand management actions on farms within 5 km of the coast. Based on current trends many of these farms will be abandoned as farming units before such actions could be implemented. On those remaining farms water quality would have deteriorated to such an extent that there will be few if any viable options for water saving.

The evaluation of demand management on farms more than 5 km inland, indicates that current levels of abstraction would have to be reduced by more than 50% to have a noticeable impact on saline intrusion. Such high levels of reduction, are unlikely to be

achieved alone through improvements in irrigation management, crop changes, or relocation of grass farms, and will have to be accompanied by severe limits on abstraction. Given the scale of reduction and the fact that these measures would apply to farms with relative good quality water, they are unlikely to readily acceptable to the farm owners.

The water model analysis indicates that the scale of water depletion within the catchments of Wadi Taww and Ma'awil, is so great, that there are unlikely to be any acceptable demand management actions that can be implemented to save a significant area of farm land. As discussed above, the current problem is the result of accumulative over pumping over a 30 year period. Based on the 'non-intervention' scenario, saline intrusion will continue for at least another 30 years, albeit at a declining rate, as demand in near coast areas progressively declines. The conclusion of this process will be the loss, for agricultural purposes, of land and water resources within 5-6 km of the coast. This will impact not only on the farming community, but also on coastal villages, with the need for alternative water supplies. At present this is largely being catered for with tankered water from up-catchment and in the near future with the development of the Barka desalination unit.

For these catchments the only option for controlling saline intrusion would be the import of substantial quantities of water. The catchments are adjacent to the Greater Municipal Area, and there may be potential to import treated wastewater from the city either for direct use or recharge. The study evaluated the impact of the import and reuse of treated wastewater for irrigation of farms south of the Batinah highway. It showed that water levels would recover to mid 1970s levels within 10 to 20 years, and that the extent of saline intrusion was less than the non-intervention case. While this is the best technical solution to the problems being encountered on the southern Batinah, there are number of financial and social issues to be fully addressed before this could be considered a viable option.

The impact of saline intrusion within Wadis Taww and Ma'awil, demonstrates the need to implement demand management actions, earlier rather later. While the problems was identified and has been monitored since the early 1980s, the actions to prevent it worsening were insufficient. This study shows the process is continuing, however, there are few options, short of large scale water import that could provide a solution. This

area should serve as an example to water resource managers of the need to identify the problem in the early stage and to implement effective actions.

8.2.2. Irrigation Management

While the irrigation management component of the study was limited to a small number of 'sample' and 'case' study farms it nevertheless provided an indication of current irrigation management efficiency on the Batinah.

Since the 1980s sprinkler irrigation has been adopted on the Batinah and elsewhere in Oman. The adoption of this method was part of the expanison of farming, in particular the shift from the traditional fodder crop, alfalfa, to Rhodes grass. Grass was well suited to overhead irrigation, and sprinklers provided a relatively low cost method with low labour requirements. Several MAF programmes promoted sprinklers including the "Goat Development Project" in the 1980s (Stephens, 1993) and the "Modern Irrigation Programme" (MAF, 1992) in the early 1990s.

The results of this study show that there is considerable variation between the uniformity and efficiency of sprinklers between plots and farms. Part of this variability is due to uniformity of application, which is a functions of a number of factors such sprinkler make, operating pressure, sprinkler maintenance and wind. On approximately 20% of plots uniformity was substantially below levels which would enable efficient irrigation.

The detailed study of five grass plots indicated that there are consideration variations in irrigation management between farms. Annual irrigation rates varied between 1,700 - 3,600 mmy^{-1}, which is similar to rates reported by Stephens (1993). On several plots irrigation rates were inadequate for optimum crop growth leading to high soil moisture tensions. While on two plots rates were well in excess of crop water requirements. Rates and scheduling varied widely within and between plots. The variability of gross application and scheduling tends to indicate the inconsistency and ad hoc nature of current irrigation management. It also highlights the potential water saving and crop benefits from improved management of sprinklers. The adoption of irrigation scheduling based on a systematic methodology of irrigation depth per cycle, such as those published by the Khaburah Action Research Centre (Foster, 1988) would be good

starting point.

The study of uniformity of bubbler irrigation on tree crops also indicated considerable variation between plots and farms. No published information is currently available on the use of bubblers in Oman to compare with the study results. The recommended CU for selection of bubblers for irrigation design purposes is typically 0.9. While the field measurement indicated a number of plots were 0.9 or higher, there were also a large number of plots below this level. Like sprinklers, there are a number of possible explanations for the lower than anticipated CU, such as low operating pressure, high headloss (resulting in wide variations in operating pressure and therefore discharge between bubblers) and poor maintenance (such as clogging of internal strainers and build up of precipitates). In Oman bubblers are the principal emitter type used for tree crops, including dates, on the MAF modern irrigation systems (MAF, 1992). The results of this study highlight the need for further research to evaluate the performance of bubblers under field conditions to better assess their efficiency, and operation and maintenance requirements.

The results of the evaluation of surface irrigation (using *gelba*) of alfalfa indicated that irrigation rates were substantially higher than calculated crop water requirements. Annual application rates for the plots were within the range of 3,500 to 8,000 mmy^{-1}. These are similar rates previously reported at the Khaburah Action Research Centre in the 1980s (Dutton, 1999). The high rates of application appear to be a function of the design and operation of *gelba,* and local soil conditions. It would appear, from observations on the study farms, that high rates of water application are required to compensate for high soil permeability, to ensure complete water coverage. It may also be a function of the more labour intensive nature of surface irrigation (compared to sprinklers) with high rates intended to compensate for a low frequency of application. Again the results indicate that there still room for improvement of surface irrigation methods and management on the Batinah. This may include optimisation of *gelba* size to match soil conditions and discharge rates, and improvements in water scheduling.

8.2.3. Water Resource Management

The problems of saline intrusion on the South Batinah of Oman are symptomatic of the water management challenges facing the arid zone. Rising demand is putting increasing pressure on limited groundwater resources. While supply options have generally been adopted to meet increasing demand for the domestic and industrial sectors, with the development of desalination and use of non renewable resources, this is not always an economically or environmentally acceptable option for the agricultural sector.

The South Batinah example demonstrates the potential long-term dangers of prolonged over development of groundwater resources. The catchments of Wadis Taww and Ma'awil have effectively been closed for the past 20 or so years. Water use in the lower catchment has progressively depleted groundwater storage, creating the gradient for saline intrusion. While the problem was recognised in the early stages, it has proven difficult to identify and implement effective solutions. In this example the problem may ultimately be self correcting, but this is a long term and less than optimum solution. Apart from the environment cost to the lower catchment, there are economic and social costs, such as the loss of private and public sector investment in farm and infrastructure development. For the coastal communities there is loss of drinking water supplies, and cost of more expensive replacements, and social impact of a less desirable natural habitat.

While demand management is often cited as the preferred option to achieve sustainable water demand in the agricultural sector, experience in the Middle East tends to prove it is difficult to implement. With one or two exceptions (Israel being one) few countries in the region have implemented effective demand management programmes. While sustainable water resource management may be enshrined in national water management policy, the reality for most countries in the region is unsustainable agricultural demand (Mena, 1999).

8.3. CONCLUSIONS

The programme investigated three principal objectives related to saline intrusion and agricultural water management within the catchments of Wadis Taww and Ma'awil in the Batinah region of northern Oman. The study area within these catchments was the zone of intensive agriculture located on the lower coastal plain, within 10 km of the sea. A sample of 138 farms was selected within the area to investigate the relationships between water quality, and groundwater abstraction, and irrigation management. The results of these investigations were applied to a groundwater profile model to evaluate the impact of current trends in abstraction and management options. The preceding chapters, five, six and seven, presented the research methods, results and analysis. Based on this work, the following subsections present the study conclusions.

8.3.1. Relationship between Abstraction and Water Quality

The first objective was the investigation of the impact of saline intrusion on water abstraction within the study area, most notably on farms within the zone of high salinity water nearer the coast. As presented in Chapter Six, on the 138 study farms over the three year period, 1996/7-98/9 water quality deteriorated with an increase in EC on 75% of wells. As a result the average quality of irrigation on the farms increased from 4,000 to 5,000 μScm^{-1} (Chapter Seven). The analysis of ECav showed a good correlation between water quality and farm location. Average ECav is more than 10,000 μScm^{-1} within a 4 km zone of from the coast and progressively decreased to less than 1,000 μScm^{-1} at more than 7 km from the coast. During 1996/7-98/9 water quality deteriorated faster in the near coast zones, with a raise in ECav of more than 2,000 μScm^{-1}

The overall trend was for a decrease in abstraction, by 3.3% and 12.4% on Phase 1 and 2 farms respectively. The decrease was generally greatest for the group of farms with poorest water quality (highest ECav). On farms with a more than 20% decline in abstraction in 1996-99, ECav increased from 6,000 to 7,500 $uScm^{-1}$. While on farms with a 20% increase in abstraction, ECav was less than 2,000 μScm^{-1}.

The decline in abstraction is a result of a reduction in cropped area which declined by 10% in 1995/6-98. The rate of decline was highest on the farms irrigating with more

saline water. For example the average ECav on farms with a more than 20% decline in cropped area was over 8,000 μScm^{-1}.

The analysis in Chapter Seven demonstrated the spatial nature of the relationship between declines in abstraction and increase in water salinity. It showed that abstraction rates are declining by more than 10% per year on farms within four km of the coast, and that the rate of decline is lower further inland. The higher rate of abstraction decline is a result of higher ECs and greater rates of loss of cropped area. The differential rate of changes in abstraction forms the basis of the 'non-intervention' case for evaluation of the management options (Section 8.3.3).

8.3.2. Irrigation Management

The second objective was to investigate current levels of irrigation efficiency and the potential for water savings through improvements in management and methods. The programme evaluated the uniformity of application of sprinklers and bubblers (sample farms) and carried out a detailed study of irrigation rates of sprinkler and surface methods on five case study farms.

The overall coefficient of uniformity (CU) for bubbler and sprinkler methods were 0.8 and 0.7 respectively. While CU can not be directly correlated to field efficiency, values of greater than 0.8 are recommended for equipment selection and system design (Benami, 1983). Low CU levels result in uneven and inefficient irrigation.

The average CU for bubblers was equal to the minimum recommended value of 0.8. However, as indicated in Chapter Six, on 40% of plots CU was lower than 0.8 and 5% were less than 0.5. The low CUs are symptomatic of a range of equipment and management constraints, such as poor equipment maintenance, low system operating pressures and poor system design.

The average CU of 0.7 is lower than recommended levels for efficient irrigation. As indicated in Chapter Six, CU was less than 0.8 on more than 50% of plots, and less than 0.5 on 15% of plots. As with bubbler, low CU values are related to system design, maintenance and operation.

Annual irrigation rates for sprinkler systems on the five case study farms ranged from less than 1,700 to more than 3,500 mm. These are similar to previously reported rates on the Batinah. Field efficiency was high for four of the farms, in part due to under-irrigation and/or high leaching requirements. Low efficiency, 50% was recorded on one farm (farm 10).

High irrigation rates were recorded for surface irrigated alfalfa. Rates ranged from 4,000 to 9,500 mmy^{-1}, which are of a similar magnitude to those reported on the Batinah by Dutton (1999). These are high rate relative to crop water requirements, and results in low field efficiencies, of less than 50% on four farms. They confirm the potential for improvement in methods and management of surface irrigation on the Batinah. These improvements may include improved *gelba* design to increase uniformity, irrigation scheduling and better regulation of irrigation applications.

8.3.3. Management Options

The third objective was the evaluation the impact on current trends in abstraction on management options to reduce the impact of saline intrusion within the study area. This was evaluated using a groundwater model of the representative 'slice' of the catchments. The model results provide information on predicted trends in water levels, water use, saline intrusion and groundwater depletion.

The model was used to evaluated:

- Non-intervention; the impact of current trends in abstraction (Section 8.2.1).
- Demand management; two levels of reduction of abstraction (30% and 50%) on farms more than four km from the coast at two commencement dates, 2000 and 2008.
- Supply management; the reuse of treated wastewater for irrigation of farms inland of the saline front.

The non-intervention case indicates that water levels will progressively recover over the next 40 years, as water use declines. The rate of saline intrusion will also decline over this period to 1977 levels. The saline front will be approximately 6.2 km from the coast by 2041.

The results indicate that high levels of reduction in abstraction will be required to significantly reduce the extent of saline intrusion. A 30% reduction only limited the extent saline intrusion by less than 300 metres (compared to non-intervention). Even with a 50% reduction in demand the extent of saline intrusion was only limited by 700 metres. The results indicate that if current trends of declining abstraction continue, they will produce a similar response to the demand management strategy (at both the 30% and 50% levels) would produce a similar response. Earlier intervention, 2000 compared to 2008, was of limited benefit, as the benefits of a greater reduction will be negated by continued decline in abstraction levels as a result saline intrusion.

While the results indicate that demand management actions will be of limited effectiveness, it should be borne in mind that these are based on trends measured over a relatively short period (1994-1999), compared to the total timeframe of the saline intrusion process (60-90 years) on the south Batinah

The analysis of the supply management options indicates that the large scale import of water, in this case for irrigation (but may alternatively include aquifer recharge), could reduce the final extent of saline intrusion by nearly 2 kilometres. This may ultimately be the only acceptable and technically feasible option, to substantially reducing the impact of saline intrusion on the southern Batinah.

8.4. RECOMMENDATIONS

This study has highlighted the water management challenges being faced on the South Batinah and the impact of saline intrusion on future management options. It provides the opportunity to identify and recommend future actions, within the study area, on the Batinah and nationally within Oman. The following subsections present a list of recommendations for the future.

South Batinah

- Current policies restricting the development of new farms and limiting issuing of well permits should be maintained and strengthened. Further development within the catchments will further deplete groundwater resources and promote continued saline intrusion.
- Future water and land resource planning for the catchments should take into

consideration the current and future impact of saline intrusion. This should include the ultimate abandonment of farming activities for up 6 km from the coast. Planning options should include alternative land uses for commercial and industrial development, which may be linked to development within the Greater Muscat area.

- Future planning of treatment and reuse of wastewater water within the Greater Muscat area should include the South Batinah as a potential sink for reuse or recharge. This may be included as part of a sub-region resource plan.
- Further studies are recommended to evaluate the economic and social impacts of saline intrusion within the catchments. These studies could serve as a case study for resource planning of other catchments endangered by saline intrusion, to help identify key issues and options.

Batinah

The impact of saline intrusion within Wadis Taww and Ma'awil serves as a case of study to avoid similar impacts on the Batinah to the north.

- Current restrictions of new farm development should be maintained in catchment endangered by saline intrusion.
- Agricultural strategies on the Batinah should focus on vertical development of the sector, within improved productivity and returns per unit volume of water.
- Catchments currently experiencing saline intrusion and those at risk should be identified and prioritised for implementation of demand managment strategies.
- Further research is recommended to identify practical improvements to current management of surface irrigation.
- Further research is recommended to identify improvements to the operation and maintenace of sprinkler, bubbler and drip irrigation systems.
- Further evaluation of the application of demand management options in catchments where they can contribute to achieving sustainable water use.

Oman

Water management has a unique and rich history in Oman. One in which survival and posterity was dependent on the ability of individuals and communities to develop and manage water resources. The past 30 years have been a period of unprecedented development, which has brought with it, new challenges to manage these resources under conditions of rapidly rising demand. One of these challenges has been the rapid

expansion of agriculture and unsustainable use of groundwater, particularly on the Batinah and Salalah Plains.

Sustainable water use is enshrined in national laws and plans (Vision 2020 and Royal Decree 29/2000), as well as being recognised by key institutions. Development of demand management is an essential part of sustainable use. The challenge for the future is to develop and implement a programme for the long-term management of water resources for all sectors of Omani society.

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