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HIGH WATER COUNCIL

WATER RESOURCES MANAGEMENT in the TIHAMA

FINAL REPORT

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Foreword

The Technical Secretariat of the High Water Council (TS-HWC) started preparing the groundwork for a National Water Action Plan for the northern governorates of the Republic of Yemen (formerly known as the Yemen Arab Republic) in 1988. The major objective of the National Water Action Plan is to describe strategies and policy reforms that would ensure an optimum allocation of potentially available water resources. This requires the collection and analysis of information over a wide range of issues. In many cases the information is limited and the results obtained are of necessity tentative. For this reason these reports should be seen as the basis for further collection of needed information and for the continuation of analysis of the issues to be resolved.

A number of studies have been completed under the auspices of the HWC to collect information, assess the quality and sufficiency of this information for the studies needed for resolving planning and policy issues, and to perform initial analysis and synthesis where possible. These studies, reported on in this final report, cover the following subjects:

Water resources management in the context of national economic development (Volume I)

Legal and institutional issues related to water resource use and development (Volume II)

Assessment of available surface and groundwater resources and their present and future uses (Volume III and IV)

Analysis of present and future regional water requirement (Volume V)

Status and future development of water supply and sanitation (Volume VI)

Planning support system for the Technical Secretariat (Volume VII)

Assessment of present and future environmental issues (Volume VIII)

Two case studies for the development of water resources management plans, one for the Sana'a basin and one for the Tihama (Volume IX and X)

The above studies were supported by the UNDP project "Assistance to the High Council for Water" YEM/88/001. The scope of work of this project originally included only the northern governorates of the Republic of Yemen. In view of the need for a national document that includes information on all the governorates, efforts were made to add, at a late stage in the project and without any increases in the budget, information on the southern governorates. As the result of the late stage and the limited budget, the information and analysis for the southern governorates is not as extensive as for the northern. In some cases an integrated report could be written, and in other cases a separate section for the south was added as part two.

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List of Abbreviations

CHRDP	Central Highlands Rural Development Project
DGV	Delft Hydraulics
DHV	DHV Consulting Engineers
FAO	Food and Agriculture Organization of the United Nations
GDH	General Department of Hydrogeology (MOMR) (former General Department of Water Resources Studies - GDWRS)
HWC	High Water Council
MAWR	Ministry of Agriculture and Water Resources (former Ministry of Agriculture and Fisheries)
MEW	Ministry of Electricity and Water
NRADP	Northern Regional Agricultural Development Project
NWSA	National Water and Sewerage Authority (MEW)
RWSD	Rural Water Supply Department (MEW)
SRADP	Southern Regional Agricultural Development Project
TBWRS	Tihama Basin Water Resources Study
TDA	Tihama Development Authority
TNO	TNO-DGV Institute of Applied Geoscience
TS-HWC	Technical Secretariat of the High Water Council
WRAY	Water Resources Assessment Yemen

CU	conjunctive use
decade	ten-day period
dS/m	deci-Siemens per meter
EPM	Economic Policy Model
ETc	crop evapotranspiration
ETo	reference evapotranspiration
ETP	evapotranspiration
GSM	Groundwater Simulation Model
GVP	gross value product
ha	hectare
ISM	Irrigation Simulation Model
K	hydraulic conductivity
km^2	square kilometres
LP	Linear Programming
LR	leaching ratio
l/s	litres per second
m^3/s	cubic meters per second
masl	meters above mean sea level
mm	millimetres
Mm^3	million cubic meters
Sy	specific yield
T	transmissivity
tcm	thousand cubic meters
tcmd	thousand cubic meters per day
TDS	total dissolved solids
UTM	universal transverse Mercator coordinate
YR	Yemen rials

CHAPTER 1
INTRODUCTION

1.1 General

The Tihama region is the agricultural mainstay of Yemen. It is currently undergoing dramatic social and economic transformations that place growing pressure upon its natural resources. The Tihama water resources are under evident stress as the limited surface water is insufficient to meet demands, leading to an increasing rate of groundwater abstractions that are depleting the reserves. It is necessary to gain a better understanding of the physical and socioeconomic setting of the nature of the problems facing the Tihama, and of the potential and limitations in order to plan for the future.

The coastal wadis in Yemen share some common features that make them amenable to the application of planning approaches with similar elements. They have dynamic agricultural environments in which similar soils, climate and irrigation practices are found. Their hydrology share various characteristics: a runoff-producing upper catchment with escarpments sharply descending towards the foothills; from the foothills a change of slope in the wadi courses and a gentler, more open topography inducing the formation of ample alluvial fans; a softly sloping plain on the coast, where the bulk of agricultural activities takes place, preferably at either side of each main wadi; and an alluvial aquifer with good transmissivity and storage properties having a saline interface bounding it from the sea. The society along the coastal wadis also share numerous cultural, social, and institutional features.

Groundwater irrigation has been growing steadily over the last two decades, and the groundwater table has been suffering an overall regional decline (preliminarily estimated at an average of 0.4 m per year, and more at high-intensity exploitation areas). This trend is a bad sign for the Tihama since it has evident and disquieting implications for the future availability of water (which would be reduced, due to diminished aquifer extent and accessibility), for the costs of water (which would increase, due to larger pumping depths), and for the water quality (which would be deteriorated, due to local salt sources and encroaching sea water). The goal of achieving a sustainable regional development would thus be jeopardized.

1.2 Scope of the Report

This report reviews briefly the setting and the issues related to water resources management in the Tihama and proposes an analytical framework for planning. It further illustrates the application of the analytical tools developed to a particular wadi.

The development of a planning methodology appropriate to the Tihama has been a major concern of the Technical Secretariat of the High Water Council (TS-HWC). A number of wadis have been studied separately, with different methodologies, objectives, coverage and priorities. DHV [1988] studied the Tihama plain in an integral fashion. Valuable information on water resources and farming activities was generated, and policy recommendations were made. DHV did, however, not formulate wadi-specific water resources development and management plans.

The TS-HWC undertook the development of a planning approach for the Tihama which is described in this report. The suggested planning objectives are meant to contribute to the goal of sustainable development of the Tihama. A reasonable water resources management objective was considered to be the maintenance of a healthy agriculture in the long run, while catering to other uses (domestic supply and agricultural processing industries) and ensuring the sustainability of the water resources. Equity and environmental considerations must also be taken into account. Equity may be included in the form, say, of a satisfactory income distribution among farmers. Environmental concerns might include terrace conservation in the upper catchment, containment of the saline interface, and ensuring a livable habitat for sea life along the coast. The components of possible water resources management strategies and evaluation criteria are discussed.

Two analytic instruments developed by the TS-HWC are reported here. One is the irrigation simulation model, which describes the surface hydrological system and the irrigation system in a wadi plain and simulates their operation. Any reasonable physical configuration of a wadi system may be represented by specifying type and sequence of modules in the input. The second instrument is the groundwater simulation model. Based on a generalized conceptual model of a Tihama wadi aquifer, a wadi-specific model was developed. The models are designed to work complementarily. They can be readily extended or adapted to other wadis, facilitating the application of a consistent methodology to coastal wadis in Yemen. The implementation of a third model, the economic policy model, is proposed. It would be an optimization model to aid in the identification of economic policies to be explored by the simulation models.

In order to test the capabilities of the models, a wadi with a consistent and complete set of up-to-date data needed to be selected. The wadi that most closely met those requirements was Wadi Surdud, recently studied by the General Department of Hydrogeology of the Ministry of Oil and Mineral Resources with support of the WRAY project [Van der Gun and Wesseling, 1991]. Hence this wadi was chosen for our purposes. It should be noted that this work of the HWC does not duplicate the previous effort, but illustrates the application of an alternative methodology.

CHAPTER 2
WATER RESOURCES IN THE TIHAMA REGION

This chapter highlights aspects of special relevance to the water resources management studies of the Tihama. The reports on Surface Water Resources, Volume III, and Groundwater Resources, Volume IV (Annex C - Groundwater Resources Assessment of the Western Basin), already cover comprehensively the water resources assessment of the Tihama and related topics, including climatology. The Tihama Basin Water Resources Study [DHV, 1988a], produced a previous water resources assessment and covered in fair detail the land use and agricultural activities of the Tihama. There have also been a number of wadi-specific studies, such as those for Wadi Mawr [Sir Malcolm MacDonald & Partners, 1987], Wadi Siham [NESPAK, 1989], and Wadi Surdud [van der Gun and Wesseling, 1991]. The reader desiring detailed information on any of those aspects may wish to consult the above mentioned sources. The chapter closes pointing out some of the more pressing water resources management issues in the Tihama.

2.1 The Institutional Setting

There are a number of government institutions exercising authority on water related matters in the Tihama region. Notable among them is the Tihama Development Authority (TDA), administratively and technically answerable to the Minister of the Ministry of Agriculture and Water Resources (MAWR). TDA was created in 1973 as part of the effort to facilitate and decentralize agricultural development and associated endeavours in the former Yemen Arab Republic. It is endowed with wide-ranging and fairly autonomous authority to act in the Hodeidah governorate, covering the full range of agricultural programs, including irrigation and community development. Geographically, TDA's jurisdiction encompasses a major portion of the Tihama coastal plain and part of the mountain catchments corresponding to five major wadis (Mawr, Surdud, Siham, Rima, Zabid, Hays). Figure 2.1 presents a catchment map of the Tihama.

The Northern Region Agricultural Development Authority (NRADP) mandate stretches over part of the Sana'a governorate and all of the Hajjah and Sa'dah governorates, covering the northernmost segment of the Tihama plain, corresponding mainly to the Harad and Abs wadis, and a substantial part of the mountain catchments of the central and northern Tihama wadis. The Central Highlands Rural Development Project (CHRDP) covers portions of the mountain catchments of wadis Siham, Rima and Zabid. The Southern Regional Agricultural Development Project (SRADP) extends over the entire catchment and Tihama plain parts of wadis Rasyan and Mawza. The Al Mahwit Rural Development Project holds authority over the Al-Mahwit governorate, located principally in the upper catchment area of Wadi Surdud.

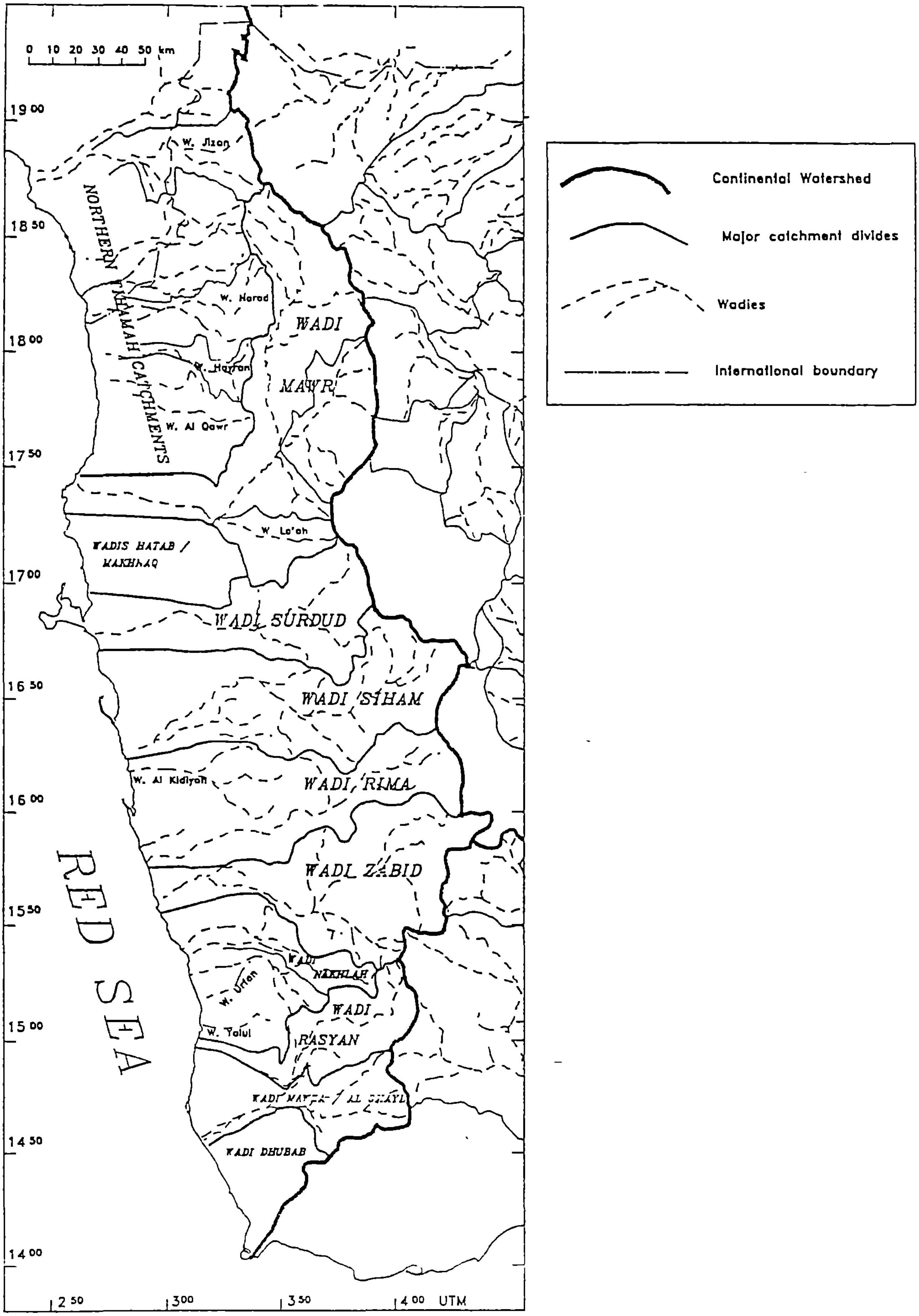

Figure 2.1 Main Catchments of the Tihama Region

Various other government agencies manage water programs in the Tihama. Of major importance is the National Water and Sanitation Authority (NWSA) of the Ministry of Electricity and Water, charged with providing urban water supply and sewerage services. In the Tihama region, Hodeidah, the major urban centre, and Bajil, Al Mansuriyah, Bayt Al Faqih, Zabid, and Al Mokha, secondary towns, are part of NWSA's program. The Rural Water Supply Department (RWSD) is involved in activities of its competence in the Tihama. The Ministry of Oil and Mineral Resources, through the General Department of Hydrogeology, carries out water resources monitoring, assessment, and planning activities in the region, particularly in Wadi Surdud.

2.2 The Water Resources

The Tihama region lies in the Western Escarpment of Yemen. Water drains westwards towards the Red Sea, though the surface flow rarely reaches it. Along some segments of the coast there is groundwater discharge to the sea. There are numerous surface water courses, wadis, of varying size and yield. A simple land and hydrologic classification of the Tihama distinguishes the catchments, the upper steep sloping runoff-producing areas, and the plain, the lower gently sloping area with ample alluvial aquifers which extends to the sea and which hosts extensive agriculture. Each main wadi defines a hydrogeological province in the plain whose operation is virtually independent from the other provinces.

2.2.1 Climate

The Tihama plain is hot, windy and semi-arid. Mean annual rainfall varies from about 50-100 mm along the coast to about 300 mm (occasionally 400 mm in the southern reaches) along the foothills at the lower end of the catchments. Potential evapotranspiration in the 20-30 km fringe closest to the sea is in the range of 2,000-2,200 mm. The eastern part of the plain, where most agricultural development is located, has a potential evapotranspiration of 1,800-2,000 mm. Relative humidity is high, varying between 60% to 75%.

The catchments, which rise from about 300 masl to the divide (often above 3,000 masl), have rainfalls going from a mean annual total of about 300 mm at the lowest parts to at least 600 mm in the north up to 900 mm in the south (Green Yemen). The rainfall over the agricultural areas on the plain occurs in two seasons, either separately (lower and middle sections) or as connected seasons (eastern section). The first season (March to May) obeys the Red Sea Convergence Zone effect, and the second one (July-September), the monsoonal Intertropical Convergence Zone effect. Typically, the first season yields one-third of the mean annual rainfall and the second season the remaining two-thirds.

2.2.2 Surface Water

Table 2.1 gives general information on the major Tihama catchments: area, mean annual runoff and the proportion of baseflow of the total runoff in each catchment. The following comments are applicable:

Table 2.1 Major Catchments of the Tihama

Wadi	Area in km^2	Annual Runoff Mm^3	Baseflow percent	Foothill runoff
Mawr	8,000	129	67	0
Surdud	2,700	82	62	0.4
Siham	4,900	73	68	1.5
Rima	2,700	50	72	9
Zabid	4,700	86	76	2
Rasyan	2,000	16	82	4
Mawza	1,500	20		

Note: Table adapted from Volume III - Surface Water

(1) The runoff given is at the catchment base (foothill area) where normally the wadi gauging stations are located, upstream of the plain. This does not mean that all the runoff is available for agriculture and other uses, because a substantial portion of it infiltrates and contributes to the recharge of the underlying aquifer.

(2) The proportion of baseflow is high, roughly 65% in the northern Tihama catchments and 75% in the southern catchments. This means that most of the water can be easily diverted in the upstream sections of the wadi. The unpredictable and sharply-peaked flood flows, which has a greater chance of reaching the downstream sections, account for a minor portion of the total flow.

(3) Foothill runoff includes the runoff from areas draining directly to the plain (and not to the wadi channel) and that from ungauged parts of the catchments.

(4) Though a long-term trend in annual rainfall has not been detected in Yemen, there are indications, though not unequivocal, that runoff may be declining in some wadis. This could also be linked there has to intensified water use upstream and other man-made interventions.

The inspection of the time series in wadis Zabid and Rima gave contradictory results: Wadi Zabid flows show little, if any trend; Wadi Rima flows show a decline in the frequency and magnitude of floods and progressively lower minimum base flows. The traditional means to secure water for upstream uses in the catchments include rainfall harvesting, wadi flow diversion, spring water collection and hand-dug wells in wadi beds. There is circumstantial evidence that the exploitation of pumped groundwater to satisfy domestic and agricultural uses is growing within the catchments [Al-Eryani et al., 1991]. Even the capture and conveyance of seepage waters using a modest technological innovation such as rubber hoses can have a telling effect when multiplied innumerable times by individual farmers [Linden, 1991]. At the same time at certain locations there is an accentuated phenomenon of terrace abandonment, which, in addition to increasing soil erosion in the catchment with a corresponding sediment load in the runoff, tends to produce larger flood peaks as terrace retention is lessened. This effect of increased runoff may be offset by the growing groundwater abstractions within the catchment. The combined effect of these disturbances cannot be predicted as the data base on relevant information, such as land and water use, trends and evolution of terrace agriculture, and sediment transport, is extremely limited.

2.2.3 Groundwater Resources

General

The Tihama is underlain by an extensive alluvial aquifer of the Quaternary age. There is a complex sequence of coarse to fine grained, unconsolidated deposits. They range in thickness from about 50-100 m near the foothills where the bedrock is shallow, to about 250-300 m in the coast. The thickness is largely controlled by several major step faults which descend towards the west. The Quaternary deposits may be broadly divided into (1) an upper, more permeable, layer of up to 100 m thick, and (2) a lower, more consolidated or finer grained and less permeable layer to depths of 350 m. Groundwater is at a depth of about 30-50 m near the mountain front, to about 10-30 m in the central plains and under 10 m deep in the coastal area. The water table gradients decrease from east to west from about 1% in the alluvial fans near the foothills to 0.5% in the central plain and 0.1% at the coast, where the sea water level acts as a control.

There are considerable variations in groundwater quality both horizontally and vertically. The occurrence of brackish to saline water is more widespread in the northern part of the Tihama, where there are salt domes and a more pronounced saline intrusion. Localized deteriorating water quality is reported in areas of intensive groundwater exploitation.

For groundwater studies purposes, the Tihama plain usually is divided into a number of "groundwater provinces", usually corresponding to the area under each wadi catchment, including the alluvial fan area and extending to the coast. There is little interaction among the provinces, facilitating modelling efforts.

Groundwater Development

Historically, a major portion of the recharge to the Tihama wadi aquifers came from infiltration of surface flood waters in the wadi into the alluvial channel. Even in the absence of irrigation diversions, flood waters entering the wadis from the mountain catchments infrequently reached the Red Sea, but rather infiltrated into the dry channel.

With the development of spate diversion structures during the last 1,500 to 2,000 years along the eastern portion of the Tihama plain, net recharge to the groundwater system has been spread over a larger area due to the spreading of diverted surface waters during large flood events. In general, irrigation development on the Tihama plain has significantly decreased total potential groundwater recharge due to evapotranspiration losses (consumptive use) by irrigated crops. This process has been intensified with the introduction of pumped groundwater irrigation.

During the last 20 years groundwater abstraction in the Tihama has grown enormously due to the widespread and unrestricted introduction of well drilling equipment and motorized pumps and the attractiveness of a permanent, secure and apparently limitless source of water as compared to the variability and limitations of wadi flow. By the mid-1980s there were about 12,600 inventoried wells in the Tihama [DHV, 1988a], growing by 400 wells per year. Dug wells were the most common type, but drilled wells are being constructed at an increasing rate and dug wells are commonly being deepened by drilling. Nearly 70% of the wells were pumped wells. The greatest rate of growth of pumped wells is shown by the mid-Tihama groundwater provinces: Zabid-Rima, Jahabah (north of Rima) and Hays (south of Zabid). Table 2.2 shows extrapolated estimates of the number of pumped wells and corresponding groundwater abstraction for 1990.

The average depth of wells is 25 m, ranging typically from 20 m to 40 m, but reaching 60 m in the alluvial fan area. The average abstraction rate is about 10 l/s, operating 12 hr/day, 24 days/month. The average command are of each well is 9 ha. The abstraction of wells in the northern provinces is larger on average than those in the southern provinces (0.16 Mm^3/year/well vs. 0.07 Mm^3/year/well).

Tihama Water Balance

In the groundwater assessment of the Tihama (Volume IV, Annex C) a water balance analysis was carried out. Table 2.3 summarizes the results; a simple approach based on a per basin lumped quantification was employed. A more detailed analysis was performed only on Wadi Surdud using a numerical model, as presented in Annex B to this report. The simpler approach for the whole of Tihama is justified in that neither the data or time available was sufficient to attempt modelling all wadis, yet it can broadly illustrate the overall hydrogeological process.

Table 2.2 Estimated number of pumped wells and abstraction in 1990

Groundwater Province	Pumped Wells	Abstraction Mm^3/year
Harad	562	99
Abs	400	61
Mawr	1,335	174
Surdud	1,005	131
Siham	1,075	140
Jahabah	1,376	178
Zabid	2,221	291
Hays	676	72
Rasyan	515	36
Mawza	543	36
Dhubab	26	0.5
Total	9,734	1,218

Table 2.3 Groundwater Balance in the Tihama

	Groundwater Province											
	Harad	Abs/Bahwal	Mawr	Surdud	Siham	Jahabah	Zabid/Rima	Hays	Rasyan	Mawza	Dhubab/ Samadah	Total
Wadi inflow Mm^3/year	19	9	129	82	73	7	136	16	16.5	12	6	505.5
Foothill runoff Mm^3/year	0	0	0	0.4	1.5	2	11	2	2	0	0	18.9
Recharge Mm^3/year:												
Rain	8.8	8.3	11.5	11.8	14.7	14.7	10.2	4.1	0.9	1	0.33	86
Foothill runoff	0	0	0	0.1	0.3	0.4	4.1	0.9	1	0.33	0	3.8
Wadi channel	12	5.7	73.1	47.2	41.1	4.5	74.8	10.6	8.9	7.9	4	289.7
Field seepage	2.1	1	16.8	10.4	9.6	0.8	18.4	1.6	6.8	1.2	0.6	64.8
Subsurface flow	3	4	5	2	5	3	44	12	1.2	0.2	0.2	79.6
Total recharge	25.9	19	106.4	71.5	70.7	23.3	149.6	28.7	13.6	10.3	5.1	524.1
Gross abstraction Mm^3/year:												
Agricultural	99	61	174	131	140	178	291	72	36	36	.4	1218
Rural	3	1.4	2.6	1.1	1.3	3.6	9	0.3	0.1	0.7	0.1	23.2
Urban/industrial	0	0	0	0	7	0	0	0	0	0	0	7
Discharge Mm^3/year:												
Net Abstraction	72.3	44.1	124.4	92.8	106.3	128.2	212.7	50.7	25.3	25.9	0.4	883
Interprov. loss	10	0	0	0	0	0	0	0	0	0	0	10
Coastal evap.	27	34	87	62	66	14	10	12	12	11	7.5	342.5
Coastal disch.	0	0	0	0	6	16	156	8	0	0	0	186
Total discharge	109.3	78.1	211.4	154.8	178.3	158.2	378.7	70.7	37.3	36.9	7.9	1421.6
Balance	-83.4	-59.1	-105.0	-83.3	-107.6	-134.9	-229.1	-42.0	-23.7	-26.6	-2.5	-897.5

Note: Adapted from Volume IV, Annex C: Groundwater Assessment of the Western Basin

The recharge mechanisms considered for each hydrogeological province are the following:

- rainfall: a direct recharge rate of 4% of rainfall over areas receiving more than 200 mm a year was adopted.

- foothill runoff: it was assumed that 20% of foothill runoff contributed to recharge.

- wadi flow: it was assumed that 50% of baseflow and 70% of flood flow infiltrated through the wadi bed. This is based on a generalization of observed values in one wadi.

- field seepage: this was assumed equal to 30% of the wadi flow diversion (diversion = wadi flow - wadi infiltration). According to the Tihama baseflow and flood flow values given in Table 2.3, only about 30% of the total wadi flow would be consumed by wadi irrigated agriculture (wadi inflow minus wadi channel recharge and field seepage)

- subsurface inflow: composed of underflow through wadi deposits (primarily at gauging station section) and of contribution to recharge by bedrock inflow as conditioned by the faulting system. These were estimated using reasonable assumptions for each wadi for parameters, such as permeabilities, gradients, and section areas.

For newly irrigated areas, an important question for the aquifer operation is how soon return flows that percolate become effective recharge. The unsaturated soil profile may be assumed to have been in hydraulic equilibrium under natural recharge conditions. The introduction of additional amounts of percolated water upsets the balance and a new equilibrium has to be reached so that recharge flow is normalized. The unsaturated soil will "absorb" the new percolated water until normalcy is reached. As explained in Technical Note 1 of Annex C to this report, the process of establishment of new equilibrium conditions in the Tihama is fortunately relatively quick. For typical conditions, it would take on the order of four years of less for a completely new irrigated area. Thus, the assumption that return from agriculture can be considered recharge for practical balancing purposes is justified.

The discharge components considered are the following:

- coastal evaporative losses: shallow groundwater along the coast evaporates at the saline sebkha depressions. Values were estimated using assumptions of potential evaporation with depth to groundwater and type of soil. Evapotranspiration losses by phreatophyte vegetation bordering saline soils were also added in.

- coastal discharge: for approximately half of the Tihama coastline, the saline front lies off-shore. It has been assumed that coastal discharge takes place there. Estimates were based on a Darcy flow approach.

- groundwater abstractions: abstractions in Table 2.3 refer primarily to agricultural withdrawal; minor additional abstractions for domestic and industrial use have been considered in the balance. Net groundwater abstractions have been assumed to be

70% of the gross agricultural abstractions (30% return flow) and 100% of the urban abstractions (no return flow to aquifer). Wastewater from Hodeidah, the main urban centre, is mostly discharged to the sea.

- inter-province loss: the only item included represents outflow of the Harad aquifer to Saudi Arabia.

The final balance shows a total annual loss of groundwater in the Tihama of 897 Mm^3 for the situation in 1990. This loss comes out of the water storage of the aquifers and is equivalent to an overall water table decline of 0.4 m/year, or, if referred to the cultivated area where most of the abstractions take place, the decline reaches 0.9 m/year.

The storage depletion poses several risks that have to be evaluated: decrease of the exploitable stock, which could lead to its eventual exhaustion, with higher costs of water as the water levels drop; inland displacement of the saline interface preceded by local upconing causing the degradation of the aquifer along the coast; quality deterioration not only from the saline intrusion but from increased encroachment of local sources of unsuitable water.

In the groundwater assessment study (Volume IV, Annex C), an estimate of the potential and usable groundwater storage in the Tihama was made. Table 2.4 shows the resulting estimates per groundwater province. First, potentially exploitable storage was estimated based on several considerations, mainly: (1) the saline front could be permitted to move inland to a prescribed position (not invading sound quality aquifer) where it would be stabilized, allowing a greater portion of above sea level storage to be used, (2) areas with high salinity groundwater (electrical conductivity above 4 dS/m) have not been included, and (3) storage underlying land unsuitable for irrigation has also been excluded. This considerations, along

Table 2.4 Groundwater Storage Estimates in the Tihama (in billion m^3)

Groundwater Province	Potential Storage	Usable Storage
Harad	3.0	1.0
Abs	4.5	1.5
Mawr	7.4	2.4
Surdud	8.9	2.9
Siham	10.1	2.6
Jahabah	5.1	2.3
Zabid	12.8	4.2
Hays	5.6	1.9
Rasyan	1.9	0.6
Mawza	3.5	1.2
Dhubab	0.5	0.2
Total	63.3	20.8

with simple zoning techniques in order to employ applicable parameter values yielded the potential storage estimates. Usable storage represents the portion of potential storage that would be available for development without incurring adverse effects. It was considered that the depletion of roughly one-third of the potential storage did not pose serious dangers of degradation of the aquifer.

The potential groundwater storage for the Tihama was thus estimated in about 63,000 Mm^3, of which about 21,000 Mm^3 was usable. Given the approximately 900 Mm^3/year of storage depletion estimated from the water balance exercise, this would suggest that in about 23 years the usable aquifer would be depleted at current rates of exploitation. Problems may be worse at some high intensity exploitation zones, and abstraction rates can be expected to increase. On the other hand, the estimate of usable storage has been derived based on simplified assumptions, and coastal discharge and evaporative losses can be expected to decrease over time as the groundwater gradient at the sea border decreases and the water table grows less shallow. A time horizon of about 15-20 years can be considered a threshold after which groundwater problems in the Tihama might grow critically acute, not on account of quantity but more probably because of quality degradation, if appropriate management strategies are not applied. The above is admittedly an oversimplified approach which might be viewed as a first approximation to gauge the acuteness of the problem. More specific results for each hydrogeological province should be obtained using a groundwater model (see for instance Chapter 4 of this report).

Factors Affecting Yields and Sustainability

The insights gained from the evaluation of the Tihama groundwater resources and the associated modelling studies (see Annex B to this report) allow summarizing the following relevant points:

- <u>over-exploitation</u>: abstractions currently exceed recharge by a large measure. The exploitable long-term yield to attain the stability of the Tihama aquifer is in the order of 60% of present day recharge.

- <u>falling yields</u>: evidence suggests that permeabilities decrease with depth (and the proportion of more permeable layers may decrease towards the coast); declining water levels may result in decreased productivity of wells, forcing further deepening and/or construction of boreholes to keep up abstraction levels.

- <u>quality</u>: lateral movement of poorer quality water adjacent to main areas of groundwater abstraction (e.g. Wadi Mawr) may constitute the main control on future abstraction; indications are that saline intrusion may be slow (perhaps a few km per century), but may intrude faster in areas with E-W orientation of intensive exploitation (e.g. Wadi Zabid); upconing in advance of the saline front is a risk which may be lessened by using shallow wells and low abstraction rates.

- <u>well distribution</u>: some other studies have suggested that with a spatial rearrangement of the abstraction patterns the sustainability of the aquifers would be enhanced (DHV [1988] recommends controlled development of groundwater irrigation in areas adjacent to traditional rain-fed agriculture; van der Gun and

Wesseling [1991] suggests shifting concentration of abstraction to the western part of the aquifer in the Wadi Surdud basin). The TS-HWC modelling exercise indicate that generalizations on the best pattern to adopt are uncertain: moving the abstractions toward the coast increases the extent of saline intrusion and moving them towards the interfluvial areas tends to dewater the upper layers of the aquifer more easily.

2.3. Agriculture on the Plain

As in the rest of Yemen, rain-fed agriculture is the predominant mode of farming in the Tihama. The main concern, however, is with agriculture that can be influenced by means of water resources management instruments. Irrigated agriculture clearly responds to this type of measures, and is the subject in this report. There is an ample and vigorous irrigated agriculture development in the Tihama plain. Various factors have contributed to this: a rather flat topography, relative abundance of water resources (as compared to the rest of Yemen), a climate permitting year-round agriculture, and a rooted farming and spate irrigation tradition. Approximately 115,000 ha are irrigated in the Tihama plain [DHV, 1988a], of which about 35,000 ha are wadi-irrigated and 70,000 ha are groundwater-irrigated. It is estimated that a total of 250,000 ha of the cropped land is irrigated in the northern governorates of Yemen (ex-YAR) [World Bank, 1989], of which about 130,000 ha is controlled irrigation (mainly pumped groundwater and springs). The importance of the Tihama agriculture from the national standpoint is evident.

2.3.1 Irrigation Practices and Schemes

Types of Irrigation Units

Conventionally, three basic types of irrigation units are considered in the Tihama according to the irrigation methods employed: spate, conjunctive use, and groundwater. In many cases this classification suffices for analysis. The Wadi Surdud study by TNO [van der Gun and Wesseling, 1991] and many others used it. The Wadi Siham study NESPAK [1988] adopted a more elaborate classification using the following types of irrigation sectors:

- irrigation by pumping wells;
- regular spate irrigation (permanent flow or 6 to 10 floods/year);
- irregular spate (about 2 to 4 floods/year);
- exceptional spate (one flood in 2 to 3 years);
- each of the three above spates + pumping

Sir M. MacDonald & Partners [Sephton and Allum, 1987] divided surface water irrigation in Wadi Mawr into: (1) upper area: perennial + spate flows, (2) middle area: predominantly spate flows, and (3) lower area: spate flows only.

The above categorizations reflect primarily the source of irrigation water (surface water, groundwater, or both), plus, in other cases, a more subtle distinction: the reliability of surface water supply to users, decreasing from upstream to downstream given the positional advantage of those situated upstream for diverting wadi flows.

Allocation of Water

Traditionally in Yemen the two major types of irrigation systems according have been *sayl* (seasonal flood or spate) and *ghayl* (spring flow) [Varisco, 1983]. Spring flow irrigation, normally practised in the highlands, lends itself to very clear and easily applied allocation rules and to a stable political organization of the users due to the predictable and continuous nature of the spring flows. In contrast, spate irrigation places stress on traditional political organization stemming from upstream-downstream conflicts. The unpredictable timing and magnitude of floods and their short duration is at the root of the problem. Customary water rights give priority in the use of water to the upstream fields, but it is not meant to be a wasteful use.

Water is generally allocated on a "head-ender"/"tail-ender" type of priority, where farms close to the spate diversion (head-enders) fully receive irrigation water needs before the water is routed down gradient to lower lying or more downstream farms (tail enders). Where traditional spate irrigation exists, a water master is often employed and charged with direction of water distribution and allotment among head-enders and tail-enders, and to resolve disputes. Often, though, flood waters recede before tail-enders receive a sufficient amount, if any, of the diversion.

Groups of farmers under different spate diversions function in a similar manner, where spate structures higher up on the wadi generally have access and a right to capture part or all of the wadi discharge. Flow around the higher spate structures and excess runoff from higher irrigated lands recollects in the wadi channel and travels downstream to lower-lying spate diversions.

Historically there have numerous interventions in the system to protect the downstream users from unfair actions of upstream irrigators. Significant changes in water allocation have occurred in the major wadis in Yemen (limiting number and size of barrages, limiting the time period of appropriation of water, limiting the number of times the upstream irrigators may water their fields). Locally appointed water masters have been common. The Rasulids (13th-15th centuries) appointed irrigation officials in areas of wadi irrigation under state control. Recently a number of traditional systems (notably Wadi Mawr and Wadi Zabid) have been upset by the introduction of modern diversion and conveyance structures which could technically be managed to provide a more controlled and fair allocation of water; unfortunately these have usually resulted in an even greater predominance of the upstream users [see, for instance, Shahin, 1990]. Thus, currently, there is in general no stable system of water allocation in coastal wadis; on the contrary, there are numerous conflicts needing resolution.

Irrigation Methods

A general description of spate irrigation practices in the Tihama may be found in Technical Note 3 of Annex C to this report. The role of spate structures and water distribution process in the bunded fields is discussed there. Some main characteristics of spate irrigation are:

(1) The source of water may be classified into a reliable, basically permanent, component (baseflow) and an unreliable and ephemeral one (flood flow). The baseflow component (plus a portion of flood flow when it occurs) is generally captured in the upstream reaches of the wadi. Thus, supply reliability decreases downstream.

(2) The farmer's tendency is to divert as much water as possible and to over-irrigate, if allowed, in anticipation of reduced supply or access to water.

(3) The lack of reliability of supply (except for the uppermost farmers) drives the farmers to a low technology, subsistence agriculture based on a few drought resistant crops (such as sorghum), and results in depressed yields because of insufficient and untimely water availability.

(4) The water management practices that evolved during many centuries are breaking down in various wadis as a result of the implementation of modern irrigation schemes. The systems are often operated not according to a technically and equitably correct plan but to the advantage of the powerful upstream farmers.

(5) Farmers usually consider the deposition of fresh silts and sediments in spate-irrigated fields a benefit, probably because (a) silts help to replace soils eroded during large discharges through fields, (b) build-up of silt in fields may assist in the levelling process (c) silts are considered to contain nutrients. It has been argued that the amount of nutrients associated with the sediment is quite low and that the use of commercial fertilizers is more effective. Commercial fertilizers are, however, difficult and expensive to obtain. Moreover, the large infiltration depths in some fields rapidly leach soluble nutrients, such as nitrates, from the soil profiles.

Currently, three public spate irrigation systems (Wadi Zabid, Wadi Rima and Wadi Mawr) have been implemented in the Tihama by TDA. Major differences between public and private spate systems include [World Bank, 1989]: (1) private spate consists of small-scale temporary constructions; public spates are located on the larger wadis; (2) public spate systems have more substantial diversion structures with greater diversion and control capability; and (3) the operation and maintenance (O&M) of public systems is carried out by TDA; private spate O&M is done by farmers. Notwithstanding the better engineering of public spate systems and the sophisticated operating procedures designed for them, TDA officials and farmers have reported distribution and equity problems in the public systems; these are more pronounced when there is only one single diversion structure.

Irrigation methods used in both spate and groundwater-irrigated areas consist of small bunded fields, generally less than 0.1 ha in size. In groundwater areas, the fields are levelled and are corrugated with furrows to guide and distribute water. Water is generally directed into individual furrows manually. Distribution of water to individual fields in groundwater areas is generally by a small earthen canal. In some areas, 100 mm steel, plastic or flexible pipe is used. Seepage of water from the small groundwater distribution channels is probably less than 5 % of the total volume of water pumped. The majority of this seepage returns to the aquifer for reuse, so that it is generally not considered to be a net loss, except in the economic sense, where diesel fuel is invested in lifting the groundwater to the ground surface.

From observations of groundwater-irrigated areas, it appears that water application to most crops is not excessive, as many irrigated fields showed signs of moisture stress. This type of management is beneficial to sustain of the groundwater aquifer, but is probably less economic than applying a full amount of water and increasing fertilizer and seed variety inputs. Application efficiencies of groundwater irrigated areas are estimated to average about 65% due to the increase in control of the water, small field and farm sizes, small flow rates of wells (often about 10 l/s), and expense of the water. Application efficiency, as used in this study, is defined as the percentage of water abstracted from the groundwater supply which is consumed by the process of evapotranspiration by irrigated crops. The balance of the water is assumed to return to the groundwater as deep percolation beneath irrigated fields or as seepage from distribution channels.

Spate-irrigated fields are often sloping gradually towards the wadi water course and are somewhat less precisely levelled as compared to groundwater-irrigated fields. Furrows may or may not be used to direct water across the bunded fields, as deliveries of spate flood waters to fields can be quite large and difficult to control. Application efficiencies of spate-irrigated fields are generally very low due to the large depths of water often applied to individual fields. In the Irrigation Simulation model (see Chapter 4), it was assumed that application efficiencies of spate-irrigated blocks was 30%. In other words, it was estimated that only 30% of water infiltrated into spate-irrigated fields remained in the crop root zones and was utilized for evapotranspiration. The application efficiency of conjunctive use units, such as Al-Kadan in Wadi Surdud, may be higher (perhaps 60%) because of improved joint management of surface and groundwater. By itself, the security of availing groundwater at will confers a significant advantage.

2.3.2 Crops Grown

In general, sorghum is nearly the sole crop grown on spate-irrigated areas for reasons given previously, and is the majority crop grown in groundwater-irrigated areas. Up to 50% of groundwater-irrigated hectares are currently being allocated to crops of maize, cotton, sesame, tobacco, and winter vegetables.

During a field visit to the Tihama plain and Wadi Surdud area in April 1992, it was noted that the sorghum crops appeared to be deficient in nitrogen. Leaves were often yellowish-green in colour. In conversations with farmers in groundwater-irrigated areas, they noted that they do not fertilize sorghum crops, but that they do apply some fertilizer to cash crops, such as tomatoes and other vegetables. Because sorghum is by far the majority crop on the Tihama plain, it is doubtful, on the average, that sufficient nitrogen fertilizer is left in soil profiles to adequately grow a high-yielding sorghum crop. Addition of commercial nitrogen fertilizers could probably significantly increase crop production with only slightly increased water use by inducing a more vigorous and uniform crop stands. This input of fertilizer could significantly increase the kilograms of biomass and grain produced per unit of water in the Tihama plain.

Under-irrigation (or deficit irrigation) occurs primarily in spate irrigated areas, where it is very common because of the irregularity of the water supply, but, as noted above, it may also occur -- to a much lesser extent -- in groundwater irrigated units. The effect of not meeting the full irrigation requirements of a crop has to be adequately represented in any analysis of current or proposed agricultural scenarios. The usual methodology is presented by Doorenbos and Kassam [1979], who give expressions for the yield depression due to an evenly spread water shortage for the entire growth cycle of a crop and due to a water shortage in individual growth periods (vegetative, flowering, yield formation, and ripening). For the analyses of this report an extension applicable to multiperiod deficits was developed, yielding an expression of the following type:

$$Ya/Ym = 1 - 2/3\ \Sigma_i\ [ky_i(1-ETa_i/ETm_i)]$$

where Ya is the actual yield, Ym is the maximum potential yield with no water shortage, ky_i is the yield response factor for growth period i, ETA_i is the actual crop evapotranspiration and ETm_i is the crop water requirements for the same period i. The derivation of the above formula is presented in Technical Note 3 of Annex C to this report based on Tejada-Guibert [1991].

Excess salinity also has a negative effect on crop yield. In the Tihama there are definite indications that indiscriminate development and management of groundwater will lead to the use of poor quality water in agriculture. The incorporation of the effect of salinity in crop yield determination based on the approach of Brooks and Corey [1972] and is discussed in Technical Note 4 of Annex C.

2.3.3 Water Productivity in Tihama Crops

Estimates of the value of water provide a useful basis for judging agricultural performance in a region from the water utilization point of view and for evaluating economic feasibility of various means of augmenting supplies. In Yemen, where there is a growing recognition of the need of water conservation, estimates of the value of water can be used to pre-test programs proposed to contribute to regional and national economic development through more efficient use of water.

Estimates have been made here for a number of Tihama crops under spate and groundwater irrigation. Several techniques can be used to estimate the value of irrigation water (for instance, see Young and Gray [1972]). The estimates reported here were derived using the residual budgeting method. This method defines returns to irrigation water as the residual after costs of all cash and non-cash inputs, other than water, have been subtracted from gross returns. The results are summarized in Table 2.5. The detailed crop budgets showing production costs, gross income and net income for spate and groundwater irrigation are presented in Tables 2.7 to 2.11 at the end of this chapter. The crop yields, level of use, and prices of inputs adopted reflect current conditions in the Tihama, particularly in connection with Wadi Surdud.

In the spate irrigation system, estimates of the value of water range from a minimum of 0.03 rials/m^3 in the production of cowpeas to a maximum of 1.11 rials/m^3 in the production of

Table 2.5 Estimates of Value of Water for Various Crops in Tihama

Crop	Spate Irrigation (R/ha)	Spate Irrigation (R/m^3)	Groundwater Irrigation (R/ha)	Groundwater Irrigation (R/m^3)
Sorghum (kharif)	725.5	0.04	2,017.8	0.23
Sorghum (kharif)	725.5	0.04	2,017.8	0.25
Sorghum (ratoon)	472.5	0.04	799.4	0.16
Sorghum (fodder)	611.9	0.04	1,254.9	0.20
Maize	3,436.3	0.17	4,570.9	0.49
Millet	616.7	0.04	928.6	0.13
Cotton	1,071.5	0.05	2,714.0	0.25
Sesame	761.6	0.05	1,812.3	0.25
Tobacco	5,850.0	0.31	10,762.5	1.22
Tomatoes	8,692.0	0.37	10,696.0	0.99
Vegetables	17,606.0	1.11	24,276.0	3.31
Cowpeas	493.9	0.03	637.9	0.08
Fruits	56,262.5	1.09	82,748.0	3.48
Melon	6,659.0	0.36	9,039.0	1.06

vegetables. In the groundwater irrigation system, the value of water turned out to be highest (3.48 rials/m^3) for fruits and lowest (0.08 rials/m^3) for cowpeas. The profitability ranking of crops under the groundwater irrigation system was almost the same as was observed under the spate irrigation system. It is evident from Table 2.5 that the value of water is significantly higher under the groundwater irrigation system as compared to the spate irrigation system. The difference mainly stems from two reasons: (a) the crop water requirements under the spate irrigation system are considerably higher because of low irrigation efficiencies[1]; and (b) the agricultural productivity (crop yields) is low under the spate irrigation system because of unreliable water supplies and low input use.

The present operation and maintenance (O&M) pumping costs in the central part of the Tihama region are estimated in 0.38 rials/m^3 and the investment costs in 0.27 rials/m^3 for a total of 0.65 rials/m^3 (see Section 4.4). These pumping costs justify only the production of fruits, vegetables, melons, tobacco and tomatoes in the groundwater irrigated zones.

The impact of pumping costs on crop profitability is shown in Table 2.6. The per hectare net income reported in the table is defined as returns to on-farm resources i.e., gross income minus cash costs, and is higher than the values reported in Table 2.5. It should be noted that the values in Table 2.5, representing the residual after costs of all cash inputs and on-farm resources, other than water, have been substracted from gross returns. In that case fruits, vegetables, melons, tobacco and tomatoes will remain profitable to grow even if total pumping costs are increased to 1 rial/m^3 (Table 2.6). If it can be assumed that little or no investment in new or deepened wells in certain locations is necessary (sunk costs), profitability may be maintained for a longer period.

The results show that water productivity in Tihama region is fairly low with the exception of some management-intensive crops (such as fruits and vegetables) which occupy a small

(1) For the estimation of crop water requirements, irrigation efficiency was assumed to be 30 percent for the spate irrigation areas and 65 percent for the groundwater irrigation areas, as previously discussed.

Table 2.6 Impact of Pumping Costs on Crop Profitability in Tihama

Crop	Net income without ppg.costs	Net Income at Different Levels of Pumping Cost								
		0.38	0.40	0.45	0.50	0.55	0.60	0.65	0.70	1.00
Sorghum (sayf)	4318.8	926	747	301	-146					
Sorghum (kharif)	4318.8	1257	1096	693	290	-112				
Sorghum (ratoon)	2445.4	569	470	223	-24					
Sorghum (fodder)	3205.9	789	661	343	25	-293				
Maize	7246.9	3699	3513	3046	2579	2112	1646	1179	712	-2089
Millet	2809.6	110	-32							
Cotton	5265.0	1127	909	365	-180					
Sesame	3928.3	1207	1064	706	347	-11				
Tobacco	15786.5	12425	12248	11806	11363	10921	10479	10037	9594	6940
Tomatoes	14495.0	10376	10159	9617	9075	8533	7991	7449	6907	3655
Vegetables	27759.0	24968	24821	24454	24087	23719	23352	22985	22618	20414
Cowpeas	2629.0	-584								
Fruits	91550.0	82510	82034	80845	79655	78466	77276	76087	74898	67761
Melon	12705.0	9464	9294	8868	8441	8015	7588	7162	6736	4177

* Defined as gross income minus cash costs. The cash costs include the costs of hired labour, tractor/machinery, fertilizer, seed, pesticides, taxes, and land rent).

fraction of the cultivated area. Low agricultural productivity and inefficient water use are considered to be the major reasons for low water productivity. Future investments in irrigation development projects in the Tihama would most likely be economically justifiable only if either the water is used to grow cash crops or productivity of other crops is substantially enhanced.

2.4 Water Resources Management Issues in the Tihama

It has been evident for a number of years that there is a need for improved water management in the Tihama region. Previous studies and projects undertaken are a good indication of this. Based on the survey of the water systems and uses in the Tihama contained in the previous sections, some basic issues that will need to be addressed to understand and improve water management practices have been identified. There have been commendable efforts in this direction before, notably in the DHV [1988a] Tihama basin study and in the recent Wadi Surdud study [van der Gun and Wesseling, 1991], in addition to other wadi specific studies. Not surprisingly, the issues cited below show a number of coincident perceptions with those of previous efforts, although emphasis may differ. The issues described below are not totally independent from each other. Unavoidably, many aspects associated to the various issues are interrelated.

2.4.1 Conflict Between Catchment and Tihama Plain Users

Both the catchments and the Tihama plain basin are areas of dynamic socio-economic evolution. The catchments show zones of terrace building and of terrace abandonment. Internal migration from the escarpments to the foothills of the Tihama as well as to the urban concentrations in the highlands is occurring. Nonetheless, there is evidence that water usage is increasing in the catchments. The direct effects are that the baseflows may be decreasing in some catchments (and also flood flow as Wadi Rima's records seem to indicate). This would reduce the availability of surface water in the plain and the recharge to the alluvial aquifer, amounting to a distressing situation in an already water-short region with mounting demands of its own. Thus, if the trend of growing water use in the catchments is verified, then it would constitute a clear competition for water resources between the two parts. The erosion and destruction of terraces not only affects soil and water conservation in the escarpment, with loss of agricultural land and production, but has negative side effects downstream (increased sediment transportation as well as larger flood peaks and volumes).

2.4.2 Inequity Between Upstream and Downstream Wadi Users in the Plain

Traditional customary rights uphold the preferential right of upstream farmers to wadi water, but within bounds. This translates into (1) a greater amount of surface water diverted by upstream farmers, (2) a greater regularity of supply (greater share of baseflow) for them, and, consequently, (3) a more reliable supply for upstream users. These characteristics have generally become more pronounced with the implementation of modern irrigation systems, since the technical operational procedures proposed by the designers have not been applied. The traditional water allocation mechanisms have broken down, reinforcing the supremacy of upstream farmers, who in most cases are large landowners.

2.4.3 Effect of Continued Over-exploitation of the Tihama Aquifer

As shown above, there is currently a net draft from the alluvial aquifer storage in the Tihama plain of about 900 Mm^3 per year. The trends detected point to growing abstractions. There are a number of undesirable effects that result from the over-exploitation of the aquifer:

(1) Dropping water table levels resulting in more expensive pumped water.

(2) Inland displacement of the saline interface preceded by occurrences of upconing in areas of intense abstraction. The progression of the sea water intrusion is sensitive to the relative density of sea water with respect to the density of fresh water; modelling studies to date have assumed an average sea water density for the Red Sea.[2] If the real density is greater than average sea water density, the salt water interface encroachment will be greater.

(3) Effective areal reduction of the exploitable aquifer because of quality constraints (such as that resulting from the inland movement of the salt water interface) and because of geological boundaries and other aquifer properties.

(2) Normal seawater is considered to have about 35,000 parts per million of total dissolved solids; according to Al-Ibrahim [1990] "... the TDS level in the Red Sea and Arabian Gulf (which varies between 40,000 and 60,000 ppm) is much higher than that of other seas and oceans".

(4) Risk of eventual exhaustion of usable storage causing enormous economic, technological and water quality problems with serious socio-economic consequences for the region and for the country.

2.4.4 Efficiency in the Use of Water

The term efficiency has a number of connotations that are applicable to the Tihama case. These may be grouped in the following two categories:

(1) Overall economic efficiency in the use of water, which is equivalent to maximizing benefits per unit of water. Achieving overall economic efficiency involves sectoral allocation, especially when domestic and industrial uses compete with agriculture (such as in Wadi Siham); spatial allocation to produce the best economic mix (catchment vs. basin, upstream vs. downstream wadi user, land use and accessible water quality mix, etc); economic return to water from the various irrigation methods; allocation of water under deficit irrigation to minimize impact of depressed yields.

(2) Irrigation efficiency, which is basically the portion of the water diverted or abstracted for irrigation that is used by crop evapotranspiration. There are a number of ways that conveyance and application of water can be improved in gravity irrigation systems to enhance the overall irrigation efficiency; also there are other higher technology methods (sprinkle, drip and bubbler irrigation) that could be implemented. The attainment of greater localized on-farm irrigation efficiency usually implies a larger water consumption and a corresponding reduction of recharge to the aquifer. A system-wide water balance will aid to discriminate effective gains from just a geographical redistribution of water use or increased aquifer imbalance.

2.4.5 Effects of Interbasin Transfer of Water

As the water shortages in the Yemeni highlands increase, particularly for the coverage of industrial and domestic needs in the main urban concentrations, the option of diverting water from the Tihama catchments will receive increased attention. The possibility of using Wadi Surdud's water for Sana'a has already been postulated. Since the Tihama is already a water short region, the potential impact of a decrease of water availability will need to be clearly articulated and trade-offs will have to be clearly identified and understood for use in the decision-making process.

2.4.6 Conflict of Current Policy of Water Use Expansion with Conservation

As a result of growing population pressure in the Tihama (even greater by the sudden influx of returnees: over 200,000 in the Hodeidah area only) and the objective of greater self-reliance in food production, it is very understandable that official policy dictates a growth of coverage of urban and rural water supply and that many official projects support irrigation expansion. The private sector is also very active in the basically unrestricted construction of additional wells, compounding the expansion-oriented outlook. There is a need to find a balance between these actions and the current and projected situation of the water resources system, particularly within a sustainable development framework.

2.4.7 Institutional Aspects

As described in Section 2.1, there are numerous institutions operating in the Tihama region, each looking after certain functions in their separate geographical jurisdictions. Though TDA already has a broad mandate, it is neither integral nor does it cover all the concerned areas. The nature of the problems facing the Tihama region requires the concerted multi-sectoral action for their solution or mitigation, as is evident, for example, from the catchment vs. plain conflict, from the uncontrolled groundwater abstraction by the private sector, and from the urban and industrial expansion in the environs of Hodeidah. There is a need for policy formulation and guidance in its implementation from the highest level, and for functionally sound institutions with proper staffing. Formulation of an institutional development plan goes, however, beyond the scope of this report.

Table 2.7 Financial Prices of Inputs and Outputs in Tihama Region (1990-91)

Item	Unit	Price	Remarks
A: COMMON INPUT PRICES			
1. Manual labour	Day	60.0	
2. Bullock labour	Day	100.0	
3. Tractor/Machinery	Hour	100.0	
4. Fertilizer	Kg	6.5	
5. Pesticides	Kg	150.0	
6. Farm manure	D.load	8.0	
7. Taxes (zakat)	Rials	5 % of GVP in spate irrigated areas and 10 % of GVP in groundwater irrigated areas	
8. Land rent	Rials	460.0	Opportunity cost: calculated on the basis of benefits foregone under dry land production conditions

B: CROP SPECIFIC PRICES		Sgm.s	Sgm.k	Sgm.r	Sgm.f	Mze	Mlt	Ctn	Sme	Tbc	Tmt	Veg	Cps	Frt*	Mel
Seed	Kg	5.7	5.7	0.0	6.0	7.0	15.3	2.0	24.0	10.0	350.0	10.0	5.3	1000.0	105.0
Main product	Kg	4.8	4.8	4.8	0.7	7.0	6.5	6.0	13.3	9.8	2.4	6.0	5.2	7.5	3.2
By product	Kg	0.6	0.6	0.6	0.0	0.6	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Sources: The above information has been derived from the following sources: (a). NESPAK [1989], Wadi Siham Project: Inception Report, TDA/MAWR; (b) Al Eryani et.al [1991], Issue Paper for Tihama Region, TS/HWC Project; (c) Chaudhry and Turkawi [1989], Economics of Irrigation Development in Yemen: Evaluation of Some Case Studies, TS/HWC Project; and Personal Communication with TDA Staff.

* Price of seed for fruit reflects the annualized cost of plants at 10% discount rate.

Table 2.8 Per Hectare Input Use of Various Crops in Tihama Region (Spate Irrigation System)

Description	Units	Sgm.s	Sgm.k	Sgm.r	Sgm.f	Mze	Mlt	Ctn	Sme	Tbc	Tmt	Veg	Cps	Frt	Mel
1. Manual labour	Days	28.1	28.1	25.0	17.8	30.0	23.0	30.0	25.0	89.2	63.9	40.0	25.0	159.3	55.0
2. Bullock labour	Days	2.5	2.5	0.0	4.4	2.8	2.8	5.0	2.0	3.6	3.9	3.0	3.0	1.0	4.0
3. Tractor/Machinery	Hours	13.1	13.1	3.0	9.2	18.0	13.0	13.6	10.0	12.8	14.2	10.0	8.0	18.9	8.0
4. Fertilizer	Kgs	0.0	0.0	0.0	0.0	7.0	0.0	15.0	0.0	50.0	70.0	100.0	0.0	75.0	0.0
5. Seeds	Kgs	23.4	23.4	0.0	23.6	23.9	18.3	40.0	19.5	1.4	1.1	3.6	2.2	*	5.0
6. Pesticides	Kgs	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	2.0	2.0	2.0	0.0	10.0	0.0
7. Farm manure	D.load	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	3.0	3.0	6.0	2.0	4.0	2.0
8. Taxes (zakat)	Rials	5 % of GVP in spate irrigated areas													
9. Land rent	Rials	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	920.0	460.0
Yield															
Main product	Kgs	1000.0	1000.0	600.0	5500.0	1200.0	700.0	1050.0	350.0	1500.0	7000.0	4000.0	725.0	10000.0	4000.0
By-product*	Kgs	40.0	40.0	24.0	0.0	48.0	28.0	42.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Same as for Table 2.7
* By-product yield is assumed as 4 percent of the main product yield.

Table 2.9 Per Hectare Input Use of Various Crops in Tihama Region (Groundwater Irrigation System)

Description	Units	Sgm.s	Sgm.k	Sgm.r	Sgm.f	Mze	Mlt	Ctn	Sme	Tbc	Tmt	Veg	Cps	Frt	Mel
1. Manual labor	Days	35.0	35.0	26.0	23.0	40.0	25.0	35.0	32.0	92.0	65.0	55.0	27.0	170.0	62.0
2. Bullock labor	Days	2.5	2.5	0.0	4.4	4.0	2.8	5.0	2.0	4.0	3.9	5.0	3.0	2.0	4.0
3. Tractor/Machinery	Hours	15.0	15.0	4.0	10.0	20.0	15.0	15.0	12.0	20.0	15.0	15.0	9.0	30.0	8.0
4. Fertilizer	Kgs	5.0	5.0	3.0	5.0	15.0	3.0	20.0	5.0	75.0	90.0	120.0	5.0	100.0	20.0
5. Seeds	Kgs	23.4	23.4	0.0	23.6	23.9	18.3	40.0	19.5	1.4	1.1	3.6	2.2	*	5.0
6. Pesticides	Kgs	0.0	0.0	0.0	0.0	0.0	0.0	4.0	3.0	10.0	10.0	10.0	0.0	20.0	5.0
7. Farm manure	D.load	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	3.0	3.0	6.0	2.0	4.0	2.0
8. Taxes (zakat)	Rials	10 % of GVP in groundwater irrigated areas													
9. Land rent	Rials	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	920.0	460.0
Yield															
Main product	Kgs	1500.0	1500.0	750.0	7500.0	1600.0	850.0	1500.0	550.0	2400.0	9000.0	6000.0	850.0	15000.0	5500.0
By-product*	Kgs	60.0	60.0	30.0	0.0	64.0	34.0	60.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Same as for Table 2.7
* By-product yield is assumed as 4 percent of the main product yield.

Table 2.10 Cost of Production and Income of Various Crops in Tihama Region (Spate Irrigation System)--Rials/ha

Description	Units	Sgm.s	Sgm.k	Sgm.r	Sgm.f	Mze	Mlt	Ctn	Sme	Tbc	Tmt	Veg	Cps	Frt	Mel
A: Production Costs															
1. Manual labor	Rials	1686.0	1686.0	1500.0	1068.0	1800.0	1380.0	1800.0	1500.0	5352.0	3834.0	2400.0	1500.0	9558.0	3300.0
2. Bullock labor	Rials	250.0	250.0	0.0	440.0	280.0	280.0	500.0	200.0	360.0	390.0	300.0	300.0	100.0	400.0
3. Tractor/Machinery	Rials	1310.0	1310.0	300.0	920.0	1800.0	1300.0	1360.0	1000.0	1280.0	1420.0	1000.0	800.0	1890.0	800.0
4. Fertilizer	Rials	0.0	0.0	0.0	0.0	45.5	0.0	97.5	0.0	325.0	455.0	650.0	0.0	487.5	0.0
5. Seeds	Rials	133.4	133.4	0.0	141.6	167.3	279.1	80.0	468.0	14.0	385.0	36.0	11.6	500.0	525.0
6. Pesticides	Rials	0.0	0.0	0.0	0.0	0.0	0.0	600.0	0.0	300.0	300.0	300.0	0.0	1500.0	0.0
7. Farm manure	Rials	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	24.0	24.0	48.0	16.0	32.0	16.0
8. Taxes (zakat)	Rials	241.1	241.1	144.7	192.5	421.3	228.0	315.0	231.9	735.0	840.0	1200.0	188.5	3750.0	640.0
9. Land rent	Rials	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	920.0	460.0
Total Costs	Rials	4096.5	4096.5	2420.7	3238.1	4990.1	3943.1	5228.5	3875.9	8850.0	8108.0	6394.0	3276.1	18737.5	6141.0
B: Income	Rials														
Main product	Rials	4800.0	4800.0	2880.0	3850.0	8400.0	4550.0	6300.0	4637.5	14700.0	16800.0	24000.0	3770.0	75000.0	12800.0
By-product	Rials	22.0	22.0	13.2	0.0	26.4	9.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gross Income	Rials	4822.0	4822.0	2893.2	3850.0	8426.4	4559.8	6300.0	4637.5	14700.0	16800.0	24000.0	3770.0	75000.0	12800.0
C: Net Income	Rials	725.5	725.5	472.5	611.9	3436.3	616.7	1071.5	761.6	5850.0	8692.0	17606.0	493.9	56262.5	6659.0

Table 2.11 Cost of Production and Income of Various Crops in Tihama Region (Groundwater Irrigation System)--Rials/ha

Description	Units	Sgm.s	Sgm.k	Sgm.r	Sgm.f	Mze	Mlt	Ctn	Sme	Tbc	Tmt	Veg	Cps	Frt	Mel
A: Production Costs															
1. Manual labor	Rials	2100.0	2100.0	1560.0	1380.0	2400.0	1500.0	2100.0	1920.0	5520.0	3900.0	3300.0	1620.0	10200.0	3720.0
2. Bullock labor	Rials	250.0	250.0	0.0	440.0	400.0	280.0	500.0	200.0	400.0	390.0	500.0	300.0	200.0	400.0
3. Tractor/Machinery	Rials	1500.0	1500.0	400.0	1000.0	2000.0	1500.0	1500.0	1200.0	2000.0	1500.0	1500.0	900.0	3000.0	800.0
4. Fertilizer	Rials	32.5	32.5	19.5	32.5	97.5	19.5	130.0	32.5	487.5	585.0	780.0	32.5	650.0	130.0
5. Seeds	Rials	133.4	133.4	0.0	141.6	167.3	279.1	80.0	468.0	14.0	385.0	36.0	11.6	500.0	525.0
6. Pesticides	Rials	0.0	0.0	0.0	0.0	0.0	0.0	600.0	450.0	1500.0	1500.0	1500.0	0.0	3000.0	750.0
7. Farm manure	Rials	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	24.0	24.0	48.0	16.0	32.0	16.0
8. Taxes (zakat)	Rials	723.3	723.3	361.7	525.0	1123.5	553.7	900.0	728.8	2352.0	2160.0	3600.0	442.0	11250.0	1760.0
9. Land rent	Rials	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	460.0	920.0	460.0
Total Costs	Rials	5215.2	5215.2	2817.2	3995.1	6664.3	4608.3	6286.0	5475.3	12757.5	10904.0	11724.0	3782.1	29752.0	8561.0
B: Income	Rials														
Main product	Rials	7200.0	7200.0	3600.0	5250.0	11200.0	5525.0	9000.0	7287.5	23520.0	21600.0	36000.0	4420.0	112500.0	17600.0
By-product	Rials	33.0	33.0	16.5	0.0	35.2	11.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gross Income	Rials	7233.0	7233.0	3616.5	5250.0	11235.2	5536.9	9000.0	7287.5	23520.0	21600.0	36000.0	4420.0	112500.0	17600.0
C: Net Income	Rials	2017.8	2017.8	799.4	1254.9	4570.9	928.6	2714.0	1812.3	10762.5	10696.0	24276.0	637.9	82748.0	9039.0

CHAPTER 3
FRAMEWORK FOR MANAGEMENT ANALYSIS

The HWC has embarked on the development of a methodological framework for water resources planning at a regional level in Yemen, aimed primarily at the consideration of alternative management strategies. The nature and scope of the water resources problems vary from region to region, thus the treatment given to the Sana'a Basin (Volume IX) differs from the one that may be applied to the Tihama region. This chapter: (1) reviews the approach that can be taken to formulate water resources management strategies appropriate for the Tihama, discussing planning objectives, possible measures that can be undertaken, and ways to evaluate alternative strategies; and (2) describes the mathematical models to support the analysis.

3.1 Water Resources Management Planning

Chapter 2 concludes with the identification of various pressing issues in water resources management in the Tihama. Implicit in that identification is the perception that there exist problems, current or potential, and that there are means and ways to guide the situation to a desirable future. What that desirable future is has to be articulated. Hence planning objectives have to be formulated and translated into specifics.

If the problems were self-correcting or self-regulating (by the market mechanism, by customary conflict resolution means, or by other balances and checks mechanisms) there would be no need for external intervention. The nature of the problems, however, call for the implementation of appropriately designed water resources management strategies by government. This may be clearly seen from the conflict of catchment users and Tihama plain users, who are spatially and socially disconnected, yet compete for the same water resources. It is also clear that inequity in water distribution between upstream and downstream wadi farmers on the plain has in many cases been made more acute with the introduction of modern irrigation infrastructure and the breakdown of traditional water allocation institutions. Competition for groundwater resources on the plain is another case in point: individuals will try to maximize their take of a resource which they may view as private property, when in fact it is common property. Unrestricted exploitation may lead to immediate gains but also to future disaster.

3.1.1 Developmental Objectives

The objectives to be defined here are those to be pursued through the application of water resources management strategies. Pressures upon water resources are mounting because of increased population, agricultural expansion and industrial growth (usually signs of "progress"). Numerous water use conflicts are emerging or are being made worse. Section 2.2.3 on Groundwater Resources pointed out evidence that there is already severe groundwater over-exploitation. Uncontrolled consumption of the water reserves is leading to grave problems of depletion and rising costs of water. Thus, government intervention is predicated on the assumption that it may be able to implement some measures which could alleviate these problems.

These interventions would be guided by the need to achieve the following objectives:

(1) Economic efficiency and social equity in sectoral and spatial water allocation in the Tihama region.

(2) Achievement of sustainable development at the regional and national level by striving for:

- sustainability of the economic and social activities in the Tihama region, maintaining the vigour required of the main agriculturally productive area of Yemen, and

- sound environmental management leading to sustainable development at regional and national levels, warding off depletion and deterioration of resources, and securing inter-generational equity.

3.1.2 Planning Approach

In its broadest sense, planning for development of the Tihama region would be a multisectorial study within a national development framework. The main focus of this report is water resources management, and how strategies may contribute to the attainment of the above development objectives. This section outlines concepts that should be helpful when performing a full-fledged analysis of water resources in the Tihama. The scope of this report allows the identification of the concerned issues, the discussion of the elements involved in defining the applicable water resources management strategies, the description of the analytical tools developed and suggested extension (Section 3.2), and the illustration of the application of the analytical methods to Wadi Surdud.

The natural planning unit in a setting such as the Tihama is the wadi catchment. It is an integral, independent physical system with water resources development schemes separated from those in other wadis. Exceptions may exist, such as the possible groundwater transfer from the highland's Tawilah Sandstone Aquifer to the upper Wadi Surdud catchment, feeding some springs, or the potential diversion of the same wadi's surface water resources for Sana'a's water supply. Nonetheless, it is convenient to develop a general approach involving the wadi as the planning unit.

In a planning effort focused on a wadi basin unit and directed primarily towards water resources management, certain aspects of great importance, such as institutional aspects, agricultural production policy, and population policy may be touched on tangentially, or not at all. Consequently, macro aspects which could be affected by the adoption of broad government policies, such as population growth, management of resources outside of the Tihama region and foodstuff importation policy, lie outside of the scope of the management options that can be proposed as a result of this narrower approach. These exogenous aspects would become part of the planning scenarios.

In order to make a planning study more targeted, initially a limited, but meaningful, number of management strategies should be analysed. The "non-intervention" case (also called "do-nothing" alternative) is the basis for further analysis. It will allow a better understanding of the physical and economic processes at work, a clearer definition of the consequences of inaction (problem characterization), and a more precise identification of the areas which need attention or that may be more responsive to intervention. Also, due to the difficulty in evaluating absolute social and economic consequences of the application of various water resources management strategies, evaluation criteria may need to be referred to this baseline case (incremental costs and benefits). Other cases can not be properly formulated without completing this first step.

Scenarios

Before embarking in the analysis of the effects of the strategies, planning scenarios need to be formulated. A scenario is the set of external conditions which are imposed on the analysis. A scenario may be expressed "statically": e.g. population or the price of fuel at a certain point in time. Better yet it should include initial state (year 0) and the rate of change or evolution throughout the planning horizon. Some of the external factors that will probably affect the formulation of scenarios (explicitly or implicitly) are:

- Population growth in its urban and rural components
- International and national market conditions
- National financial resources
- Technological progress
- Political setting
- Legislative framework

The initial (year 0) state would normally be taken as the same for all scenarios (this need not be so if, for instance, there are serious discrepancies in estimates of current population). Future conditions for the main set of analyses can reflect expected central trends, plus possibly some sensitivity explorations. The occurrence of uncertain events (e.g., the decision of transferring water resources out of the catchment at a certain date) may also be explored.

Evaluation Criteria

It is clear that in many respects the objectives indicated in 3.1.2 are conflicting: one objective is to try to keep the Tihama active and progressive (hence use up natural resources), while another objective preaches sustainability (hence protect the resources). Alternatively, the objectives are to maximize current well-being, while at the same time being fair to future generations; or to maximize the benefits to catchment and plain inhabitants who are competing for the same resources. Thus, the problem has multiple objectives.

The evaluating criteria should try to represent fairly and objectively the effect of alternative management strategies on the above objectives. It must be kept in mind that, given the primary sustainability objective, the state of the system at the end of the period of analysis may be an important element by which to judge a strategy (unlike traditional problems in which end-of-period stability is assumed, and thus net present values are significant).

Some suggested general guidelines for the formulation of evaluation criteria are presented below.

(1) Four main categories of indicators may be adopted. These include economic; social; environmental; and political, administrative and financial indicators. For each of these, possible indicators are briefly discussed.

(i) **Economic indicators.** Possible indicators include the following:

- **Net benefits to water users in the wadi basin.** This indicator will represent the economic impact of the strategy on the region. It will typically be represented primarily by the net income of the agricultural sector, the main water-consuming and productive sector. In the case of Wadi Siham, the industrial and domestic sectors are important, thus their benefits should be included. The quantification of the benefits of water supply may require the use of the concept of consumer surplus.

- **Direct and indirect costs.** The costs of the following items should be covered: (a) facilities: construction of new wells, deepening of existing ones, equipment, irrigation infrastructure, etc.; (b) operation and maintenance cost of facilities; (c) administrative costs of implementing measures that are part of the strategy; (d) benefits from water use foregone at the source in case of transfer between basins; (e) value of water depleted from aquifer storage (costs of natural resource depletion or benefits foregone by future generations).

- **Employment effects.** This indicator may represent the changes in employment in the agricultural sector, and those which may be induced in other sectors by the water related activities.

- **Cost of pumped water.** This indicator will be relevant in connection with the issue of economic viability. The maximum cost of water that can be absorbed by a productive process will correspond to a certain depth of pumping. This indicator can be used to illustrate the year in which the economic threshold will be reached for different activities, particularly agricultural crops at different locations.

(ii) **Social indicators.** Possible indicators include the following:

- **Equity.** This indicator will deal with the fairness of a given strategy to people. An attempt can be made to determine whether income distribution becomes more uniform or more skewed by the application of the strategy.

Another aspect of equity relates to the spatial (or geographical) dimension, especially when location determines priorities in access to water. Intergenerational equity must also be considered.

- **Per capita potable water consumption.** This indicator may be particularly meaningful when water supply to an urban concentration is involved in the problem. It acts as a proxy indicator for well-being and health of the urban and rural population.

(iii) **Environmental indicators.** Possible indicators may include the following:

- **Aquifer sustainability.** This is a fundamental indicator. Physical parameters, such as the aquifer drawdown trend over time, usable storage depletion, inland penetration of the saline interface, and loss of effective aquifer area may be given to define the evolution of the aquifer.

- **Agricultural water quality.** This indicator measures the expected water quality deterioration due to upconing of the saline interface and other local influences based on the strategy applied

- **Ecological impact on the Red Sea.** There is vigorous fishing activity along the coast in Yemen. If fresh water outflow to the Red Sea is curtailed, the effects on fish life must be taken into account and is expressed by this indicator.

(iv) **Political, administrative and financial indicators.** Possible indicators may include the following:

- **Political viability.** This indicator may include a qualitative assessment of (a) likely degree of support for the strategy from Yemeni government based on the content and implications of the strategy and against other priorities, (b) legal difficulties associated with formal adoption of the strategy and its ease of implementation, (c) acceptability of the strategy to public, (d) existence or likelihood of timely establishment of proper institutional framework for implementing the strategy.

- **Administrative considerations.** This indicator would provide a statement on (a) human resources needed to staff agencies and likelihood of having it available, (b) administrative difficulties in carrying out implementation of measures: possible complementarity or duplication of functions, potential shortcomings in support to logistics, potential interventions to thwart application of regulations, (c) ease of monitoring progress of application of strategy and flexibility to adapt strategy to changing conditions.

- **Financial considerations.** This indicator would provide information on the financial requirements for implementation of the strategy as well as identification of possible sources of funds, such as user charges, loans, taxes, and subsidies.

(2) The benefits and costs do not necessarily have to be measured in absolute terms but against the baseline case; that is against the "non-intervention" case as previously defined. Thus, for comparing alternative strategies, one is interested in incremental values. Things that may be important in their own right, but that remain essentially constant for the different cases, will not affect the comparision, thus need not be taken into account.

(3) If possible the indicators should be quantified. If this is not possible a concise qualitative assessment of the strategy on the indicator should be presented. It would also be desirable to be able to reduce the final rating of the set of indicators corresponding to a management strategy to a single scalar resulting from the weighting or ranking of the indicators. This may not be entirely possible, and in most cases some subjective group judgments might be called for.

(4) The final evaluation of a given strategy is based on judging the overall effect of the various strategies on the indicators selected. This choice is based on the judgement of the decision makers, who need to articulate the type of information they need to reach a decision. Early involvement of decision makers in the selection of objectives and associated indicators is therefore critical for the planning process. The task of the analyst is to present the results of the analysis and possible courses of action in a clear and concise manner.

3.1.3 Water Resources Management Strategies

The term *water resources management strategy* as used here is defined after Bower [1992] as having the following components:

- a definition of the products and services to be produced.
- the required physical measures or facilities.
- rules for operating the facilities
- implementation incentives to induce desired behaviour.
- institutional arrangement
- financial plan

Products and Services to be Produced

For the case under consideration the services to be provided consist of provision of water for various users in the planning unit, which would include the catchment and Tihama plain area corresponding to the catchment. The magnitude and spatial and temporal distribution of water have to be specified. Thus, projections of water to be provided to the different users at different places at different times have to be made. The planning of the physical infrastructure and its operating rules are thus linked to the definition of the product.

For a Tihama wadi (except perhaps Wadi Siham), the quantity of municipal water demand falls well within the margin of error in the estimates of the predominantly agricultural requirements. The magnitude of estimates of water to be provided for the different users will respond to the measures that are assumed to be implemented.

Physical Measures and Facilities

The non-intervention case ("baseline case") will normally be used as basis of comparison. Thus, only those physical measures and facilities in addition (incremental) to the ones considered in the baseline case need be taken into account as far as cost is concerned. The different physical measures or facilities include changes from the non-intervention case in

- wells, pumps, deepening of wells
- irrigation delivery and distribution infrastructure
- expansion of water supply and sewerage networks
- necessary facilities for institutional, regulation enforcement, and extension service measures which may be prescribed.

Some specific options of water management applicable to the Tihama could be:

- integrated management of mountain catchment and the Tihama plain water resources, with explicit recognition of their interrelationship and of the objectives of the inhabitants of both parts.
- in view of the high proportion of wadi flow that is usually lost as recharge to the aquifer in the upper part of the alluvial fan upstream of the existing diversions, capturing part of that surface flow with complementary diversion schemes might be economically justified against the aquifer pumping otherwise required.
- altering groundwater abstraction patterns so as to reduce local dewatering and/or to gain flow that would otherwise go to the sea.

More detailed information on groundwater management options may be found in the Tihama groundwater resources assessment report (Volume IV, Annex C).

Rules for Operating the Facilities

Many of the operating rules have to be incorporated in simulation models. Even then it is not normally possible to replicate in detail of the physical process itself, i.e, hydraulic transients in surface flows, soil moisture movement, water distribution in each field, fate of rainfall (evapotranspiration, evaporation, infiltration), etc. A number of assumptions, simplified relationships, and lumping coefficients to represent the operation of the system will be required. For instance, simplifying assumptions will be needed in the following, with special emphasis on those that may differ from the baseline case:

- wadi diversion capacity functions
- well abstractions based on average operating hours.
- irrigation efficiencies according to technology used
- water allocation rules
- farmer response on the face of water scarcity

The rules of operation employed have to reflect the effect of the incentives, described below, which might be adopted in the water management strategies.

Implementation Incentives to Induce Desired Behaviour

For the Tihama wadis this is in general expected to be the core of the strategy. The number and type of generic incentives are many, and many more can be introduced in an ad-hoc manner. It is usually difficult to predict the degree of success of an incentive or of a combination of incentives, and the success of a strategy will hinge on that. The strategies that will be proposed will seek to conserve water and attain greater efficiency in the use of water. Some of the possible measures aimed primarily to reducing abstraction and/or demand are:

(1) **General (applicable to all water consuming sectors, predominantly agriculture):**

- Raise fuel costs: (1) by increasing price to border price or local true cost level (elimination of subsidies), (2) by adding surcharge to reflect, say, cost to society of using water now. There is already a subsidy-removal program in progress.
- Establish stiffer import duties on pumps and other imported equipment and materials used for groundwater abstraction.
- Implement educational and awareness campaigns directed to government officials, farmers, and the public in general.
- Provide incentives to stem migration from escarpments to the plain.
- Control groundwater exploitation by regulations for well registration, spacing, depth, horsepower and annual abstraction volume according to zones and uses; by permits and taxes for well operators; and by the institution of protection zones.

(2) **Irrigation (measures additional to above):**

- Implement measures so that farmers achieve greater irrigation efficiency. Higher irrigation efficiencies might not make additional resources available to the system, because most of the excess surface water feeds the aquifer from where it can be re-utilized, but cost per hectare of pumped water and cost of diversion and conveyance structures may decrease. Measures proposed may include special credit for the acquisition of materials and equipment needed for efficient use of water.
- Implement research and extension services to teach and advice farmers on techniques to achieve higher productivity and economic sustainability, especially as related to water saving.
- Implement other measures to discourage expansion (or even encourage reduction [DHV, 1988a]) of irrigation areas, including charging cost of wadi irrigation to users.

(3) **Municipal and industrial (if relevant, as in Wadi Siham):**

- Reduce distribution losses and other unaccounted-for losses (that is, reduce leakages and illegal connections)
- Implement higher tariffs, reflecting higher fuel costs and willingness to pay, keeping in mind social objectives.
- Ration water supply from public network through limited hours of service.
- Reuse treated wastewater
- Charge for disposal of effluent so industries may consider recycling of water.

- Provide credit incentives for investment in measures to increase industrial water use efficiency.
- Provide technical information on water saving technology (industrial extension service).
- Provide incentives for a wider geographical distribution of industries in the Tihama region. Water demand might not be necessarily reduced, but better conservation and management of the aquifers may be achieved this way (metering would also be a requirement).

Institutional Arrangements and Financial Plan

These are the necessary complementary components to have well-rounded strategies. They will depend directly on the type of measures that are proposed for implementation. The considerations mentioned in connection with the indicators dealing with political, administrative and financial feasibility of a strategy are applicable here.

3.2 Analysis in Support of Planning

3.2.1 General

This section describes the approach adopted for the design of the planning model for the Tihama and its components. The objectives of this effort were to design an analytical framework for the Tihama that would provide:

(1) A methodology and instruments responsive to the study of the water resources management issues identified and described in Chapter 2 and in accordance with the concepts presented in Section 3.1. This will permit:

- (i) the systematic exploration of various planning scenarios and management options
- (ii) a distributed representation of the physical setting with sufficient resolution to effectively evaluate the impact of water management practices
- (iii) the evaluation of economic and other policies that may be adopted.

(2) A general methodology with corresponding models readily adaptable to specific wadis of coastal Yemen so the planning effort may be advantageously and consistently replicated across the various wadis.

(3) A methodology and a set of robust and well-defined modelling components with clear operating procedures that may be implemented by the TS-HWC.

A cornerstone for the planning process is an adequate water resources assessment. This is presented in the reports on Surface Water Resources, Volume III, and Groundwater Resources, Volume IV. The surface and groundwater assessments of the northern governorates undertook an overall appraisal of the monitoring networks, evaluated the data collected, and produced estimates of water availability using all information on hand. The northern governorates were covered at depth, and the southern governorates were the subject of a succinct water resources review. Procedures, models, and guidelines for continuing action in water resources assessment are contained in the volumes cited.

The rainfall-runoff model (see Chapter 4 and Annex C of Volume III) was developed for the surface water resources assessment to produce a more reliable estimate of wadi flows and time series of sufficient duration for the planning analyses. The model has been endowed with a number of features that can be particularly useful for planning: catchment conditions can be modified to simulate natural or man-made changes, and thus the response on surface water availability at the outlet of the catchment can be evaluated. In this sense, the rainfall-runoff model can be considered part of the suite of planning model components, and not only as an analytic support for water resources assessment.

In this section, three components of the planning model are briefly described: the Irrigation Simulation Model (ISM), the Groundwater Simulation Model (GSM), and the Economic Planning Model (EPM). The interaction among the various models is shown in Figure 3.1. The two simulation models, though they have been created as stand-alone models, complement each other and linking routines have been implemented. The ISM simulates the operation of the surface water and groundwater system (wadi and irrigation schemes, plus cropping pattern water use and yield) and provides recharge and abstraction data to the GSM. The GSM represents the response of the aquifer to the management options. A generalised Tihama groundwater model was also developed and served as the basis for the design of the GSM; it is also discussed in Section 3.2.3. The EPM, an optimization model, can be used to examine the system response to various economic policies and to determine the optimal cropping pattern and set some other conditions for the simulation runs. The first two components, the ISM and the EPM have been implemented and tested. The EPM has been conceptually formulated.

3.2.2 The Irrigation Simulation Model

The Irrigation System Simulation Model (ISM) has been designed to estimate quantities and timing of groundwater recharge, groundwater abstractions, and crop water use and yields based on wadi flood flows and on the size of irrigated development and groundwater pumping capacity. The Irrigation Simulation Model is a general purpose model and can be readily applied elsewhere in Yemen to simulate irrigation practices and recharge for other coastal wadi systems. The Irrigation Simulation Model is described in detail in Annex A. The ISM is intended to provide the following:

(1) A time-series evaluation of the results of an irrigation and cropping practice and development.

(2) A more detailed representation of the irrigation schemes than is possible in an optimizing economic planning model, especially in terms of non-linearities and a shorter time-step.

(3) Analysis of the quantitative interaction of surface and groundwater so as to produce a time-series of groundwater abstraction and recharge estimates responsive to the variations in surface water supply and rainfall.

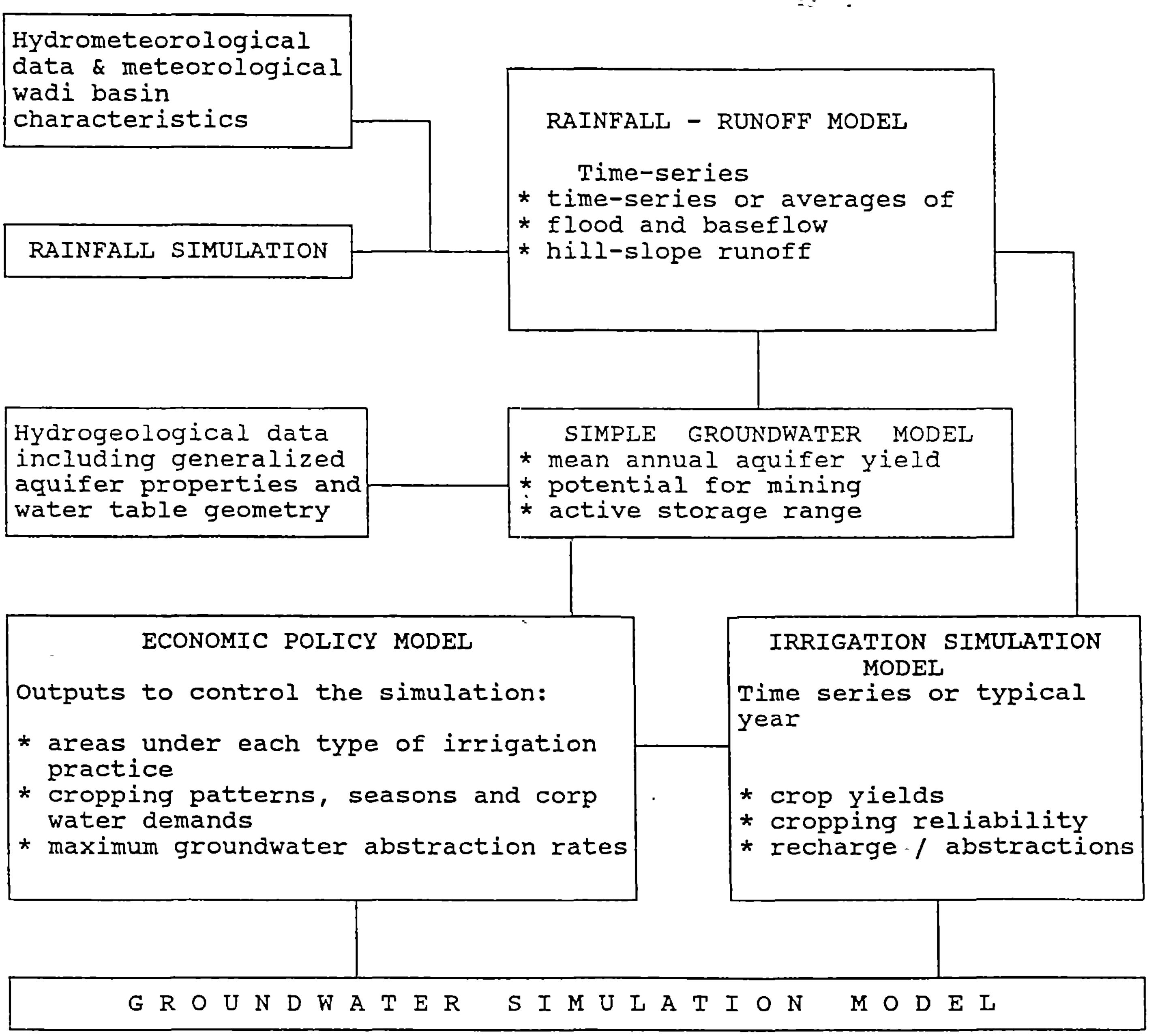

Figure 3.1 Components of the Planning Model of the Tihama

The ISM model attempts to describe two interrelated processes. It describes the overall movement of surface water through the wadi network, through spate diversion structures and within irrigated blocks. It also estimates quantities and timing of groundwater abstraction to irrigation blocks and corresponding recharge of groundwater. The ISM model describes both the demand and the supply water balance of irrigation blocks in response to a defined cropping pattern and calendar.

The ISM program has been divided into a number of subroutines so that specific processes can be treated separately and further modification made as simply as possible. Data files have been defined so that the data are divided into sections. In this way frequent changes of the more volatile data do not involve manipulation of the more permanent data.

The basic computation time step in the Irrigation Simulation Model is the decade (10 days). Wadi discharge data is read in daily time steps, but is summed into decade values. Up to twenty years of wadi flood flow and rainfall discharge can be evaluated in one simulation. Recharge and groundwater abstraction is reported in monthly time steps.

Definition of the Network

The configuration of an irrigation system to be analysed is defined by an input file, so there is no need to modify the program code. The spate and groundwater irrigation network is defined as a schematic or pattern of links and nodes that describe the flow of water through the system. Links are used to connect nodes and to represent means of transferring water from one place to another. Sections of wadi channel, irrigation canals and pipes can all be represented by links in the model.

Nodes can have several inputs and outputs, and are used to represent the processes of diversion of water, bifurcation of water between links, and the use of water in irrigation. Irrigation nodes, termed blocks, represent aggregations of member farms and fields. Each type of crop grown within an irrigation block is treated as one field for the purposes of computing a soil moisture balance.

An illustration on how to configure a wadi system is presented here using the Wadi Surdud study area. The treatment of the Irrigation Simulation Model applied to the Wadi Surdud area is described further in Annex A. Briefly, the simplified scheme for representing the Wadi Surdud study area is given in Figure 3.2. This scheme includes a total of 12 nodes (0-11), 12 links, and six irrigated blocks. Node 0 represents the source of surface water to the study area and is located at the Faj Al Hussein stream flow gauging station. Nodes 1, 3, 5, and 7 represent spate diversion structures on the Wadi Surdud. These nodes are connected by links 1, 3, 6, 8, and 10, which represent reaches of the Wadi Surdud above, between or below the spate diversion points.

Nodes 2, 4, 6, and 8 correspond to irrigation blocks 1, 2, 3, and 4, which receive spate water. In addition, node 4 (Block 2) receives additional water (conjunctive use) from groundwater wells (node 11). Blocks 1, 3 and 4 represent spate units 1, 2 and 3 of the WRAY Wadi Surdud study [van der Gun and Wesseling, 1991]. Block 2 represents the conjunctive use unit (Al-Kadan Research Centre).

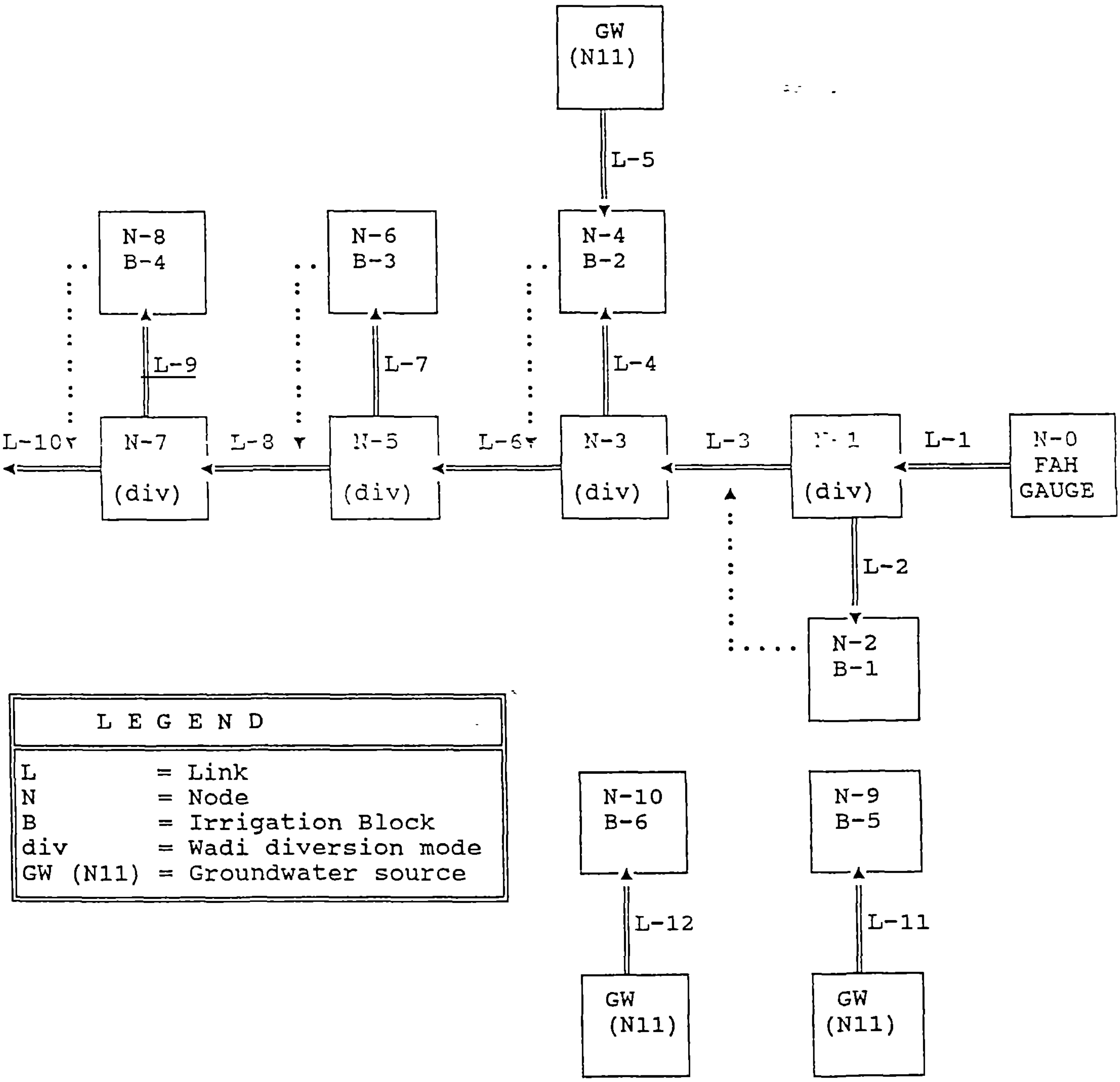

Figure 3.2 Schematic of Wadi Surdud for the Irrigation Simulation Model

Nodes 9 and 10 correspond to irrigation blocks 5 and 6. These blocks represent all groundwater irrigated areas in the study area (other than block no. 2). Block 5 represents the groundwater irrigated farms east of the Ad Dahi meteorological station (29 East UTM) and block 6 represents the groundwater irrigated farms west of this longitude. Node 11 is used to represent the supply of the groundwater aquifer as a whole.

Link number 10 represents the Wadi Surdud downstream of node 7 and spate irrigation block number 4. This link receives all excess surface water in the Wadi Surdud that is not diverted by the spates. This water eventually recharges the groundwater aquifer along link 10.

The dashed lines in Figure 3.2 represent the flow of excess surface water from irrigation blocks 1, 2, 3, and 4 (spate irrigated blocks) back into the Wadi Surdud downgradient from the blocks.

Results of the Irrigation Simulation model are used to provide estimates of groundwater recharge to the groundwater simulation model. In addition, the ISM evaluates various groundwater and surface water management and cropping strategies.

Crop types, growth stages and dates used for the Wadi Surdud are defined in Attachment 3 of Annex.

3.2.3 Groundwater Simulation Models

Two groundwater simulation models were developed for the Tihama. The first was a model of a generalised Tihama groundwater province, and was designed to:

(1) Give a rapid assessment of the available long-term yield in relation to recharge,

(2) Investigate the importance of altering abstraction patterns to improve yields, and

(3) Investigate the difference between long- and short-term yields.

A complementary and not minor objective was to provide a first approximation to a model for a typical groundwater province that would facilitate the modelling of a specific province. The second model, the one that is referred to as the Groundwater Simulation Model (GSM) in other parts of the report, illustrates the development of one such province: the Wadi Surdud groundwater province. Its objectives were:

(1) Build the groundwater component of the overall planning model with linkage to the Irrigation Simulation Model described in Section 3.2.2, and

(2) Assess the long- and short-term yields for an actual Tihama groundwater province.

Both groundwater models are described in detail in Annex B.

The generalised Tihama groundwater model was designed on the basis of a conceptual model with idealised representation of the geological and hydro(geo)logical features of a typical province. A geomorphological zoning of alluvial fan, interfluvial area, and plain was adopted. The underlying bedrock with a representative step-fault was taken as the base of the aquifer. Recharge components of direct recharge from rainfall and indirect recharge from surface water (wadi channel and irrigation) are considered; hill slope runoff and bedrock inflow are included as a combined component. Discharge components of borehole abstraction and coastal discharge are represented. Sebkha shallow groundwater evaporation is not included separately but considered as part of coastal discharge.

The east-west wadi course is taken as an axis of symmetry. The coastline is represented by a fixed head boundary, and no-flow boundaries are used for the other sides of the model. The model is divided into two layers based on hydrogeological judgment. These are used for studying the effects of drawdown on groundwater abstractions and levels - the upper level constitutes the layer where abstractions may preferentially take place. A specific yield of 13 % for the aquifer was adopted based on previous studies. The hydraulic conductivities adopted were of 12 m/d in the upper wadi zone, 8 m/d in the main alluvial fan area, and 12 m/d in the coarser soil of the coastal plain; lower conductivities were assume off the main alluvial fan. The saline interface is not explicitly represented, but its position can be inferred from the resulting fresh groundwater head inland from the sea. The model was developed using the MODFLOW (version 3) code, which is commercially well-supported.

The Wadi Surdud Groundwater Simulation Model (GSM) benefitted from the basic work done on that wadi by the WRAY Project team [see, for instance, van der Gun and Wesseling, 1991]. The Wadi Surdud groundwater province fits the general conceptual model of the Tihama provinces. The area modeled and the 2.5 km square grid used are shown in Figure 3.3. The boundary conditions assumed are similar to those of the generalised model. A one layer quaternary alluvium aquifer representation was adopted with a specific yield of 15%. The hydraulic conductivities used follow the same broad pattern as the generalised model, although they are somewhat lower in the main alluvial fan and upper wadi areas.

The recharge components considered include:

- precipitation
- wadi bed infiltration
- groundwater inflow in wadi bed (underflow)
- return flow from spate irrigated fields
- losses from irrigation canals
- returns from groundwater irrigation

The discharge is composed by the following terms:

- coastal outflows (including sebkha evaporation)
- abstraction by wells

Precipitation recharge in the upper alluvial fan area was assumed to be about 11 mm/year (4% of 275 mm annual rainfall); in the middle and eastern section precipitation recharge was taken as 3 mm/year (2% of 150 mm/year annual rainfall). The other recharge terms will normally be taken from the output of the Irrigation Simulation Model runs. The ISM produces time series of the recharge values associated with links (wadi segments and

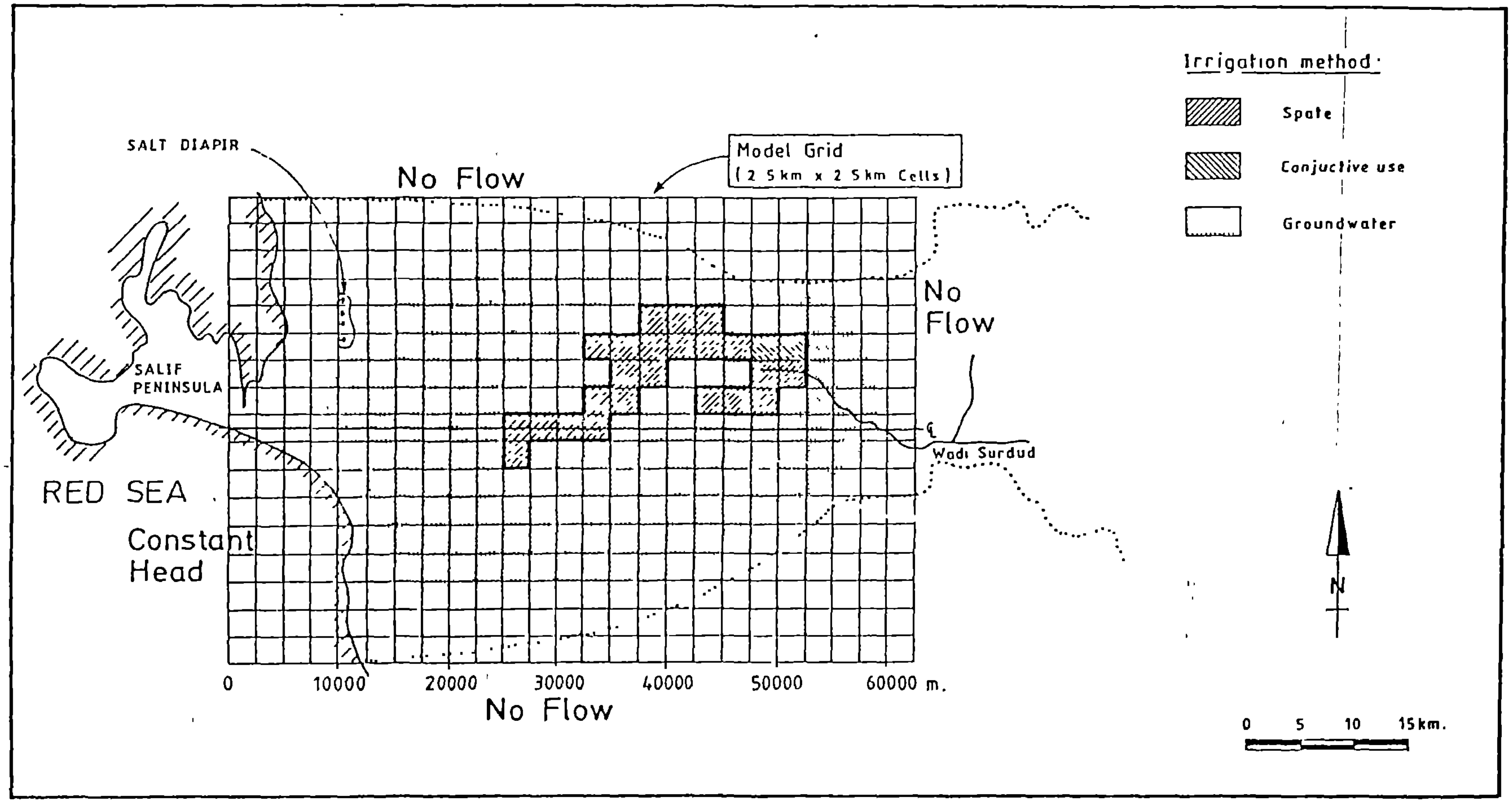

Figure 3.3 Arrangement of the Wadi Surdud Groundwater Simulation Model

conveyance canals) and from irrigation units. Underflow is considered to be included in the wadi recharge term, since it is assumed that at the wadi section at Faj Al Hussein station all wadi flows surface and are measured (time series of flows at Faj Al Hussein are an input to the ISM). A procedure was developed to perform an easy conversion from the ISM output files to the input formats required by the Wadi Surdud model.

The Wadi Surdud groundwater model uses the MODFLOW EM code. As with the generalised model, there is no direct representation of the salt water-fresh water interface. Calibration was aimed mainly at reproducing the historical 1984 levels, for which data was available. Significant groundwater abstractions started well before 1984. It was necessary to simulate the period of abstraction up to 1984 in order to reproduce the dynamic condition at that date.

3.2.4 The Economic Policy Model

General

The major objective of the Economic Policy Model (EPM) will be to maximize net benefits for the given level of technical, physical, and institutional constraints. The model will also assist in the determination of the optimum allocation of the potentially available water resources among different water consuming sectors. The linear programming (LP) mathematical optimization technique can be used to formulate the economic policy model. The model can be used as an effective tool to analyze the impact of a variety of water management strategies and economic policy measures on resource allocation and regional economic development.

The optimal solution generated by the model (defined in terms of cropping patterns and outputs) in response to various water management strategies can be imposed on the irrigation simulation model with the purpose of capturing the farmers' behavioral response in the later model. The water management models may employ the techniques of both simulation and optimization in deriving their outputs [Bachmat et al., 1980]. Linked application of the EPM optimization model with the Irrigation Simulation Model and the Groundwater Simulation model will yield predictions, which are more meaningful in the formulation of a water management policy as compared to predictions based on trial and error.

Structure and Scope of the Proposed Model

The use of LP models to characterize resource allocation problems is now well established. The focus of any water management strategy in Tihama region should be to induce a planned rationalization and/or curtailment of water demands in the agricultural sector since it consumes more than 90 percent of the total water resources of the region and there is an evident process of groundwater depletion. Therefore, the model discussed here is aimed at characterizing the agricultural features of the region. The industrial and municipal water demands can, however, be exogenously supplied to the model with corresponding objective function values to evaluate the water trade-off possibilities among different water consuming sectors. In view of the variations in cropping pattern, soil types, market conditions, and resource availability within the region, it is advisable to apply and calibrate the model for each wadi in the region.

The LP model has four basic components: objective, activities, constraints, and technical coefficient matrix. The objective of the model characterizing Tihama agriculture is to maximize net benefits (defined as gross value of production minus costs associated with agricultural production). The model will incorporate activities such as crop production, livestock production, input purchasing, output selling, labour hiring, pumping cost, and investment in improved technologies. In order to capture the effect of water stress (shortages) on crop production, a water-yield production function for each crop needs to be incorporated in the model (see Technical Note 3 in Annex C for details). The basic model will be formulated for a one-year period, which could later be extended to a multi-year sequence.

The proposed model will be subject to constraints on land, family labour, hiring of labour, subsistence requirements, marketing, surface water, and groundwater. In view of the interdependencies involved in agricultural production system (as different crops compete for scarce resources throughout the production period), the land, labour and water constraints may be defined on monthly basis. Monthly pumping capacity constraints may also be incorporated in the model. Constraints on the seasonal, yearly or multi-year pumped water quantities may also be imposed. Surface water constraints are fairly straightforward as related to baseflow; flood flows, which are random and of short duration will, however, require a specific treatment in this deterministic model.

The technical coefficient matrix of the model will have two types of coefficients. The coefficients of the first category represent the quantity of resources required to produce a hectare of crop or a unit of livestock. The coefficients of the other category convert per hectare activities into outputs.

The model should be subject to calibration; its predictions for the baseline case should be compared with the observed data to determine its reliability. The model can be used to analyze various water management strategies to determine to what extent these strategies would contribute towards regional economic development and resource sustainability. Each water management strategy is certainly going to have certain costs and benefits. Therefore, values of relevant variables in the model must be amended accordingly. Model runs may be made over the planning horizon in response to changes in water availability and pumping costs. The yearly net benefits should be discounted to express these in terms of their present value in order to compare the economics of various strategies.

The proposed model may be utilized to examine the impact of following strategies or policy measures on net benefits and resource sustainability: (a) different groundwater abstraction rates with corresponding change in pumping costs; (b) water conservation measures designed to improve irrigation efficiency; (c) input substitution possibilities such as trade-off between water and non-water inputs; (d) conjunctive use of surface and ground water resources; (e) water pricing policy; (f) removal of subsidies; and (g) improved water allocation rules. The above enumeration is tentative and can be further expanded depending upon the nature and extent of the problem faced in a particular wadi. Moreover, various water development projects being considered for implementation in the study area can be incorporated in the model to assess their impact on the regional economic development.

Because of the nature and structure of the proposed model, it has a simplified representation of the physical schemes and processes. Thus, the cropping patterns and water allocation suggested by the EPM can be tested in detail with the simulation models using hydrometeorological time series having a shorter time step where needed and incorporating the simulation of physical processes such as the use of effective rainfall for cropping purposes, the soil moisture balance, and the groundwater depletion. The simulation can provide feed-back to the EPM in the form of more accurate pumping costs based on the drawdown determinations of the Groundwater Simulation Model.

An extension of the EPM that merits consideration is casting it in the form of Goal Programming method [Goodman, 1984], which also uses LP techniques and permits the consideration of multiple objectives. This method facilitates the simultaneous incorporation of several deserving objectives, i.e., the maximization of net income to farmers, the attainment of the most balanced income distribution, and the minimization of groundwater exploitation in certain restricted areas.

CHAPTER 4
WADI SURDUD: AN EXAMPLE

4.1 Objective

Wadi Surdud is used here to illustrate certain capabilities of the analytical tools developed by the High Water Council and discussed in Section 3.2. The main concern is to adequately represent the physical setting of the irrigation system on the Tihama plain and underlying aquifer and their responses to varying conditions imposed by users and managers of the system. The two models used, the Irrigation Simulation Model (ISM) and the Groundwater Simulation Model (GSM), were calibrated to initial and current conditions. Three cases were then tested. Some economic implications are also examined (without the use of the Economic Policy Model). Full-fledged water resources management strategies are not treated here.

4.2 Setting

4.2.1 Climate and Soils

Climate

The climate of the Wadi Surdud plain is hot and humid and is characteristic of a tropical desert climate. Table 4.1 summarizes mean monthly climatic parameters at the Ad Dahi meteorological station (based on the report on Surface Water Resources, Volume III - Part One), which is near the geographical centre of the Wadi Surdud plain.

The air temperature of the Ad Dahi area is quite high. The high humidity levels coupled with moderate levels of solar radiation, however, help to moderate the evaporative demand. Maximum average monthly evapotranspiration occurs in May, but is only 6.7 mm/day.

The Al Hodeidah weather station is on the coast of the Red Sea, about 100 km southwest of Ad Dahi. Air temperatures are similar at Al Hodeidah as compared to Ad Dahi. Winds at Al Hodeidah are, however, up to three times stronger than at Ad Dahi, due to the proximity and influence of the sea. As a result, reference evapotranspiration at Al Hodeidah averages about 10 to 15 percent higher than at Ad Dahi.

Annual rainfall in the Wadi Surdud plain increases from an average of 100 mm near the Red See coast to 300 to 400 mm near the foothills at the eastern edge of the plain. The rainfall is, in general, insufficient for agricultural cultivation. It does, however, promote sparse growth of native, desert plant life in areas of medium to fine textured soils which serves as pasture for small herds of goats, sheep and camels.

Table 4.1 Mean Monthly Weather Parameters at Ad Dahi, Yemen, 1984-1987

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Mean	Total
Tmax,C	29.9	30.6	32.7	35.2	37.0	38.9	39.3	39.4	38.1	35.3	33.0	31.2	35.0	
Tmin,C	20.0	21.3	23.1	25.1	27.2	27.9	28.4	28.2	27.3	24.5	22.3	21.5	24.7	
Tmean,C	25.0	25.3	27.9	29.9	31.9	33.2	33.9	32.4	32.8	30.0	26.8	25.7	29.6	
Rs,W m^{-2}	180.0	180.0	190.0	256.0	233.0	247.0	243.0	225.0	234.0	234.0	205.0	176.0	217.0	
Sunshine,hrs	7.7	6.5	6.5	8.2	8.2	6.9	6.4	5.4	5.6	8.7	8.6	6.4	7.1	
Rel.Hum,%	71.0	70.0	65.0	62.0	60.0	57.0	56.0	59.0	60.0	59.0	62.0	70.0	63.0	
Wind, m s^{-1}	2.0	2.1	2.0	1.9	1.9	2.0	2.2	2.1	1.8	1.6	1.7	1.8	1.9	
E_{to}, mm d^{-1}	4.1	4.5	5.1	6.5	6.7	6.1	5.5	5.6	5.5	5.8	5.4	4.2	5.4	
Rainfall, mm	0.0	1.0	2.0	17.0	11.0	0.0	10.0	35.0	35.0	18.0	2.0	1.0		132.0

Note:

E_{to} represents reference evapotranspiration from a well-watered, clipped grass surface, 8-15 cm in height, following FAO-24 recommendations.

Rainfall summary obtained from 1984-1989 series in van der Gun and Wesseling [1991]

Latitude = 15.22 degrees N, Elevation = 70 m.

Soils

Soils along the Wadi Surdud water course tend to be deep and silty due to deposition by flooding and by terracing activities of farms. Most deep silt soils are found in the eastern and central portions of the Wadi Surdud plain along the wadi, where wadi flood flows are more frequent. Soils to the north and south of the Wadi Surdud are mixed, with some areas of fine textured silt loams and other areas of sandy loams and sands. These soils are older than wadi soils and are generally aeolian in origin.

Irrigated farms are generally developed on patches of soils having medium, silty textures and on flat slopes. Slopes away from the wadi are gradual and many areas are generally quite flat. Concentrations of groundwater development frequently occur along the Wadi Surdud water course due to the depth, texture and relative richness of the soils along the water course and due to more shallow pumping depths caused by lower elevation and proximity to recharge sources.

Soils tend to become more sandy toward the western half of the Wadi Surdud plain. Areas of deep silt loam soils seem to be in the minority.

In the Irrigation Simulation Model, maximum available soil moisture for the medium textured soils was assumed to be 150 mm per meter depth. Maximum available soil moisture for the sandier textured soils was assumed to be 75 mm per meter depth. Maximum available soil moisture is defined as the water stored in the soil between field capacity and wilting point moisture levels.

There are large areas of sand dunes as well as blowing and drifting sand in areas of the Tihama plain, especially towards the western half. In many areas, these dunes are continually shifting and are even encroaching on small, groundwater-irrigated areas in some places. The presence of the dunes and absence of native vegetation increases the "hostility" of the environment on irrigated crop production, as air temperatures over the dune areas are increased due to the conversion of nearly all net solar radiation into sensible heating of the air. The increase in temperature, in association with strong winds, causes advection of large amounts of evaporative energy into small irrigated areas, thereby increasing the evapotranspiration of water per unit area of crop. It is estimated that these increases may be in the order of 20 to 30 percent. In these situations, small irrigated areas (less than 4 ha) function as small oases. The oasis effect on evapotranspiration requirements was not included in the Irrigation Simulation Model, as the 20 to 30 percent variation in water use is within the magnitude of uncertainty in the estimates for crop coefficients and the reference evapotranspiration. It has been shown that the FAO Corrected Penman equation, which was used to estimate reference evapotranspiration in this study, generally provides estimates that are 10 to 20% high [Jensen et al., 1990]. This overestimation partly compensates for the oasis effect.

4.2.2 Irrigation Units

The locations and areal extent of the irrigation units (block) are depicted on the map of Wadi Surdud shown in Figure 4.1. Categorization of the Wadi Surdud study area has followed basically the approach of the WRAY study [van der Gun and Wesseling, 1991], where irrigated areas have been grouped into three spate-irrigated areas (SPU-1, SPU-2, SPU-3), a conjunctive use unit (CUU) which represents the Al Kadan Research Centre, and two ground-water blocks (GW-1 and GW-2). The groundwater blocks can be considered as zones of similar patterns of groundwater abstraction. These zones can overlay spate-irrigated blocks as described in the next few paragraphs. Groundwater zone GW-1 includes the WRAY GWU units 1-5 (eastern half of the study area) and GW-2 includes the WRAY GWU units 6-8 (western half of the study area).

Spate irrigation development begins about 26 km west of the Faj Al Hussein gauging station near the mouth of the Wadi Surdud canyon. No significant irrigated development occurs between the gauge and the 26 km distance due to the elevation of adjacent lands along the wadi relative to the wadi along this reach (up to 100 m) and due to the coarse (gravelly) texture of both soils and the sides of the wadi watercourse. These coarse textured soils would result in a large amount of seepage in long conveyance channels required to convey water along elevation contours to lower lands to the west. Lining of constructed channels would be expensive. The coarse texture of soils results from the proximity of the lands to the wadi canyon mouth where deposition of coarse alluvium has occurred during wadi floods.

Most spate structures along the Wadi Surdud are constructed from gravels and rocks of the wadi bed. These structures are often destroyed during flood events, but are rebuilt subsequent to the flood using heavy equipment (bull-dozers). The porosity and vulnerability of the spate structures is beneficial in that it helps to foster the flow of some flood water down the wadi system to lower lying farms and spate structures. This also promotes infiltration of water into the wadi bed to recharge the aquifer. Installation of permanent spate diversion structures in the wadi would be an expensive, complex process, as sediment and bedloads during wadi floods are extreme.

Seepage and deep percolation from spate-irrigated areas recharges the groundwater system. Some of the surface water diversions to spates, which is in excess of gross irrigation water requirements, returns to the wadi channel for subsequent diversion downstream. The balance of excess surface water diversions infiltrates the ground and becomes groundwater recharge.

Groundwater irrigated blocks have been delineated independently of spate irrigated blocks. It is assumed that no excess surface water occurs from groundwater irrigated blocks and that all return flow is recharged directly to the aquifer. The exception is for conjunctive use units, where the irrigated block receives water from a spate diversion and supplemental water from groundwater supplies.

In the irrigation block representation for the Wadi Surdud, irrigable land within the boundaries of spate-irrigated blocks is not excluded from being supplied by and included within a groundwater block (zone). This will often be the case where there is groundwater development within a spate-irrigated block, but where the groundwater irrigated farms do not receive any surface water. Therefore, the block does not technically qualify as a conjunctive

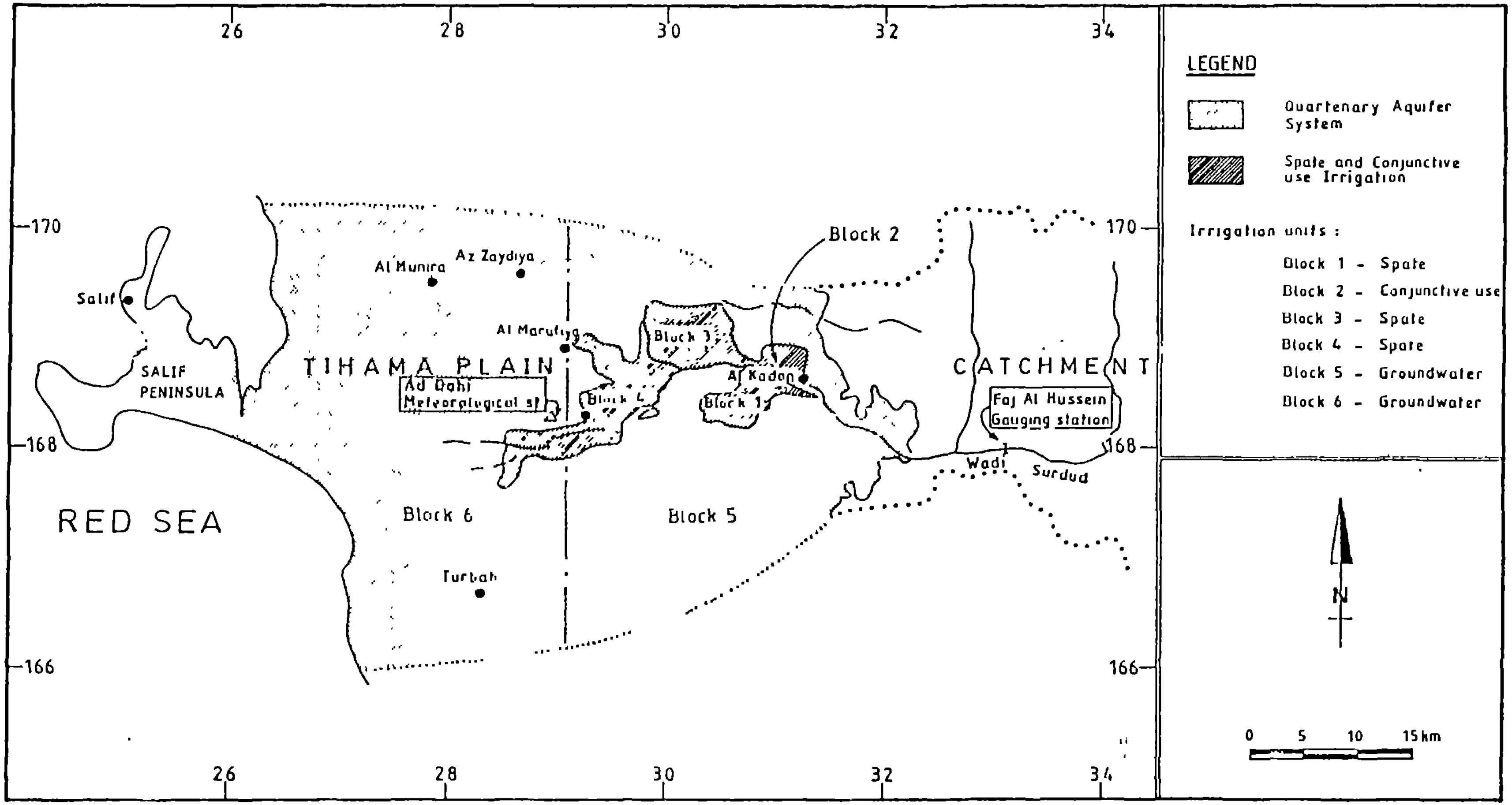

Figure 4.1 Scheme of the Wadi Surdud Study Zone and Irrigation System

use block. A conjunctive use block is defined as a block that receives the primary supply from surface water, but where all irrigated areas identified and listed for the block receive supplemental supplies from groundwater when needed. These areas usually have improved water distribution and control systems.

Independent groundwater development occurs frequently in spate-irrigated areas where spate distribution systems are not well constructed or controlled. Groundwater development provides an insured and frequent water supply. Farmers using groundwater supplies may not wish to risk using spate water diversions due to problems with soil and crop erosion by large spate discharges, but rely only upon groundwater. Therefore, the groundwater developments within spate areas are no longer technically a part of the spate system. As a result, groundwater blocks (zones) can physically overlie spate-irrigated blocks, and represent farms within the spate-irrigated blocks which are using only groundwater supplies.

According to farmers interviewed, machine dug groundwater wells (using a cable tool) cost about 1,200 Rials per m in 1992. Most groundwater pumps were powered by small diesel motors housed in small rock or block buildings.

4.2.3 Cropping Pattern

Estimated actual irrigated areas in the Wadi Surdud for the base year 1984 are summarized in Table 4.2 by crop and by irrigation unit (spate, groundwater, or conjunctive use). The abbreviated crop names used are the following:

Abbreviation	Definition
S- SF	Grain Sorghum, Saif Season
S- KF	Grain Sorghum, Kharif Season
S- RN	Grain Sorghum planted in July
S-RT1	Sorghum Ratoon Crop (following Kharif Crop)
S-FDS	Sorghum Fodder, Saif Season
S-FDK	Sorghum Fodder, Kharif Season
MAIZE	Maize
MILLT	Millet
COTTN	Cotton
SESAM	Sesame Seed
TOBAC	Tobacco
S-VEG	Spring Vegetables
W-VEG	Winter Vegetables
TOMAT	Tomatoes
CWPEA	Cow Peas
FRUIT	Bananas and Deciduous Fruit Trees
MELON	Water Melon

In general, sorghum is by far the majority crop grown under spate irrigation. This is due to several important reasons. First of all, due to irregularity of wadi discharge and flood events, farmers have recognized the convenience of the sorghum crop, which has a fairly high degree of drought tolerance and which also has a deep root zone which facilitates soil moisture extraction. Secondly, due to uncertainties and irregularities in crop yields in spate-irrigated areas, farmers are generally short on marketable products, and therefore remain in subsistence farming modes. Sorghum is the primary subsistence crop, as the grain is used for human consumption and the foliage is used for animal consumption.

Groundwater development improves the certainty and availability of water supplies, thereby reducing the risk of crop moisture stress and enabling farmers to plant higher valued, marketable crops, as shown in Table 4.2. Up to 50% of groundwater-irrigated hectares are currently being allocated to crops of maize, cotton, sesame, tobacco, and winter vegetables. Sorghum, however, still remains the dominant crop in groundwater irrigated areas due to tradition and familiarity with that crop. Also the tendency among groundwater users, who are sharecroppers and do not own their land or well, is to produce at a level sufficient for subsistence

There appears to be a large economic and agronomic potential for converting groundwater irrigated hectares currently planted to sorghum into high value vegetable crops. There is currently a growing market for vegetable crops in the cities of Yemen, and given development of transportation, preservation and shipping infrastructure, large volumes of winter vegetables could potentially be marketed to European and Arab markets. In view of the high production costs and low productivity, however, Yemeni crops are currently not competitive in the world market.

4.2.4 Recent Irrigation Development and Water Use

Situation in 1984

The operation of the irrigation system and the state of the groundwater aquifer in 1984 are of interest because systematic data were gathered for that year in Wadi Surdud [van der Gun, 1986] which facilitate the calibration of the Irrigation Simulation Model and the Groundwater Simulation Model. According to estimates in Table 4.2, there was an average, potential irrigated, cropped area of about 24,800 ha in the Wadi Surdud plain in 1984. Because the cropping intensity of groundwater areas is greater than 150%, the total cultivated area with potential for irrigation was probably about 19,000 ha. Actual land planted under spate-irrigation was only about 4,000 ha in 1984. These planted areas may be less than historical numbers due to possible decreases in wadi flood discharges along the Tihama due to increased water development and abstraction in the wadi catchment areas in the years before 1984.

Average annual surface inflow to the Tihama plain of Wadi Surdud was estimated in the report on Surface Water Resources (Volume III) as 82 Mm^3/year using the rainfall-runoff model. The groundwater modelling exercise (Annex B) shows that the recharge induced by that inflow is excessive and does not allow a satisfactory calibration. It suggests that a mean annual surface water inflow of 65 Mm^3/year would be more appropriate. This illustrates the frailty of the hydrologic database that exists in the Tihama. The rainfall-runoff model used with the runoff characteristics mapping provides an effective central-tendency runoff estimation procedure on an aggregate regional basis, but may present deviations in individual

Table 4.2 Estimated Average Potential Irrigated Areas by Block for the Wadi Surdud for the 1984 Base.

Block: SPU-1 (Spate-Irrigation Unit No. 1) (Irrigation Block No. 1)

Crops	S-SF	S-KF	S-RT1	Total
Normal area (ha)	300	300	300	900

Block: CUU (Conjunctive Use Unit) (Irrigation Block No. 2) 2

Crops	S-SF	S-KF	S-FDK	MAIZE	COTTN	SESAM	TOBAC	W-VEG	FRUIT	Total
Normal area (ha)	800	150	100	150	150	150	300	150	150	2,100

Block: SPU-2 (Spate-Irrigation Unit No. 2) (Irrigation Block No. 3)

Crops	S-SF	S-KF	S-RT1	Total
Normal area (ha)	600	600	600	1,800

Block: SPU-3 (Spate-Irrigation Unit No. 3) (Irrigation Block No. 4)

Crops	S-SF	S-KF	S-RT1	Total
Normal area (ha)	400	400	400	1,200

Block: GW-1 (Groundwater-Irrigation Unit No. 1) (Irrigation Block No. 5)

Crops	S-SF	S-KF	S-FDK	MAIZE	COTTN	SESAM	TOBAC	W-VEG	Total
Normal area (ha)	5,500	3,000	1,500	1,000	600	2,000	1,000	600	15,200

Block: GW-2 (Groundwater-Irrigation Unit No. 2) (Irrigation Block No. 6)

Crops	S-SF	S-KF	S-FDK	MAIZE	COTTN	SESAM	TOBAC	W-VEG	Total
Normal area (ha)	1,400	750	350	250	150	300	250	150	3,600

Total: 24,800

Note: Crop types and name symbols are defined in Subsection 4.2.3

wadis because of paucity of good quality calibrating data. In the analyses presented in this chapter the synthetic 20-year Wadi Surdud series adopted consists of the daily flows originally generated adjusted by a factor of 80% to obtain an average annual inflow of 65.7 Mm^3. Although this distorts somewhat the fit of the Wadi Surdud runoff to peak flows, an acceptable overall consistency is achieved. The 20-year runoff series has the built-in assumption of stationarity, thus it does not represent any trend (see Volume III-Part One). The 1984 simulation, as well as the other cases analyzed here, used this multi-year sequence; hence, the results represent expected values.

The rainfall input over the irrigated units consisted of a 20-year synthetic series at Ad Dahi station generated by the daily rainfall simulation model described in Volume III- Part One. The daily synthetic data was grouped into decades (10-day totals for the first 20 days of a month plus the balance for each month). For each irrigation block it was multiplied by a factor (greater than 1 to the east of Ad Dahi and less than 1 to the west) in broad accordance to the annual rainfall distribution of the area.

Average annual groundwater pumping capacities and abstractions are summarized in Table 4.3 for the conjunctive use unit and for the two groundwater irrigation zones. These represent initial sets of figures to guide the joint calibration of the Irrigation Simulation Model and the Groundwater Simulation Model. The crop water requirements estimates were based on the Modified Penman evapotranspiration calculation method and crop coefficients primarily drawn from current literature [Doorenbos and Pruitt, 1977].

A summary of monthly total irrigation fields and wadi recharge to the groundwater system of Wadi Surdud and gross and net abstractions is listed in Table 4.4 for 1984. Various components of the system fluxes are shown in Table 4.5. The figures shown result from the joint calibration of the irrigation and groundwater simulation models (see Annex B). Because the agricultural year was assumed to start in the month of February, the simulation using 20-year sequences of runoff and rainfall covered actually 19 agricultural years (February year 1-January year 20) on which the averages of Tables 4.4 and 4.5 were based. Thus, there is a slight discrepancy with 20-year inflow mean (65.9 Mm^3 for the 19 agricultural years vs. 65.7 Mm^3 for the 20-year series).

Table 4.3 Estimated Pumping Capacities for 1989 and Abstraction during 1984 for the Six Irrigation Blocks in the Wadi Surdud Study Area.

Block	1989 Capacity[1] (m^3/s)	1984 Base Year Estimated Usage[2] Mm^3/year	1989 Estimated Usage[3] Mm^3/year
SPU-1	0.0	0.0	0.0
CUU	0.66	4.5	6.5
SPU-2	0.0	0.0	0.0
SPU-3	0.0	0.0	0.0
GW-1	10.0	68.0	99.0
GW-2	2.4	17.0	24.0
Total:	13.06	89.5	129.5

[1] Based on summaries reported by van der Gun and Wesseling [1991].
[2] Computed by multiplying abstraction estimates for 1989 by 0.69, which is the estimated ratio of 1984 groundwater irrigation abstraction [van der Gun, 1986] to 1989 abstraction.
[3] The 1989 abstraction estimates were computed by multiplying 1989 capacities by 0.32, which represents the average annual portion of pump operation (average of 7.7 hours/day).

Table 4.4 Mean Monthly and Annual Recharge, Abstraction and Net Abstraction from Wadi and Irrigated Areas of Wadi Surdud for the 1984 Base Year.

Month	Recharge from the wadi and irrigated lands (tcm)	Abstraction for irrigation (tcm)	Net Abstraction for irrigated lands (tcm)
Jan	4,049	5,211	1,161
Feb	3,272	4,950	1,678
Mar	4,775	5,491	716
Apr	10,927	7,146	-3,780
May	8,344	7,655	-690
Jun	7,306	7,683	377
Jul	11,188	7,676	-3,512
Aug	17,551	6,188	-11,363
Sep	8,053	7,396	-657
Oct	5,406	7,647	2,241
Nov	4,899	7,681	2,782
Dec	4,268	6,078	1,810
Annual ave.	90,038	80,801	-9,237

tcm = thousand cubic meter

Table 4.5 Components of the Fluxes of the Wadi Surdud Irrigation System for the 1984 Base Year.

Component	Annual Volume Mm^3
Wadi:	
-inflow at Faj Al Hussein	65.9
- diversion to irrigation blocks	28.4
Recharge:	
- wadi bed	38.8
- surface water canals	0.8
- all conveyances	2.7
- surface water irrigation	19.8
- groundwater irrigation	28.7
- all irrigated fields	48.5
Total recharge	90.0
Abstraction:	
- gross	80.8
- net	-9.2
Consumptive use:	
- surface water irrigation	6.5
- groundwater irrigation	50.2
Total consumptive use	56.6

Abstractions total about 81 Mm^3, which is less than the 89.5 Mm^3 given in Table 4.4, but given the range of probable errors in the various estimations, this was considered satisfactory. Recharge includes infiltration of flood flows along the wadi and deep percolation and seepage from both spate and groundwater-irrigated blocks. Recharge from precipitation on non-irrigated portions of the Wadi Surdud study area was estimated separately in 6.5 Mm^3 (see Annex B); it is not included in the figures reported in Tables 4.4 and 4.5. In addition, natural discharge of the Wadi Surdud aquifer to the Red Sea and associated evapotranspiration via seeps and natural vegetation along the Red Sea coast is not included in Tables 4.4 and 4.5. These latter quantities are estimated to be about 50 Mm^3/year (see Annex B). It should be noted that the terminology used in Table 4.4 is somewhat different from that used in Table 2.3. For instance, net abstraction here means gross abstraction minus all wadi and irrigation recharge (but not including recharge from precipitation), while in Table 2.3 net abstraction was taken to mean gross abstraction minus groundwater return flow (non-consumed groundwater).

Values reported in Tables 4.4 and 4.5 indicate a negative net abstraction of water, on an annual basis, from the groundwater system (-9.2 Mm^3). This indicates that more water was recharged from the wadi flood flows and from the spate and groundwater-irrigated areas than was abstracted by wells in 1984. It must be borne in mind, however, that when the approximately 6.5 Mm^3 of rainfall recharge and the 50 Mm^3 of aquifer outflow to the Red Sea and coastline is factored in, the aquifer experienced a net depletion of approximately 34 Mm^3 at 1984 pumping levels. Because pumping levels increased by about 40 percent between 1984 and 1989 and have increased substantially since that time, net depletion of the Wadi Surdud aquifer system is significant.

Of the 81 Mm^3 estimated to have been abstracted from the groundwater system in 1984 in Wadi Surdud, it is estimated that approximately 29 Mm^3 (36%) was returned to the aquiferas deep percolation. Some of this recharge may have been intercepted by the vadose zone, by the process described in Technical Note 1 of Annex C to this report. From Table 4.5 it can be seen that approximately 39 Mm^3 of this inflow infiltrates the wadi channel and 28 Mm^3 is diverted into spate or conjunctively irrigated units. Part of the water diverted into the conveyance canals and the spate and conjunctive units (20 Mm^3) is recharged to the groundwater as deep percolation, leaving only about 6.5 Mm^3/year, or 10% of the total estimated annual surface inflow at the Faj Al Hussein gauging station, as being consumptively used via crop evapotranspiration. The figures show that already in 1984 consumptive use in groundwater irrigated areas was by far greater (50.2 Mm^3 including a share of the conjunctive use unit) than in surface irrigated areas.

The recharge from the CU unit at Al Kadan was divided into surface water irrigation and groundwater irrigation recharge components by the expedient method of splitting the total recharge proportionately to the amounts of surface water and groundwater (net of transmission losses) flowing into the unit. The underlying assumption is that water from both sources are subject to the same irrigation efficiency. The surface water in excess of the gross irrigation requirements (=net requirements/efficiency) is assumed to return to the wadi. This explains why the addition of wadi recharge and diversions yields 67.2 Mm^3 slightly in excess of the wadi inflow (65.9 million cubic meters) - part of the return flow has been diverted more than once. As discussed in Chapter 2, the values of on-farm irrigation efficiencies adopted were 30% for the spate units, 60% for the conjunctive use unit and 65% in the groundwater irrigated units.

Table 4.6 presents a summary of the average actual cropped areas and crop yield ratios per crop for the base year 1984 from the simulation performed. The results for each of the irrigation methods (spate, conjunctive use, groundwater irrigated) are shown as well as the consolidated results for all irrigation units. The total actual average cropped area, 24,416 ha, is smaller than the 24,800 ha shown in Table 4.2 because pre-irrigation soil moisture conditions did not permit planting the normal area every year of the simulation in the spate units. This case was more frequent than the opposite (having more than the target soil moisture content) enabling the planting of more than the normal area.

Table 4.6 Average Annual Cropped Areas and Crop Yield Ratios for the 1984 Base Year.

	Crop	Area (ha)	Yield ratio
Spate irrigated (blocks 1, 3, 4):			
	S- SF	1139.	.634
	S- KF	914.	.731
	S-RT1	1463.	.850
Total average cropped area:		3516.	
Conjunctive use unit (block 2):			
	S- SF	800.	.953
	S- KF	150.	.988
	S-FDK	100.	.999
	MAIZE	150.	.976
	COTTN	150.	.990
	SESAM	150.	.927
	TOBAC	300.	.950
	W-VEG	150.	.843
	FRUIT	150.	.987
Total average cropped area:		2100.	
Groundwater irrigation units (blocks 5, 6):			
	S- SF	6900.	.570
	S- KF	3750.	.640
	S-FDK	1850.	.634
	MAIZE	1250.	.395
	COTTN	750.	.792
	SESAM	2300.	.372
	TOBAC	1250.	.674
	W-VEG	750.	.911
Total average cropped area:		18800.	
All irrigation units (blocks 1, 2, 3, 4, 5, 6):			
	S- SF	8839.	.613
	S- KF	4814.	.668
	S-RT1	1463.	.850
	S-FDK	1950.	.653
	MAIZE	1400.	.457
	COTTN	900.	.825
	SESAM	2450.	.406
	TOBAC	1550.	.728
	W-VEG	900.	.900
	FRUIT	150.	.987
Total average cropped area:		24416.	

The crop yield ratios represent the ratio between the actual yield and the potential yield (no water shortages or inappropriate water salinity). The highest possible ratio is 1, when the actual yield equals the potential yield. Some crops are very sensitive to water shortages, such as maize, and others are much more tolerant to water stress, such as sorghum. The procedures to calculate the yield reduction because of water deficits or excessive salinity are referred to in Chapter 2 and described in Technical Notes 3 and 4 of Annex C. Understandably, crop yield ratios for spate units, even for drought resistant crops, are inferior to those of the conjunctive use units. Perhaps surprisingly, the crop yield ratios for the groundwater irrigated units are relatively low. This, in part, reflects the observation that even today there is evidence of moisture stress in groundwater irrigated areas (Section 2.3.1). Also, farmers are likely to employ more ad-hoc and empirical rules to distribute water among the different crops when there is insufficient water to get higher yields from stress sensitive crops instead of the straight proportion to water requirements used in the simulation model.

Situation in 1989

For purposes of this study, 1989 is considered the current situation because it is the last year for which there is fairly comprehensive information. The average irrigated, cropped area in 1989 is estimated at 32,000 ha [van der Gun and Wesseling, 1991] due to significant groundwater development between 1984 and 1989, as illustrated in Table 4.3. Groundwater irrigated areas were considered to have expanded from 18,800 ha in 1984 to 26,000 ha in 1989, with a corresponding increase in pumping capacity. Areas under spate and conjunctive use irrigation were assumed to remain the same. The land and water management parameters of diversion capacity, irrigation efficiencies and cropping composition for the different irrigation methods were also not altered.

Tables 4.7 and 4.8 summarize the main results of the irrigation system simulation. Gross abstraction reaches 126.1 Mm^3, which compares well with 129.5 Mm^3 estimated in Table 4.3. Net abstraction over the irrigation system area (not considering rainfall recharge) is 19.0 Mm^3, that is, about 28 Mm^3 greater than in 1984. Table 4.8 shows that the crop yield ratios for groundwater irrigated area improved over 1984, despite the growth of these areas.

4.3 Test Cases

Three illustrative cases were analyzed using the Irrigation Simulation Model and the Groundwater Simulation Model to examine the effect of certain assumed irrigation system evolution and corresponding groundwater exploitation patterns. These may be considered preparatory runs to the analysis of full management strategies packages. Though the more definitive analyses may be carried out using the irrigation and groundwater simulation models, their joint application with the Economic Policy Model would be a more powerful analytical instrument.

Table 4.7 Components of the Fluxes of the Wadi Surdud Irrigation System for 1989

Component	Annual Volume Mm^3
Wadi:	
-inflowat Faj Al Hussein	65.9
- diversion to irrigation blocks	28.4
Recharge:	
- wadi bed	38.8
- surface water canals	0.8
- all conveyances	3.9
- surface water irrigation	19.8
- groundwater irrigation	44.6
- all irrigated fields	64.4
Total recharge	107.1
Abstraction:	
- gross	126.2
- net	19.0
Consumptive use:	
- surface water irrigation	6.5
- groundwater irrigation	78.5
Total consumptive use	84.9

The three cases were:

Case A: The 1989 irrigation system status and resulting abstractions are maintained through year 2040.

Case B: The irrigation system continues to expand with groundwater abstractions based on historical growth rates.

Case C: More efficient use of surface water is made, while maintaining groundwater irrigation at 1989 levels.

4.3.1 Case A

This case explores the hypothetical case of having the 1989 situation extended into the future with no change (same irrigation units, areas, methods, efficiencies, cropping patterns and water use). This is unrealistic on several counts: first, there is at present an uncontainable trend to expand irrigation and groundwater exploitation; second, the fact of having declining water levels would force some adjustment; and third, other external conditions (market, technology, national priorities) will undoubtedly change, which will force changes in the agricultural sector. Nonetheless, it was considered useful to examine what would be the long-term effects of maintaining the present situation.

The results presented in Tables 4.7 and 4.8 for the irrigation system operation in 1989 is applicable for the entire 1990-2040 period. The consequences on the aquifer are described and illustrated in Annex B. The groundwater model predicts that the regional groundwater

Table 4.8 Average Annual Cropped Areas and Crop Yield Ratios for 1989

	Crop	Area (ha)	Yield ratio
Spate irrigated (blocks 1, 3, 4):			
	S- SF	1139.	.634
	S- KF	914.	.731
	S-RT1	1463.	.850
Total average cropped area:		3516.	
Conjunctive use unit (block 2):			
	S- SF	800.	.953
	S- KF	150.	.988
	S-FDK	100.	.999
	MAIZE	150.	.976
	COTTN	150.	.990
	SESAM	150.	.927
	TOBAC	300.	.950
	W-VEG	150.	.843
	FRUIT	150.	.987
Total average cropped area:		2100.	
Groundwater irrigation units (blocks 5, 6):			
	S- SF	9550.	.656
	S- KF	5150.	.722
	S-FDK	2600.	.712
	MAIZE	1750.	.538
	COTTN	1000.	.829
	SESAM	3200.	.456
	TOBAC	1750.	.744
	W-VEG	1000.	.916
Total average cropped area:		26000.	
All irrigation units (blocks 1, 2, 3, 4, 5, 6):			
	S- SF	11489.	.674
	S- KF	6214.	.730
	S-RT1	1463.	.850
	S-FDK	2700.	.723
	MAIZE	1900.	.572
	COTTN	1150.	.850
	SESAM	3350.	.477
	TOBAC	2050.	.774
	W-VEG	1150.	.906
	FRUIT	150.	.987
Total average cropped area:		31616.	

levels will continue to fall, with drawdowns from 1984 to 2040 reaching 15 m over a wide area, with maximum depths about 50 m, but with depths not dropping below sea level. Depths at individual wells will be even greater due to local cones of depression and interference with other wells. Though the rate of exploitation might be sustained during the period of analysis, there is the latent risk of localized water quality degradation and falling groundwater yields.

It is interesting to note that the application of a numerical aquifer model yields a different answer than the simplified water balance exercise and quantification of usable storage of

Section 2.2. According to Table 2.3, there is a net withdrawal from the Wadi Surdud aquifer of 83.3 Mm^3/year, and from Table 2.4, the usable storage of this aquifer would be 2,900 Mm^3. With simple arithmetic this would give a duration of the aquifer at current rates of exploitation of about 35 years. In the present simulation wadi inflow has been adjusted downward from 82 to 65 Mm^3/year, but there are other components which partially offset this effect (for instance greater field recharge). In the simulation at the end of a 50 year simulation (year 2040), however, the aquifer can not be said to be already in a decidedly critical state. The response of the aquifer and the overall balance is more faithfully reproduced with the simulation model, such as the tendency to decreasing coastal losses (see Annex B), and the results are therefore expected to be closer to reality.

4.3.2 Case B

Case B is an attempt to replicate a situation where current trends are maintained into the future. A certain evolution in irrigation practices is assumed. In a way, this case is similar to the "non-intervention" case which could serve as the baseline case to compare the effect of alternative water resources management alternatives, but there has been no thorough analysis to formally postulate the make-up of the non-intervention case. For the period 1990-2040, five irrigation system development stages, one for each decade, were considered. The trend of increasing groundwater exploitation, conversion of spate units to conjunctive use irrigation, and the progression towards greater irrigation efficiencies are represented in the sequence of stages. These scenarios were analyzed with the Irrigation Simulation Model. A reasonable planning horizon would not go beyond the year 2010 because of the many uncertainties, but the last three decades were added to explore the long-term aquifer response to the assumed cases. The groundwater model processed in a transient mode the full 1990-2040 period adopting multi-year abstraction and recharge averages as inputs.

Each of the five irrigation stages are valid for the relevant decade and represent the situation at midpoint of each decade. The assumptions for the stages were:

1990-2000:
- Spate and conjunctive use irrigation areas and crops remain the same as in 1989, as well as pumping capacity in the conjunctive use unit.
- Groundwater irrigated area grows to 29,700 ha, keeping a similar cropping pattern with a corresponding increase in pumping capacity.

2001-2010:
- All three former spate irrigation units are transformed to conjunctive use units and are equipped with pumping capacities comparable to Al Kadan's CU unit. Total area under CU irrigation grows to 7,700 ha. All CU units have a 60% irrigation efficiency and adopt similar cropping patterns as Al Kadan.
- Groundwater irrigated area grows to 37,500 ha with a corresponding increase in pumping capacity.

2011-2020
- Diversion capacities at existing wadi intakes are improved.
- Total area under CU irrigation grows to 9,000 ha with a moderate increase in pumping capacity.

- Groundwater irrigated area increases to 44,000 ha with a corresponding increase in pumping capacity and a gain in irrigation efficiency from 70% to 75%.

2021-2030 - Complementary intakes are installed upstream of the current scheme and in the longest internal wadi link (between diversions to irrigation blocks 2 and 3).
- CU irrigation area grows to 11,200 ha with corresponding increases in pumping capacities.
- Groundwater irrigated area grows to 50,500 ha with corresponding increase in pumping capacity.

2031-2040 - CU irrigation area grows to 13,800 ha with a corresponding increase in pumping capacity.
- Groundwater irrigated area grows to 57,000 ha with a corresponding increase in pumping capacity.

Basically the same composition of cropping patterns for each of the three irrigation methods was maintained throughout the simulation horizon, except for some minor adjustments. A slow tendency away from sorghum crops and toward more profitable crops (i.e., fruits) was built into the cropping pattern series to reflect the expected increased water supply reliability. The effect of having complementary wadi intakes was expediently handled in the simulation model by reducing infiltration losses in the upstream link of the wadi to avoid having to reconfigure the irrigation system with additional nodes.

The summary of results is presented in Tables 4.9, 4.10 and 4.11. Table 4.9 shows the evolution of the water fluxes in the irrigation area. It shows that the net abstraction grows steadily from about 19 Mm^3/year in year 1989 (see Table 4.7), to about 143 Mm^3/year in the decade 2011-2020 and 240 Mm^3/year in the decade 2031-2040. Even with numerous improvements for the utilization of the surface water, no more than 25% of the wadi flow available at Faj Al Hussein was being used consumptively by the crops in the decade 2011-2020, and only 33% by the decade 2020-2030. Table 4.10 summarizes the time series of cropping areas and crop yield ratios for the entire system. There is a substantial growth in irrigated area during the period of analysis and a sustained trend to raise the crop yield ratios. Table 4.11 shows a more detailed break down of cropping areas and yields (spate, conjunctive use and groundwater irrigation) for the 1990-2000 and 2001-2010 situations; these may be considered within the planning horizon and are examined in the economic analysis of Section 4.4.

The groundwater model revealed that for this case drawdowns become very large. Depths to groundwater would exceed 80 m (drawdowns of 50 m from 1984) over large parts of the aquifer. In practice, this rate of abstraction would be unsustainable because of saline intrusion along the coast, local water quality problems, high cost of replacing/deepening wells, and the costs of pumping itself.

Table 4.9 Case B: Components of the Fluxes of the Wadi Surdud Irrigation System for 1990-2040

Component	Annual Volumes (Mm^3)				
	1990-2000	2001-2010	2011-2020	2021-2030	2031-2040
Wadi:					
- inflow at Faj Al Hussein	65.9	65.9	65.9	65.9	65.9
- diversion to irrigation blocks	28.4	29.9	32.0	36.5	36.0
Recharge:					
- wadi bed	38.8	39.3	36.5	32.2	32.4
- surface water canals	0.8	0.9	0.9	1.1	1.1
- all conveyances	5.0	6.7	7.8	9.6	11.1
- surface water irrigation	19.8	11.1	12.1	14.0	10.9
- groundwater irrigation	60.0	84.1	75.9	95.1	106.4
- all irrigated fields	79.8	95.2	88.1	109.1	117.3
Total recharge	123.6	141.2	132.4	150.8	160.9
Abstraction:					
- gross	169.5	235.8	275.8	341.7	400.7
- net	45.9	94.6	143.4	190.9	239.9
Consumptive					
- surface water irrigation	6.5	14.6	16.3	18.6	21.5
- groundwater irrigation	105.4	145.8	193.0	238.1	284.3
Total consumptive use	111.8	160.5	209.3	256.7	205.7

Table 4.10 Case B: Summary of Average Annual Cropped Areas and Crop Yield Ratios, 1990-2040. All irrigation units (blocks 1, 2, 3, 4, 5, 6)

Crop	1990-2000 Area ha	1990-2000 Yield ratio	2001-2010 Area ha	2001-2010 Yield ratio	2011-2020 Area ha	2011-2020 Yield ratio	2021-2030 Area ha	2021-2030 Yield ratio	2031-2040 Area ha	2031-2040 Yield ratio
S-SF	12889.	.771	16750.	.763	19200.	.848	22400.	.881	25700.	.903
S-KF	6964.	.815	7300.	.824	8550.	.885	10070.	.907	11500.	.919
S-RT1	1463.	.850								
S-FDK	3050.	.818	4400.	.815	5000.	.886	5680.	.917	6430.	.929
MAIZE	2100.	.706	3300.	.693	4200.	.761	4970.	.786	5760.	.818
COTTN	1300.	.896	2200.	.887	3100.	.905	3770.	.926	4460.	.943
SESAM	3850.	.581	5150.	.586	6100.	.679	7120.	.712	8060.	.734
TOBAC	2250.	.833	3650.	.793	4200.	.794	4650.	.841	5250.	.867
W-VEG	1300.	.906	1850.	.901	2050.	.893	2370.	.877	2750.	.883
FRUIT	150.	.987	600.	.827	600.	.825	670.	.877	890.	.921
Total area:	35316.		45200.		53000.		61700.		70800.	

Table 4.11 Case B: Average Annual Cropped Areas and Crop Yield Ratios for 1990-2000 and 2001-2010.

Crop	1990-2000 Area (ha)	1990-2000 Yield ratio	2001-2010 Area (ha)	2001-2010 Yield ratio
Spate irrigated (blocks 1, 3, 4):				
S- SF	1139.	.634		
S- KF	914.	.731		
S-RT1	1463.	.850		
Total ave. cropped area:	3516.			
Conjunctive use unit (block 2):				
S- SF	800.	.953	2950.	.787
S- KF	150.	.988	550.	.893
S-FDK	100.	.999	400.	.909
MAIZE	150.	.976	550.	.800
COTTN	150.	.990	550.	.906
SESAM	150.	.927	700.	.753
TOBAC	300.	.950	1100.	.757
W-VEG	150.	.843	300.	.820
FRUIT	150.	.987	600.	.827
Total ave. cropped area:	2100		7700.	
Groundwater irrigation units (blocks 5, 6):				
S- SF	10950.	.772	13800.	.758
S- KF	5900.	.824	6750.	.818
S-FDK	2950.	.812	4000.	.806
MAIZE	1950.	.686	2750.	.672
COTTN	1150.	.883	1650.	.880
SESAM	3700.	.566	4450.	.560
TOBAC	1950.	.815	2550.	.808
W-VEG	1150.	.914	1550.	.916
Total ave. cropped area:	29700.		37500.	
Overall total cropped area:	35316.		45200	

4.3.3 Case C.

This is a hypothetical case where it is asumed that starting in 1990 greater use of surface wadi flow will be made, while maintaining the groundwater irrigation units areas and water usage constant at 1989 levels. The working assumptions for this case are:

- Diversion capacities at existing intakes are increased.
- Complementary intakes are incorporated in the upper and longest internal link of the wadi.
- All spate irrigation units are converted to conjunctive use irrigation, retaining their original areas and incorporating a modest pumping capacity. The Al-Kadan CU unit retains its initial characteristics. All adopt a 60% irrigation efficiency.

Tables 4.12 and 4.13 summarize the results obtained with the Irrigation Simulation Model. Net abstraction is about 34 Mm^3, that is 15 Mm^3 more than the 1989 situation. The average cropped area is slightly more than in 1989 (32,000 ha vs. 31,616 ha) and the crop yield

Table 4.12 Case C: Components of the Fluxes of the Wadi Surdud Irrigation System

Component	Annual Volume Mm^3
Wadi:	
- inflow at Faj Al Hussein	65.8
- diversion to irrigation blocks	39.3
Recharge:	
- wadi bed	32.8
- surface water canals	1.2
- all conveyances	4.4
- surface water irrigation	13.1
- groundwater irrigation	45.9
- all irrigated fields	59.0
Total recharge	96.2
Abstraction:	
- gross	130.2
- net	34.4
Consumptive use:	
- surface water irrigation	18.7
- groundwater irrigation	81.6
Total consumptive use	100.3

ratios are slightly higher. Crops with higher returns were included for the area where conjunctive use replaces spate irrigation. Also a higher productivity per ha will be achieved for those crops that were previously planted under spate irrigation given the larger potential yield in the CU units (superior technological level).

The groundwater model showed that the drawdowns would be greater by up to 10-15 m by year 2040 than in Case A. The increment in drawdown is more marked near the upstream irrigation units because of the compounded effect of reduced wadi recharge, particularly in the upper reach, and of reduced field recharge (because of greater irrigation efficiencies in the former spate units).

4.4 Economic Implications

4.4.1 General

The results obtained with the simulation models have been subjected to some very direct and simplified economic analyses to gain insights in their economic implications. The performances of cases A, B, and C above are evaluated deriving indicators of net benefits and returns to water for the period 1990-2010. The analyses considered the returns to irrigated agriculture, using the same parameters and values shown in Section 2.3.3 in the part dealing with water productivity for the various crops in the Tihama. The effect of crop yield ratios (depressed yields) resulting from the simulations were incorporated into the economic analyses. The quantification of applicable pumping costs took into consideration the results of the Groundwater Simulation Model (Annex B), as explained in Section 4.4.2 below. The

Table 4.13 Case C: Average Annual Cropped Areas and Crop Yield Ratios

	Crop	Area (ha)	Yield ratio
Conjunctive use units (blocks 1, 2, 3, 4):			
	S- SF	2150.	.835
	S- KF	1100.	.785
	S-FDK	350.	.840
	MAIZE	380.	.750
	COTTN	390.	.862
	SESAM	510.	.767
	TOBAC	500.	.859
	W-VEG	250.	.826
	FRUIT	370.	.821
Total average cropped area:		6000.	
Groundwater irrigation units (blocks 5, 6):			
	S- SF	9550.	.656
	S- KF	5150.	.722
	S-FDK	2600.	.712
	MAIZE	1750.	.538
	COTTN	1000.	.829
	SESAM	3200.	.456
	TOBAC	1750.	.744
	W-VEG	1000.	.916
Total average cropped area:		26000.	
All irrigation units (blocks 1, 2, 3, 4, 5, 6):			
	S- SF	11700.	.689
	S- KF	6250.	.733
	S-RT1	-	-
	S-FDK	2950.	.727
	MAIZE	2130.	.576
	COTTN	1390.	.838
	SESAM	3710.	.498
	TOBAC	2250.	.770
	W-VEG	1250.	.898
	FRUIT	370.	.821
Total average cropped area:		32000.	

analyses were carried out using financial prices, thus the results reflect more the costs and benefits to the farmers than true economic consequences to the nation.

A complementary analysis of the benefits of conversion of spate irrigated units to conjunctive use irrigation was also performed. The simulation results for individual spate units, which were assumed to adopt a groundwater complement for irrigation, were used for the comparison. The contrasting performance of the various units was studied.

4.4.2 Pumping Costs

The pumping costs used here are derived using the assumptions employed in Annex E on pumping costs in the report on Groundwater Resources, Volume IV. The main assumptions for a representative well are:

- Pumping rate of 36 m^3/h (10 l/s)
- Pumping hours per year: 3,600
- Capital goods:

	Cost	Life (years)
borehole:	YR 2,000/m	20
pump/engine and installation:	YR 160,000	20
pumphouse and tank:	YR 25,000	30

- Diesel fuel cost: YR 3.00/l, oil cost: YR 10.00/l.

The pumping costs are presented as a cost per m^3 pumped and, given the above premises, they will depend mainly on the depth of the borehole and on the pumping head. The depth-to-groundwater can be obtained from the Groundwater Simulation Model runs. The dynamic pumping head has been assumed to be 5 m greater than the depth-to-groundwater. The borehole depth has been assumed to be at least 20 m greater than the pumping head. For convenience, the pumping costs adopted correspond to depths to the water table at the central position of the surface water irrigation system. Depths there tend to be similar to the ones found at the western limits of the system (though water levels grow shallower towards the Red Sea). At the eastern limits of the surface irrigation system, depths-to-groundwater are somewhat greater. Nonetheless the costs adopted are believed to be representative and adequate for these analyses. Table 4.14 presents the depths and costs in the central zone of the irrigation system for the current situation as well as for year 2040 (final year for the groundwater simulation tests) for cases A, B and C Capital costs were based on the annualized cost of the well using a 10% discount rate. Operating pumping costs for each year of the period of economic analysis (years 1990-2010) were interpolated from the values shown in the table. Capital costs were included, considering investment and replacement costs when necessary.

Table 4.14 Pumping Costs in the Tihama

	Present (1990)	Case A (2040)	Case B (2040)	Case C (2040)
Depth to groundwater, m	32	50	95	58
Depth to borehole, m	57	80	130	88
Head, m	37	55	100	63
Capital cost, YR/m^3	0.27	0.31	0.40	0.32
Operating cost, YR/m^3	0.38	0.52	0.89	0.59
Total cost, YR/m^3	0.65	0.83	1.29	0.91

4.4.3 Analysis of Cases A, B and C

The cropping patterns and yields upon which the analysis was based were detailed in the previous section. Case A maintains the 1989 cropping pattern shown in Table 4.8 through the entire period of analysis; Case B has the cropping patterns shown in Table 4.11, one for 1990-2000 and the other for 2001-2010; Case C has the pattern presented in Table 4.13 during the full 1990-2010 period. The average cropped areas and yields indicated in the tables were employed as expected values for every year of the 21-year series. It was not deemed advisable to use the year-by-year simulated performance because the order of the sequence can affect the economic indicators due to the discounting procedure (e.g. if a series of wet years occur at the beginning of the period, the net present value of benefits would be overestimated, and the opposite happens if a series of dry years is present at the beginning of the period). An analysis of the uncertain distribution over time of the economic variables, i.e. farmer's income, is an important one, and the actual time series would be essential for this. This aspect has, however, not been considered here.

The main focus of the analysis was to examine the returns to water. As such, given current prices of inputs and agricultural products, the net income, excluding cost of water, were calculated for each crop under spate and under conjunctive use or groundwater irrigation as described in Section 2.3.3. This net income may be considered the residual that gives the upper bound to the cost of water for a given crop to remain profitable. This income represents the return to water, expressed either a per m^3 of water or per hectare irrigated. The potential yields (crop yield ratio=1.000) were not normally achieved as a long-run average, as shown in the tables cited above. The actual yields (product of crop yield ratio times the potential yield) were considered in the analysis. Due to higher farming technology reflecting greater water costs and supply reliability associated with groundwater irrigation, the potential yields for this type of farming were assumed to be higher than for spate irrigation (see Section 2.3.3). The potential yields and technological level for conjunctive use irrigation were considered to be the same as for groundwater irrigation.

When water costs are also deducted from the gross income, the actual net benefits to the farmer are obtained. Surface water was assumed to be costless, though this is not strictly the case. Even if permanent diversion structures are considered sunk costs, the performance of O&M activities and the erection of temporary structures such as *aqms*, entail some costs. Groundwater was considered to have a cost equal to the amount necessary to pump it. The 21-year time series of gradually rising pumping costs were considered, as described in Section 4.4.2.

The results of the analysis are summarized in Table 4.15. Case A shows that the returns to water in spate irrigated agriculture are marginal (536 YR/ha, 0.12 YR/m^3), while those for conjunctive use irrigation (15,928 YR/ha, 1.66 YR/m^3) are quite attractive. The returns to water for groundwater irrigation (3,279 YR/ha, 0.72 YR/m^3) are in an intermediate range. The inspection of the returns to water for Case B reveals a similar result. Case C presents comparable results for groundwater irrigation, but a lower performance for the conjunctive use units. To shed more light on these results the following should be noted:

- gross water use, not net consumptive use, by the various types of irrigation methods is used to derive rials/m^3 indicators,

- in the **conjunctive use** units the breakdown of source of water for irrigation in Mm^3/year is as follows:

	Period	Surface water	Ground-water	Total
Case A:	1990-2010	12.4	7.7	20.1
Case B:	1990-2000	12.4	7.7	20.1
	2001-2010	29.9	33.3	63.2
Case C:	1990-2010	39.3	12.3	51.6

- the large amounts of surface water diverted to the spate and conjunctive use units, largely a function of the diversion capacity, are only partially utilized as consumptive use (see Section 4.3): 6.5 Mm^3/year for Case A; 6.5 Mm^3/year (1990-2000) and 14.6 Mm^3/year (2001-2010) for Case B; and 18.5 Mm^3/year for Case C. The excess diversion above gross irrigation requirements is considered to flow back to the wadi.

Hence, the values of the indicators giving the returns to water for spate and conjunctive use units are significantly reduced because of the excess diversions included in the gross water use accounting, even though it is returned for further use by the surface system. Because of this, a more fair indicator of performance for returns to water may be rials/ha. It also becomes evident that the economic advantage that the conjunctive are due to the relatively small proportion of groundwater use with respect to total water use (about one third, except for Case B, 2001-2010). A more detailed look at the benefits of the conversion of spate to conjunctive units is given in Section 4.4.4.

It is also interesting to note the use of water per irrigated hectare. Spate and groundwater units use approximately 5,000 m^3/ha per year, and conjunctive use units about 8,000-9,000 m^3/ha. Notwithstanding the low irrigation efficiency of the spate units, it is noted that the cropping intensity is very low, drought-resistant crops are cultivated, and crops are generally under-irrigated because of the variability of the wadi flow. All these together yield a low water use. Though the water use per hectare is similar in the groundwater units, the latter units have a much larger efficiency, and consumptive use is a substantial portion of the gross abstractions. The water use in conjunctive use units is high because they have a high cropping intensity, an irrigation efficiency lower than in groundwater units, and also there are significant amounts of excess diversions.

The analysis of the total net benefit for the three cases yields a surprising result: the net present benefits for Case A (1989 farming practices sustained indefinitely) are not significantly different from Case B (continued irrigation and groundwater exploitation expansion); Case C (hold the groundwater units constant, convert the rest to conjunctive use and increase diversion capacity) shows somewhat higher benefits. Evidently, even though there is unrestricted irrigation development with Case B, the higher pumping costs nearly offset the gains of greater agricultural production. For Case C, the benefits are overstated since no costs were included for additional diversion works. Thus, there is no strong comparative advantage for either of the three cases. The recommendation for a course of action very likely has to be based on other considerations, such as objectives of water

Table 4.15 Economic Analysis of Cases A, B, and C: Summary of Results

Description	SWU	GWU	CWU	Total
CASE A:				
Total net income (mil rials)	16.3	737.4	289.3	1042.9
Yearly cropped area (ha)				
1990-2000	3516	26000	2100	31616
2001-2010	3516	26000	2100	31616
Water use (Mm^3/year)				
1990-2000	16.0	118.4	20.1	154.6
2001-2010	16.0	118.4	20.1	154.6
Water use (m^3/ha)				
1990-2000	4562	4553	9590	4889
2001-2010	4562	4553	9590	4889
Returns to water (rials/ha)	536	3279	15928	3814
Returns to water (rials/m^3)	0.12	0.72	1.66	0.78
Pumping cost (mil rials)	0.0	496.0	32.2	528.2
Net benefits (mil rials)	16.3	241.4	257.1	514.8
CASE B:				
Total net income (mil rials)	12.2	1189.9	422.9	1625.1
Yearly cropped area (ha)				
1990-2000	3516	29700	2100	35316
2001-2010	0	37500	7700	45200
Water use (Mm^3)				
1990-2000	16.0	161.8	20.1	197.9
2001-2010	0.0	202.6	63.2	265.7
Water use (m^3/ha)				
1990-2000	4562	5446	9590	5605
2001-2010	0	5401	8203	5879
Returns to water (rials/ha)	534	4348	13993	4974
Returns to water (rials/m^3)	0.12	0.80	1.58	0.87
Pumping cost (mil rials)	0.0	1003.4	62.8	1066.2
Net benefits (mil rials)	12.2	186.5	360.1	558.9
CASE C:				
Total net income (mil rials)	0.0	737.4	543.5	1280.9
Yearly cropped area (ha)				
1990-2000	0	26000	6000	32000
2001-2010	0	26000	6000	32000
Water use (Mm^3)				
1990-2000	0.0	118.4	51.6	170.0
2001-2010	0.0	118.4	51.6	170.0
Water use (m^3/ha)				
1990-2000	0	4553	8597	5312
2001-2010	0	4553	8597	5312
Returns to water (rials/ha)	0	3279	10474	4628
Returns to water (rials/m^3)	0	0.72	1.22	0.87
Pumping cost (mil rials)	0.0	583.7	62.4	646.1
Net benefits (mil rials)	0.0	153.7	481.1	634.8

Notes:
a. Total net income represents present value excluding pumping costs.
b. Returns to water are calculated from annualized streams of net income, hectares cropped, and water used over the planning horizon.
c. Pumping costs are present value of investment and O&M costs.
d. Net benefits are present value of net income minus pumping costs.

conservation, or the need for the production of foodstuff at a national level. Also the simulations on which this analysis was based did not take into account the risk of water quality degradation, which is a very real, though difficult to quantify, factor to consider in a water management plan.

4.4.4 Conversion from Spate to Conjunctive Use Irrigation

A comparison was carried out to estimate the benefits of converting the spate irrigation units to conjunctive use. The methodology is simple and direct, but one that can yield some meaningful insights. The current (1989) spate units were assumed to go on with the same cropping pattern and water use for the 1990-2010 period in a similar fashion to Case A above. Their economic performance was compared to that of the same units assuming they had adopted conjunctive use irrigation for the same period. The crop areas and yields used in this analysis for both cases are shown in Table 4.16.

The results of the analysis are summarized in Table 4.17. As before, surface water costs were assumed to be zero; pumping costs used for conjunctive use units were based on: (1) water level decline over time as in Case B above, (2) investment at beginning of period in new wells required for conversion to conjunctive use, and (3) operating costs as described in Section 4.4.2. The pumping capacities assumed for the new CU units are similar to the capacity that the Al Kadan unit currently possesses: 250 tcm/decade in Block 1, 200 tcm/decade in Block 3, and 250 tcm/decade in Block 4.

Table 4.16 Cropping Patterns and Yields for Spate and Conjunctive Use Irrigated Blocks 1990-2010

Crop	Block 1		Block 3		Block 4	
	Area (ha)	Yield ratio	Area (ha)	Yield ratio	Area (ha)	Yield ratio
Spate irrigated:						
S- SF	235.	.521	592.	.783	312.	.438
S- KF	179.	.611	490.	.898	245.	.484
S-RT1	319.	.849	740.	.942	404.	.681
Cropped area:	733.		1822.		961.	
Converted conjunctive use units:						
S- SF	550.	.724	800.	.907	800.	.518
S- KF	100.	.889	150.	.977	150.	.706
S-FDK	100.	.917	100.	.995	100.	.724
MAIZE	100.	.804	150.	.948	150.	.462
COTTN	100.	.943	150.	.976	150.	.719
SESAM	150.	.771	150.	.915	250.	.538
TOBAC	200.	.869	300.	.851	300.	.345
W-VEG	150.	.652				
FRUIT	100.	.896	150.	.969	200.	.558
Cropped area:	1400.		2100.		1900.	

Table 4.17 Conversion from Spate to Groundwater Irrigation: Indicators

Indicator	Spate system (1)	Conjunctive system (2)
Block 1:		
Net income (Mil rials)	0.73	134.38
Yearly cropped area (ha)	733.00	1,400.00
Yearly water use (Mm^3)	1.11	10.10
Surface water	1.11	1.11
Groundwater		8.99
Returns to water (rials/m^3)	0.08	1.54
Returns to water (rials/ha)	114.00	11,099.00
Pumping costs (Mil rials)	0.00	55.04
Net benefits (Mil rials)	0.73	79.34
Block 3:		
Net income (Mil rials)	19.86	262.60
Yearly cropped area (ha)	1,822.00	2,100.00
Yearly water use (Mm^3)	13.64	20.31
Surface water	13.64	13.78
Groundwater	6.53	6.53
Returns to water (rials/m^3)	0.17	1.50
Returns to water (rials/ha)	1,260.00	14,458.00
Pumping costs (Mil rials)	0.00	41.90
Net benefits (Mil rials)	19.86	220.70
Block 4:		
Net income (Mil rials)	-4.29	102.48
Yearly cropped area (ha)	961.00	2,100.00
Yearly water use (Mm^3)	1.29	11.54
Surface water	1.29	2.63
Groundwater	8.90	8.90
Returns to water (Rials/m^3)	-0.38	1.03
Returns to water (rials/ha)	-517.00	5,642.00
Pumping costs (Mil rials)	0.00	54.73
Net benefits (Mil rials)	-4.29	47.75

Notes:
a. Net income is present value without pumping costs.
b. Returns to water calculated from the annualized stream of income and the yearly water use.
c. Pumping costs are present value of investment and O&M costs.
d. Net benefits are the present value of net income minus pumping costs.

The following observations can be drawn from the results:

(1) Taken individually, the performance of the three spate units show significant variation: Block 1 is marginally profitable, Block 2 performs noticeably better, and Block 4 is unprofitable. This is undoubtedly due to the difference in water availability among them: in Block 1, access to water is severely limited because of the low diversion capacity: Block 3 receives an ample supply of water, even though it is downstream of Block 1, because of its significantly larger diversion capacity;

Block 4, despite having the same diversion capacity than Block 3, captures much less water mainly because the residual flow in the wadi is small at that point.

(2) The introduction of conjunctive use is highly beneficial judging from the increase of returns to water per hectare (114 to 11,099 R/ha for Block 1; 1,260 R/ha to 14,458 R/ha for Block 3; and -517 to 5,642 for Block 4) and from the returns to water per cubic meter (0.08 to 1.54 R/m^3 for Block 1; 0.17 to 1.5 R/m^3 for Block 3; and -0.38 to 1.03 R/m^3 for Block 4). When calculated at the margin (incremental benefits per incremental unit of water used), the returns to water are clearly illustrative (1.72 R/m^3 for Block 1; 4.21 R/m^3 for Block 3; and 1.21 R/m^3 for Block 4). All units show attractive returns under conjunctive use, particularly Block 3. Block 4 does not quite catch up, but its returns are comparable now to those of purely groundwater irrigation, a substantial improvement with respect to its former condition.

(3) As shown in Table 4.15 the returns to water in purely ground water irrigation range from about 3,300 to 4,300 R/ha and from 0.72 to 0.80 R/m^3. From (2) above, it is evident that the incremental value of groundwater is considerably greater when employed in conjunctive use irrigation, that is ranging from 4.21 to 1.21 R/m^3.

(4) An important characteristic not captured by the above indicators is the greater stability over time of the income of the new conjunctive use units as compared to that of spate irrigation units, which are subject to the randomness of wadi flow occurrence. The stability thus achieved is of greater consequence with respect to spate irrigation as one proceeds downstream. This is a social and economic benefit that should be taken into account.

CHAPTER 5
OUTLOOK

5.1 The Issues

The Tihama is a rapidly evolving region of Yemen with a complex set of problems related to water resources development and management. Other important regions in the country are also undergoing drastic transformations with increasingly acute water supply shortages, particularly in the highlands. The physical and socioeconomic setting makes the Tihama, however, unique. Its surface and ground water resources, its climate, topography and farming tradition allow a large-scale agricultural development unlike other parts of northern Yemen.

In Chapter 2 a number of water resources management issues in the Tihama were identified. These are summarised as follows:

- **Conflict between catchment and Tihama plain users.** Evidence suggests that an increase in the use of water in the catchment area of wadis is occurring. This can have serious consequences for the amount of water available to users in the plain and for recharge of the aquifer.

- **Inequity between upstream and downstream spate irrigators in the plain.** Upstream users have traditional priority rights to wadi flow. They divert the major portion of baseflow and thus enjoy access to a greater quantity of water with greater regularity and reliability than the downstream users. This effect, in cases, has grown more pronounced with government implementation of modern irrigation works as the upstream users gain unintended control.

- **Effects of unbridled over-exploitation of the aquifer.** This is threatening the aquifer's sustainability in the long run and makes the degradation of water quality worse. The private sector, driven principally by market incentives, is the main groundwater developer and user. The more evident economic repercussions are the rising pumping costs due to declining water levels.

- **Inefficiency in the use of water.** Current allocation of water to the various uses and users and productivity of water leaves ample room for improvement. No consistent and overall development objective is pursued.

- **Consequences of potential interbasin transfers away from the Tihama to highlands.** The Tihama is already depleting its reserves and any further reduction of its resource will make the imbalance more acute with serious socio-economic implications. Reduction of baseflow and aquifer recharge would be two evident physical consequences of any interbasin transfer. Political feasibility and trade-offs of such transfers have to be carefully considered.

- **Conflict of water use expansion policy with water resources conservation objective.** Private and government initiatives in the agricultural and municipal sectors are implementing a policy of expansion in the use of water. Though these are laudable efforts that will likely result in short-term benefits for the population, they overlook the long-run consequences of increased pumping costs, degradation of water quality, and aquifer depletion.

- **Institutional inadequacy.** There already are important and positive steps in providing the necessary institutions, in particular with the creation of the Tihama Development Authority. The nature and extent of the problems cited above require, however, the strengthening of the institutional framework from the highest to the local level.

5.2 Lessons Learned

The present report was meant as an overview of the Tihama region, gathering past knowledge and insights, and adding concepts and information generated by the TS-HWC. Some analytical tools were developed and their application illustrated with specific applications Wadi Surdud, though the procedures can easily be generalized to other wadis. A conceptual framework for the formulation of a water resources management strategy was described. This report can be seen as an exploration on how to proceed in the future in water resources development in the Tihama.

Some of the lessons learned (or verified) in this exercise are:

- The Tihama plain aquifer is undoubtedly undergoing stress, with abstractions exceeding replenishment. The safe yield was roughly estimated at 60% of current recharge (rain contribution, wadi seepage, irrigated fields seepage) in order to gain equilibrium, as there would be unavoidable coastal losses to restrain salt water intrusion. With current estimates, the safe yield is less than half the net withdrawal from the aquifers. Regaining a stable situation without incurring in detrimental irreversibilities would require a timely and substantial curtailment of current abstractions.

- Depletion not only implies falling water levels and loss of reserves by dewatering of aquifers, but groundwater quality deterioration as well. Local sources (poor quality water adjacent to main exploitation areas) probably pose a greater risk to agriculture than upconing from the saline front. Water quality problems might constitute a constraint to groundwater use before pumping costs rise to uneconomical levels.

- Nevertheless, it is expected that, in general, no major problems may arise in the medium- or short-term (5 to 10 years) even if present trends of abstraction continue. The high yield of the aquifer, comparatively large storage, and slow process of salt water intrusion grant these advantages. It would, however, be foolhardy not to start taking precautions to curb present tendencies which could prove disastrous in the long run. The issues of the desirability of continued social and economic vigour in the future and of intergenerational equity need to be considered. The positive point is that there is time to act and to find satisfactory management solutions.

- To act effectively, proper water resources strategies, as described in Chapter 3, must be formulated and implemented. Government intervention is required given that private initiative and market mechanisms cannot solve successfully the problems facing the Tihama. With the realization that there is an impending, though perhaps not immediate, water resources crisis, actions should start now. For instance, the establishment of the appropriate institutional framework with appropriate staffing is a time-consuming effort; the implementation of regulatory and monitoring mechanisms, say, for groundwater abstraction control, is a demanding process; the necessary extension and research programs require a sustained effort for implementation; and public awareness and support can be gained only after prolonged campaigns.

- Action will need to start with the present knowledge about the situation, although this is imperfect. Nonetheless it is necessary to launch vigorous data collecting programs, which may allow improvements in the making of decisions in the future, or the adjustment of ongoing initiatives. For instance, regarding the physical setting, the need for information includes:

    * in the upper catchments: surveying and monitoring location and extent of terraces, the trends of construction and abandonment of terraces, present water use and sources; hydrological processes in the catchments, which would require the establishment of experimental watersheds as well as expansion of the hydrometeorological network (see report on Surface Water Resources, Volume III); and present water use patterns and evolution along the wadi valley.

    * improved monitoring and quality control of the wadi gauging stations so they may provide reliable flow measurements, particularly to detect trends on the occurrence of base and flood flows.

    * aquifer system: expansion of monitoring network to gain sufficient information on aspects such as conditions in the coastal zone, groundwater losses, variability of permeability and reliable specific yield values (laterally and with depth). The verification of salinity values of the Red Sea is important for salt water intrusion analyses. Impact of potential reduction of coastal discharge and evaporative losses on coastal ecology needs to be investigated.

On the socioeconomic setting, there are various aspects which need attention such as:

* detection and quantification of migration patterns, and conditions and incentives which cause migration.

* understanding of the social system and traditional conflict resolution mechanisms to be able to propose workable solutions and to avoid mistakes, such as the spate irrigation works in Wadi Mawr which widened the inequity gap between upstream and downstream farmers in water distribution.

* better understanding of the decision process of the farmer, particularly in spate irrigation (when and what he plants), of receptiveness to change to conjunctive use, and of expected performance under conjunctive use.

* fuller information on farming systems, continuing the work initiated by DHV [1988].

- There needs to be awareness that, if unimpeded, the policy of agricultural expansion, which is supported and applied by the government and actively pursued by the private sector, can have ruinous consequences on the sustainability of the region's water resources in the long run. In the short analysis performed in this report with respect to Wadi Surdud it was seen that the net economic benefits to farmers of unrestricted expansion of abstraction were not significantly larger than maintaining the current agricultural situation. On the other hand, the benefits of conversion of spate to conjunctive use irrigation were evident.

- The decision on how far the aquifer reserves in the Tihama may be allowed to drop, while maintaining an expanding agriculture has to be considered at national not only regional level, since self-reliance in food production is worthy objective. There has to be, however, a clear vision of the consequences of the various courses of action. Likewise, the decision on transferring water out of the Tihama catchments requires an integral evaluation in which both regional and national interests and trade-offs need to be considered.

- The problems that need to be solved in the Tihama starting now surpass the capabilities of the current institutional set-up. There is sectoral (mainly agriculture and municipal) and geographical fragmentation. An effective central authority is required, which can define sectoral objectives in harmony with Yemen's developmental plans and can set guidelines and resolve conflicts at regional level. Mandates of regional authorities (and of national authorities acting in the Tihama) have to be extended and/or made compatible so that a concerted, integrated effort can be carried out in the application of water resources management strategies in the Tihama.

- A natural planning unit in the Tihama is the catchment with its corresponding groundwater province (assuming the higher level national and regional objectives are defined), given the almost closed water resources system it constitutes. The development of a planning methodology at the catchment level and corresponding analytical framework, which may be applied to the various catchments and their corresponding groundwater provinces, was recognized at the TS-HWC and was part of the scope of this effort. The development of the Irrigation Simulation Model and the Groundwater Simulation Model applied to Wadi Surdud, but which are readily transferable to other catchments, show that the development of a flexible analytical framework is a viable effort.

In the report on Groundwater Resources, Volume IV, Annex C: Groundwater Assessment of the Western Basin options for the management of the groundwater resources of the Tihama are proposed. The measures that may be finally adopted will need to be part of an overall strategy, which considers the above aspects.

5.3 What Next?

The concerns and suggestions voiced in the above sections have to be translated into viable courses of action. At this writing (July 1992), the situation in Yemen, particularly with respect to the water sector institutional set-up, is fluid. It is thus not possible to suggest a detailed and rigid plan, nor does the TS-HWC have now the necessary information and resources to design an action plan the Tihama. Nevertheless, the following actions should be undertaken as soon as possible:

(1) Definition of the institutional structure and responsibilities and associated legislation in matters pertaining to the water sector in Yemen.

(2) Incorporation into the scope of the next national water resources planning project the formulation of the water resources management strategy for the Tihama, reflecting in the terms of reference the aspects referred to above.

(3) Inclusion in the upcoming National Development Plan of the short- and long-term objectives related to agricultural sector and water resources management in the Tihama and of the relevant initiatives.

(4) Design and implementation of an expanded data collection effort as well as monitoring the performance and upgrading of current hydrometeorological and hydrogeological networks.

The first action involves high level decisions for policy-making and the management of the water sector at a national level. It is a prerequisite, particularly for the second and third action. The Yemeni government is actively working on that aspect and a definition is expected soon. This matter has been a concern to donors, as evidenced in the recent Round Table Conference (Geneva, 30 June-1 July 1992). The second and third action are interrelated. The water management strategy for the Tihama formulated as a result of the second action would become part of the National Development Plan.

The fourth action was initiated with the handing over by the TS-HWC of measuring equipment for the extension of the hydrometeorological network in the Tihama. The installation and the start of operation of this equipment should be secured. The three entities involved are the Tihama Development Authority, the Southern Regional Development Authority, and the Al Mahwit Regional Development Project. Other aspects which need data collection still have to be considered.

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