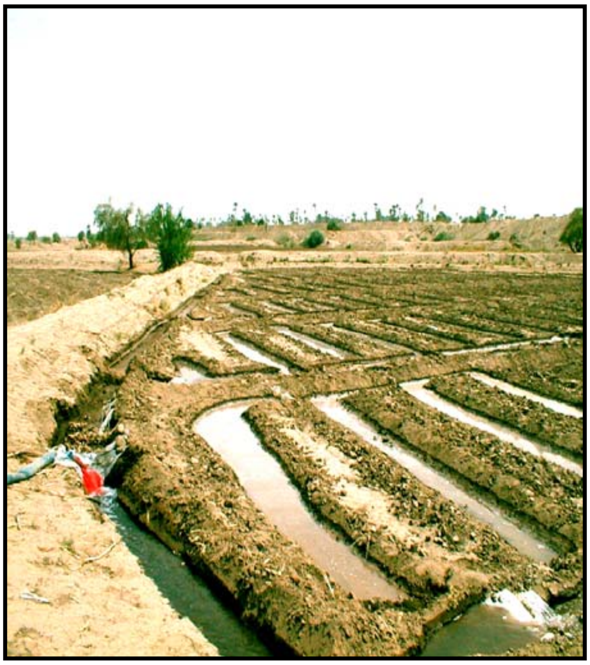 

MINISTRY OF AGRICULTURE & IRRIGATION

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THE WORLD BANK

MAIN TECHNICAL ASSISTANCE PACKAGE FOR IRRIGATION IMPROVEMENT PROJECT (IIP)

Working Paper 1

Water Management in Wadi Tuban & Wadi Zabid, Water Management Plans & Spate Management Models

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IN ASSOCIATION WITH:

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Working Paper 1
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Glossary

Ain	Spring of Water
Command delta	Depth of water applied over the Command Area
Crop delta	Depth of water applied over the (seasonal) Cropped Area
Distributary	Canal offtaking from the Primary Canal (Note: terminology as used on all the original drawings for the Tuban scheme)
Feddan	Unit of land (1 feddan = 0.42ha; 1.038 acres)
Intensive Command Area	The area of land that can be sustainable cropped using both spate and groundwater. (Term specific to this report only).
Kharif	Spate Irrigation Season (in this report taken as the period from 1st July to 31st December)
Ogma	Earthen embankment jutting into, or occasionally carried right across, the wadi in order to divert water into a canal
Peripheral Command Area	The area of land which may receive spate flow in "wet" years but which cannot be regularly cropped, or use groundwater, without over exploiting the available water resource. (Term specific to this report only).
Seif	Spate Irrigation Season (in this report taken as the period from 1st January to 30th June)
Sheik al Obar	(Irrigation) Water Master
Wadi	River or watercourse, often dry. Commonly refers to the whole valley containing the watercourse.

1 Summary

Water Management Practices in both Wadi Tuban and Wadi Zabid have changed over the last 30-40 years as higher value vegetable crops and banana orchards have displaced traditional spate field crops such as sorgum (fodder and grain), cotton and sesame in importance. This has become possible by the construction of permanent weirs across the wadis and the investment by farmers in wells and pumped ground water irrigated agriculture. There are now more than 2000 wells in both Wadi Tuban and Wadi Zabid. Vegetables and banana require provide more employment (eg picking banana and cutting out old stems) than traditional field crops. However, due to their high value they provide higher returns to land and water than traditional field crops, and similar returns to labour.

In these schemes water is the critical resource constraint to increasing agricultural production, and crops that maximise returns to water should be adopted. Vegetables provide a financial return to water 4-5 times higher than field crops, while banana, despite its high water requirements, gives a return 2-3 times higher than field crops.

The proximity of Aden, a large and growing market for vegetables, means that the trend to grow more vegetables in Wadi Tuban is almost inevitable and should be supported. No such market exists for Wadi Zabid, but marketing of banana to Syria and Saudi Arabia is now well established, and the area under banana is likely to continue to grow from the about 3,500ha presently cultivated.

To maximise crop production better use of the water should be made, growing more "crop per drop". The conjunctive use of spate flows and ground water needs to be improved, and yield losses due to over-irrigation or under-irrigation reduced.

The objectives of the Water Management Plans for both Wadi Tuban and Wadi Zabid should therefore be to:

- Improve yields of both higher value vegetable and (banana) orchards and traditional spate irrigated field crops to get more "crop per drop".
- Encourage the cultivation of higher value vegetables, and to a lesser extent banana, should be encouraged, subject to market opportunities, in both Wadi Tuban and Wadi Zabid. However, the interests of the poorer farmers should not be ignored (see below);
- Promote the conjunctive and sustainable use of surface and groundwater by determining and agreeing with farmers' the areas for intensive cultivation. These proposed "*Intensive Command Areas*" are likely to be about 6,500ha in Wadi Tuban and about 8,000 ha in Wadi Zabid. Intensive cropping over larger areas would gradually deplete the groundwater resource. The area for Tuban

will be smaller if a substantial increase in abstraction for water supply for Aden has to be allowed for.

- Ensure that spate flows continue to be fully diverted during wet years, so that surface water does not escape to the sea. "P*eripheral Command Areas*" to absorb spate flows in wet years are proposed and would comprise those lands which historically received some spate water.

The project would therefore support the on-going trend to higher value cropping, while promoting improved and sustainable use of spate and groundwater.

To address the risk that only farmers with wells would benefit, the project would have to support and expand water markets, whereby farmers without wells would have (secure) access to pumped water. This would likely continue to be in the form of sharecropping with the well owners.

Farmer and management practices that could be improved to maximise "crop per drop" include:

- Timing and amount of water applications to better meet crop water requirements by conjunctive use of spate and groundwater.
- Improved land levelling, or land preparation, particularly where more than one irrigations are applied, so that yield losses due to over, or under, irrigation are minimised.
- Increased areas of high value (vegetables and fruits) cropping.
- Formal agreements within each WUG/WUA so that farmers without wells have access to well water, on a sharecropping or cash basis.
- Allowing more than one irrigation application using spate flows, but at the same time enforcing a maximum depth of water to be applied per spate irrigation. This depth should be about 300mm.
- Encouraging farmers to seek advice on the use of agro-chemicals, improved seed, etc. However, care should be taken to ensure that the groundwater is not contaminated, particularly in Wadi Tuban where a considerable volume is pumped to help meet Aden's potable water supply requirements.

Infrastructure to divert and distribute spate flows should be rehabilitated and improved within the proposed Intensive Command Areas in Wadi Tuban and Wadi Zabid.

In Wadi Tuban, works could include the construction of new Distributary canals and (field) access roads, and provision of gated structures, in the traditional schemes. Ogmas may be made semi-permanent by replacing with gabion walls or gabion protected earthen spurs. For the modern schemes, few new works are required, as Distributary canals and (field) access roads have already been built, and only need rehabilitating where discharge capacity and/or condition is poor. However, the poor condition of existing gates means that most will need to be replaced.

In Wadi Zabid, even for the schemes where permanent diversion weirs were constructed, Distributary canals were never provided, and Primary canals may not extend far enough into the proposed Intensive Command Areas. Where traditional spate canals are to be remodelled, realignment should be carried out to minimize meandering. Check structures in the Primary canals are without gates. In Wadi Zabid, new Distributary canals, (field) access roads, and gated checks in the Primary canals are required. There appears to more of a problem than in Wadi Tuban of sediment entering into the Primary canals from the weirs, reducing capacity, and sediment exclusion options need to be studied as well. Major wadi works are also to be considered in Wadi Zabid, such as the bifucation of flows into the Wadi Nasery and Wadi Ain. The suggested new link canals along either side of Wadi Nasery to replace the traditional canals supplied from seven ogmas may not be economically justified given the short time that this area (in Group 2), has the prior right to divert spate water (only 42 days at present), and the high design capacity therefore needed.

The absence of Distributary canals, and the resulting practice of irrigating from field to field, means that crops near to the Primary canal receive too much water, while those further away often receive too little. Crop yields are depressed for both cases.

Intensive infrastructure works in the proposed Peripheral Command Areas, which would only receive water in "wet" years, would be unlikely to be economic and should be minimal.

The proposed Intensive Command Area boundaries for each Primary canal system should be delineated to guard against head – tail inequity along the wadis by taking the following into consideration:

- Maintaining the existing status quo, ie: lands which have not in the past few years received spate flow should be excluded. This should be evident from the high resolution (1m) satellite imagery being obtained under the project.
- Discussions with farmers to obtain a consensus on a reasonable head-tail distribution of spate flows along the wadis. It is likely that the traditional distribution rules will be maintained. However, in Wadi Zabid, the possibility of increasing the period that water is provided to Group 2 canals, and reducing the period for Group 1 canals, could be considered to increase equity of water distribution along the wadi.

Consensus on a Wadi Water Management Plan must be achieved with all stakeholders in both Wadi Tuban and Wadi Zabid, so that water is distributed reasonably equitably along the wadis to each of the main canal systems. Involving local influential landowners and gaining their support is vital for success. The project will have to act, along with Government agencies, as a mediator between different parties with conflicting interests.

The Wadi Water Management Plan would:

- define the proposed Intensive Command Areas for each Primary Canal.
- Agree spate water distribution rules along the wadi.
- Agree depths of water applications, and therefore volumes, to be diverted to each Primary canal before priority is given to another Primary canal.

Primary Canal Water Management Plans should be formulated together with the Water User Associations for each Primary canal system, or other similar hydraulic boundary. The decision to spread spate water widely along a Primary canal to grow traditional spate crops, or to use water over a smaller area for higher value crops requiring conjunctive pumping, should largely be left to the WUAs. Similarly, the application depths and whether to allow more than one application using spate water will be their decision. They would, however, be strongly encouraged to maximise "crop per drop" by growing higher value crops with the conjunctive use of spate and groundwater.

The boundaries of the new Intensive Command Areas will be influenced by the WUA's decision, and this may affect the extent of distributary canals and access roads construction and/or improvement.

It is suggested that WUA construction contracts be used as the vehicle for construction works downstream of the Primary canal offtakes. These contracts would be managed by the WUAs, and they would be paid at lower rates for work carried out than would be paid to a commercial contractor; the difference being the WUA's contribution to construction works.

Spate Management Models will be prepared for Wadi Tuban and Wadi Zabid to improve the distribution of spate water to the Primary canals, and also to check that the sizes of the proposed Intensive Command Areas for each Primary canal, as well as the Primary canal discharge capacities, are reasonable.

The data requirements for the models are envisaged to comprise: (a) fixed data which will not change regularly, at least for a single irrigation season; and (b) variable data which has to entered by the operators throughout the irrigation season.

Fixed data which will not change regularly include the following:

- Irrigation network and hydraulic properties (ie locations of structures, capacities of offtaking Primary canals, weir and head regulator discharge characteristics, etc).
- Intensive Command Area sizes for each Primary Canal.
- Priorities for water distribution based on traditional water rights, and agreed refinements, all as included in the Wadi Water Management Plans.

- Command deltas (ie water volumes divided by Intensive Command Areas) to be supplied to each Primary canal before priority for spate water is given to another Primary canal.
- Estimated Wadi bed loss – spate flow relationships.

Variable data which will need to be entered by the models operators throughout the season include:

- Spate characteristics (ie discharge over time data) as measured upstream at the gauging stations, and transmitted by the early warning systems.
- Flow volumes provided to each Primary canal along the wadi in each spate.

Output from models will comprise:

- the incremental and cumulative amount of water (delta and volume) provided to each Primary canal Intensive Command Area in previous spate flows.
- the quantity of water (volume and delta) still due to each Primary canal.
- the duration of time water is still to be diverted to each Primary canal, assuming full flow, for the next incoming spate.

By running each model using the spate runoff characteristics for its wadi, the ability of the canal system to divert the required volume to each Primary canal can be determined. Similarly, the probability of any Primary canal not receiving its due share of spate flow can be determined.

The model will also allow future scenarios to be planned in advance, by entering data for various incoming spate flows. This will allow operators to know how many Primary canals will be able to divert spate water at the same time, thus minimising the quantity of spate water that escapes downstream. Action plans may be prepared and disseminated to gate operators and stakeholders in advance.

The operators of the Spate Management Models, including those responsible for collection and input of data, need to be trained. They should therefore be identified at an early stage. Also, necessary equipment and computers need to be procured.

2 Introduction

2.1 *Introduction to Working Paper*

This Working Paper presents the water management studies for Wadi Tuban and Wadi Zabid carried out by the Water Management Specialist during his first input from 4th to 31st August 2002. During this time field visits were made to Wadi Zabid (6th to 9th August 2002), and to Wadi Tuban (10th to 15th August 2002).

Terms of Reference for this input were drafted by the Senior Irrigation Engineer/DTL and were to "*obtain a first hand understanding of the issues relating to irrigation and water allocation within the project area*". This was carried out by field visits, observations of water management practices, and discussions with both farmers and PIU staff at Wadi Tuban and Wadi Zabid.

A visit was made to the office of the National Water Resource Agency (NWRA), Aden on 13th August 2002. Notes of this visit are attached as **Appendix A**.

This Working Paper presents the findings and conclusions of the Water Management Specialist, concerning:

- Crops, crop water requirements, yield response to water and irrigation scheduling;
- Existing system operation, water rights and on-farm water management practices;
- Water use efficiency;
- Use of spate and ground water;
- Water Management Plans to maximise crop production on a sustainable basis in Wadi Tuban and Wadi Zabid;
- Recommendations concerning the scope (and structure) of the Spate Management Models.

2.2 *Schemes' Locations*

Wadi Tuban is located in Tuban District of the Lahej Governorate, north of Aden at 13^0 North and 45^0 East. It covers about 12,000 ha and extends from the hills at Dukeim, about 55km north of Aden, south to the Gulf of Aden.

Wadi Zabid is located in the Tihama coastal strip along the Red Sea in the Hodeidah Governorate, near the town of Zabid which is about 80 km south of Hodeidah, at 14^0 10' North and 43^0 20' East. It covers about 15,215 ha.

3 Climate and Reference Evapotranspiration

3.1 Climate

The climate in Wadi Tuban and Wadi Zabid , both located in coastal areas, is humid tropical, and is characterised by hot summers with mean monthly temperatures of about 31^{0}C and mild winters with mean monthly temperatures of about 25^{0}C. Humidity is high with a mean of about 65% over the year. Rainfall is scarce, and agricultural production depends on irrigation from spate, open wells and, to a lesser extent, shallow and deep tubewells. Rainfall in the higher lying catchment areas is higher.

3.1.1 *Wadi Tuban*

Climatic data for Wadi Tuban, for the years 1973 to 1985, from the station at Lahej in the command area (Lat. 13.1 ^{0}N; Long. 45.0 ^{0}E) are given in Annex B (Water resources) of the Project Preparation Report. Mean. The elevation of the climatic station is 200m amsl.

The data used in this report to determine evapotranspiration are those given in the FAO CROPWAT climatic data base for Lahej, and given in **Table 3.1**. The record base for these data is not known. However the data is similar to that in the Project Preparation Report.

Mean annual rainfall at Lahej is 62mm, with most rainfall falling in April and May, and in September, as shown in **Table 3.2**. In the catchment area most rainfall occurs in August and September, resulting in higher spate flows during these two months. Mean maximum air temperature varies from 29^{0}C in December and January, to 38^{0}C in June. The annual average maximum temperature is 33^{0}C. Mean minimum air temperature varies from 19^{0}C in December and January, to 26^{0}C in June and July. The annual average minumum temperature is 22^{0}C. Temperature data are shown on **Figure 3.1**. Mean relative humidity is 68%. Mean sunshine hours are 8.2 hours/day, varying from 7 hours/day in January, to 9 hours/day in April-May. Mean wind speed is 111km/d (1.3m/s).

3.1.2 *Wadi Zabid*

Climatic data for Wadi Zabid, for the years 1970 to 1998, from the station at Al Jerba in the eastern side (of the command area South West of Weir 2) (Lat. 14.2 ^{0}N; Long. 43.4^{0}E) are given in Annex B (Water resources) of the Project Preparation Report. The elevation of the climatic station is 240m amsl. Rainfall declines in the command area going West, and in Zabid town is about 191mm/year (1985 to 1991 data).

The data used in this report to determine evapotranspiration are those given in the FAO CROPWAT climatic data base for the Zabid area, and shown in **Table 3.3.** The record base of these data is not known. However the data are similar to those from Al Jerba given in the Project Preparation Report.

Mean annual rainfall is 352mm, with most rainfall falling from July to October, as shown in **Table 3.4**. Mean maximum air temperature varies from 32^{0}C in December and January, to 40^{0}C in June. The annual average maximum temperature is 36^{0}C. Mean minimum air temperature varies from 19^{0}C in December and January, to 27^{0}C in June and July. The annual average minumum temperature is 23^{0}C. Temperature data are shown on **Figure 3.2**. Mean relative humidity is 69%, and varies from 62% to 77% over the year. Mean sunshine hours are 7.1 hours/day, varying from 4.7 hours /day in July to 8.1 hours/day in April. Mean wind speed is 132 km/d (1.5m/s), varying from 104km/d (1.2 m/s) from October to December to 190 km/d (2.2m/s) in July.

Temperatures in Wadi Zabid are slightly higher than for Wadi Tuban. Also, there is more cloud cover in Wadi Zabid, more rain and higher winds.

3.2 Reference Evapotranspiration, ETo

3.2.1 Method

Reference evapotranspiration, ETo, is calculated using CropWat 4 Windows. The program uses the FAO (1992) Penman-Monteith method to calculate reference crop evapotranspiration. These data are then used to estimate crop water requirements and in irrigation scheduling calculations.

The FAO Penman Montieth equation is described in the following papers:

- Allen, Smith, Perrier and Pereira. "An update for the Definition of Reference Evapotranspiration". ICID Bulletin 1994 Vol 43 No 2 pages 1-34;
- Allen, Smith, Perrier and Pereira. "An update for the Calculation of Reference Evapotranspiration". ICID Bulletin 1994 Vol 43 No 2 pages 35-92.

3.2.2 Wadi Tuban

Using the climatic data for Lahej station, reference evapotranspiration has been calculated using CROPWAT.

Reference evapotranspiration varies from 3.66mm/d in December to 5.71mm/d in June, and averages 4.82mm/d over the year (see **Figure 3.3**). Total annual reference evapotranspiration is 1,759mm.

3.2.3 *Wadi Zabid*

Using the climatic data for Wadi Zabid, reference evapotranspiration has been calculated using CROPWAT.

Reference evapotranspiration varies from 3.70mm/d in January to 5.97mm/d in June, and averages 4.95mm/d over the year (see **Figure 3.4**). Total annual reference evapotranspiration is 1,807mm.

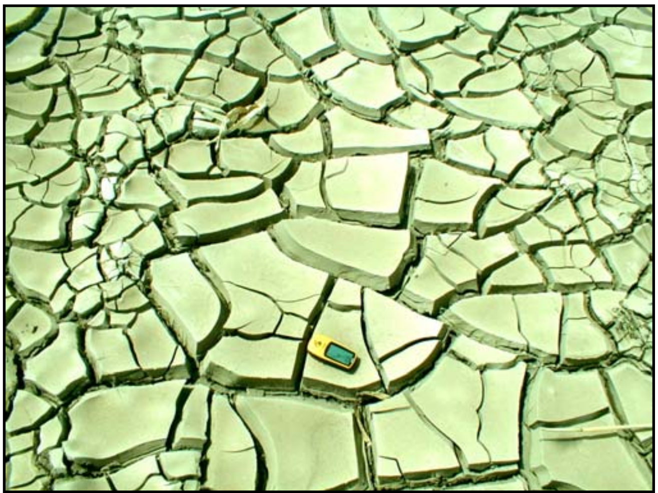
4 Soils

4.1 General

The demand for water by the crop must be met by the water in the soil, via the root system. The actual rate of water uptake by the crop from the soil is determined by whether the available water in the soil is adequate. If not the crop will suffer from water stress.

The infiltration rate and water holding capacity of the soil are therefore important considerations.

The soil water holding capacity affects the maximum irrigation intervals for crops to prevent water stress. If this maximum irrigation interval is exceeded then the plant suffers stress, evapotranspiration is reduced below maximum, and crop yield declines.



Wadi Tuban: Soil about 12days after Irrigation

The infiltration rate determines the time required to wet the soil and to some degree the distribution of moisture within the soil. This influences irrigation practice, such as irrigation flow rate, irrigation method, etc.

4.2 Description of Soils

4.2.1 General

Observations during the site visits to Wadi Zabid and Wadi Tuban, indicated that the soils being irrigated vary from loam to clay loam with silt loam perhaps predominating.

Wadi Tuban: Soil a few days after Irrigation

When dry, silt loam appears quite cloddy, but the lumps can be readily broken and when pulverised it feels smooth, soft and floury. When wet, the soil readily runs together. When moistened and squeezed between thumb and finger it will not ribbon, but will have a broken appearance.

No soils data was made available for Wadi Tuban. However, a soils report was obtained for Wadi Zabid.

4.2.2 Wadi Zabid Soils

A survey of the soils and land capability of the Wadi Zabid area was carried out in 1971. The soils were classified into four main groups:

- Alluvial soils: 30%;
- Soils affected by wind erosion: 22%;
- Arid brown soils: 47%;
- Salt effected soils 1%

The soils have a wide range in texture, field capacity, infiltration rate and permeability. Soil fertility was affected by low plant nutrient content and wind erosion. Two thirds of the surveyed area of about 20,000 ha has soils suitable for irrigated agriculture.

The alluvial soils occur in the vicinity of Wadi Zabid and the main canals. Silt deposited from spate flows diverted from the wadi has resulted in the horizontally layered profiles of the alluvial soils. The presence of the silt layers raises the available water stored in the soil. The amount of silt present, and the presence or otherwise of gravel layers near the surface, determines the water management characteristics of these soils. Silt and clay in the surface layers is indicated by the shrinkage cracks that form when the soils are dried out. The silt content of these alluvial soils varies from about 25% to

55%, and the clay content varies from about 10% to 35%. They are therefore typically loams, silt loams or clay loams.

The soils affected by wind erosion occur in the western part of the project area and extend into the desert. In these areas a layer of desert sand has covered the alluvial soils, or tropical arid brown soils. The fertility and water management characteristics of these soils depends on the thickness of the sand cover and the texture of the buried soil.

Wadi Zabid: Western Boundary of Irrigated Land

Tropical arid brown soils occur to the south of Zabid, between the alluvial soils of the wadis and areas affected by wind erosion, where loams and silty loams predominate, and in the eastern part of the project area, where silty clay loams and clay loams predominate.

4.3 Available Soil Water, Sa

Total available soil water (Sa) is defined as the depth of water in mm/m soil depth between the soil water content at field capacity (Sfc), and the soil water content at wilting point (Sw). Total available soil water (Sa) can vary widely for soils having a similar texture. Also, most soils are layered to some extent, and integrated values of Sa over soil depth should be selected.

As a general indication, Sa mm/m values for different soil textures are given in **Table 4.1.**

Table 4.1 Available Soil Water for Various Soil Textures	
Texture	**Available Soil Water, Sa (mm of water/metre of soil)**
Coarse sand and gravel	20 to 60
Sands	40 to 90
Loamy sands	60 to 120
Sandy loams	110 to 150
Fine sandy loams	140 to 180
Loams and silt loams	**170 to 230**
Clay loams and silty clay loams	**140 to 210**
Silty clays and clays	130 to 180

In this study, a value for Sa of **180mm/m** depth has been assumed for all analyses and recommendations concerning irrigation intervals.

4.4 Infiltration Rates

Infiltration rates decrease during irrigation. The rate of decrease is usually rapid initially and slowly approaches a constant final (or terminal) value. Values for the final infiltration rates depends largely on soil texture, and indicative values are given in **Table 4.2.**

Table 4.2 Infiltration Rates	Final Infiltration Rate (cm/hr)	Probable Soil Texture
High	3.0 to 8.0+	Sandy loam; sandy clay loam
Medium High	**1.5 to 3.0**	**Loam; silt loam**
Medium Low	**0.5 to 1.5**	**Clay loam; silty clay loam**
Low	0.2 to 0.5	Clay

In this study, a value for the final infiltration rate of **1.0cm/hr** (240mm/day; 9.4inches/day) has been assumed for all analyses and recommendations concerning irrigation practices.

5 Crops and Yield Response to Water

5.1 Introduction

In the planning and design of irrigation projects, production objectives are related to the physical resource base, particularly climate, soil and water supply. For spate schemes, such as Wadi Tuban and Wadi Zabid, production is determined by the extent to which water requirements can be met by the available water supply over the total growing season. In this Chapter, an assessment of the suitability of the major crops being cultivated is made, and the implications of growing these crops is discussed.

5.2 Major Crops Cultivated

The major crops being cultivated include:

- Sorghum, mainly grown for fodder in Tuban, and for fodder and grain in Zabid.
- Cotton, introduced in the 1950s and provided the impetus for the modernisation of the spate systems, particularly in Wadi Tuban.
- Maize (to a relatively small extent).
- Fruit crops, banana, particularly in Wadi Zabid, mango and citrus.
- Vegetable crops, onion, tomato, okra, etc.

Well irrigation supplements spate irrigation, and allows the cultivation of vegetable and fruit crops.

At Wadi Zabid, pumped irrigation is well developed, and as a result fruit crops, mainly banana, are widely cropped.

Banana being disinfected at Wadi Zabid

The share of land under various crops as given in the Project Preparation Report, June 2000, Annex D: Agricultural Development Component, is detailed below in **Table 5.1.**

Table 5.1 Cropping (% of net irrigation command area)	**Main Cropping Period**	**Wadi Tuban**	**Wadi Zabid**
Cotton	August to February	15	10 (6)
Sorghum: grain	August to November	7	24 (18)
Sorghum: fodder	April to May	14	19 (10)
Sesame	August to December	5	9 (6)
Other		3	7 (2)
Total Field Crops		**44**	**70 (42)**
Banana	(Perennial)	-	8 (23)
Other fruits	-	-	1 (0)
Vegetables	August to December	17	15 (15)
Total horticultural Crops		**19**	**24 (38)**
Grand total		**63**	**94 (80)**
Cropping Intensity (area under perennials counted twice)		**63**	**103 (103)**

Note: data for Zabid given in ( ) are estimated by the WMS in compiling this report.

Wadi Zabid, Looking U/S towards Weir 3, 7 August 2002

During the field trips, and from a perusal of medium resolution (10-15m) satellite imagery (attached as **Appendix B**), it would appear that these data are out of date. In particular the area of banana now being cropped at Wadi Zabid appears to be much higher, about 3,500 ha (23% of the total command area of about 15,215ha). The banana is concentrated in the commands of weirs 1, 2 and 3. Very approximate figures, allowing for the increased area of banana, but adopting the same annual cropping intensity, are given in () in the above table.

There are also areas of papaya, banana and mango in Wadi Tuban, (say 5%) which are not included in the above table.

5.3 Crop Yield and Climatic, Soil and Water Requirements

The maximum yield (Ym) of a crop is defined as the harvested yield of a high producing variety, well adapted to the given growing environment, under conditions where water, nutrients and pests and diseases do not limit yield. Under these conditions, climatic factors, which determine the maximum yield (Ym), are temperature, radiation and length of the growing season. In general, temperature determines the rate of crop development and consequently affects the length of the total growing period required for the crop to form yield.

The length of the growing period, the temperature, day length and other specific requirements of the major crops cultivated in Wadi Tuban and Wadi Zabid are given in **Table 5.2**. Soil and nutritional requirements, as well as maximum yields (Ym) are also given in this table.

Insufficient water supply, and the resulting water stress on the plant, results in reduced crop evapotranspiration and crop yield. Water stress in a plant is defined as the ratio ETa / Etm where ETa is the actual evapotranspiration and ETm is the maximum evapotranspiration. When crop water requirements are fully met, then ETa = ETm; when water supply is insufficient, then ETa < ETm.

In order to quantify the effect of water stress, the relationship between relative yield decrease and relative evapotranspiration deficit has been determined, and is given by the yield response factor, ky:

$$(1 - Ya/Ym) = ky\,(1 - ETa/ETm)$$

Ya	=	actual harvested yield
Ym	=	maximum harvested yield
ky	=	yield response factor
ETa	=	actual evapotranspiration
ETm	=	maximum evapotranspiration

Values for ky based on the evaluation of numerous research results are given in **Table 5.3**.

In the following sections, the water requirements of the main crops grown in Wadi Tuban and Wadi Zabid are determined, and the yield drop for various irrigation scenarios considered. This is done using the appropriate yield response, ky, factors for the various stages of crop development. From these theoretical analyses, optimum irrigation scheduling and water use is determined.

While all the crops are reasonably suited to the climatic conditions, only cotton, sorghum and, to a lesser extent, maize are suited to spate irrigation and an unreliable supply of water. For these crops yield is not particularly sensitive to water supply, and the crops have low water requirements and are reasonably tolerant of salinity. Banana requires a lot of water (ETm = 1,700 mm/year for mature banana), is shallow rooted and sensitive to both salinity and water supply. Banana can therefore only be grown with frequent, small irrigations mainly using of ground water. Vegetable crops, onion and tomato, also require frequent, small irrigations and mainly use ground water.

5.4 Crop Budgets: Returns to Labour, Water and Land

An appreciation of the returns to land and water of the main crops cultivated is necessary in assessing which crops farmers are likely to want to cultivate. **Table 5.4** gives returns to labour, water and land for the major crops as calculated during Project Preparation (Annex D: Agricultural Development Component).

Table 5.4
Returns to Labour, Water & Land (YRs at 1999 financial prices)

Crop	Return per labour man day	Return per cu.m of water (application depth)	Return per ha of land
Wadi Tuban			
Cotton	3,354	10 (0.40m)	39,950
Sorghum: grain	2,418	6 (0.48m)	28,776
Sorghum: fodder	2,038	3 (0.41m)	12,302
Sesame	2,447	6 (0.49m)	29,210
Tomatoes & Onions intercropped	2,560	34 (0.62m)	211,145
Wadi Zabid			
Cotton	1,630	8 (0.40m)	32,442
Sorghum (G2): grain	2,940	7 (0.41)	28,954
Sorghum (G2): fodder	641	1 (0.47)	4,688
Sesame	3,313	9 (0.39)	35,222
Tomatoes	4,085	37 (0.62)	230,085
Onions	10,224	98 (0.61)	598,442
Maize	3,132	6 (0.58)	34,585
Banana (G1)	5,391	7 (4.4m)*	308,431
Banana (G2)	3,376	5 (4.1m)*	203,181

Perusal of this table indicates that the returns to water quoted are far too low for banana. Crop deltas of about 4.2 m have been adopted, presumable because the shallow rooting depths result in high percolation losses, unless irrigations are frequent and application depths small. However, percolation losses will largely recharge the ground water and be available for reuse by pumping. Actual returns to water from banana are therefore about double those given.

Taking the argument that deep percolation is not very significant as pumping allows its reuse (albeit with costs for pumping and well development), the returns for water calculated during Project Preparation have been corrected by relating to crop consumptive use.

Table 5.5
Returns to Water (YRs at 1999 financial prices)

Crop	Consumptive Use (ETm – eff. Rainfall) (m)	Return per cu.m of water	Remarks
Cotton	0.69	6 – 9	A reasonable yield can be obtained with less water (say ET of 0.5m)
Sorghum: grain	0.39	7 – 8	A reasonable yield can be obtained with less water (say ET of 0.35m)
Sorghum: fodder	0.20	4 – 6	Not water sensitive
Maize	0.65	5	Maize is sensitive to water supply
Sesame	0.38	7 – 8	
Tomatoes	0.53	40 - 45	Require ground water to provide regular, small irrigations
Onions	0.48	100+	
Banana	1.40	22	

In these irrigation schemes, water is the key resource constraint, not land or labour. On this basis, the "best" crops are vegetables, then banana. These crops require ground water for frequent, small irrigations. This restricts cropping to farmers with wells, and works against the equitable use of available water resource. Traditional spate irrigation crops, such as cotton and sorgum, are comparatively unattractive. Unless vegetables can be processed (the Fiyush tomato paste factor near Wadi Tuban closed down in the 1990s), the market for tomatoes and onion is limited. However, the proximity and likely growth of Aden will sustain a steady increase for Wadi Tuban.

5.5 Banana

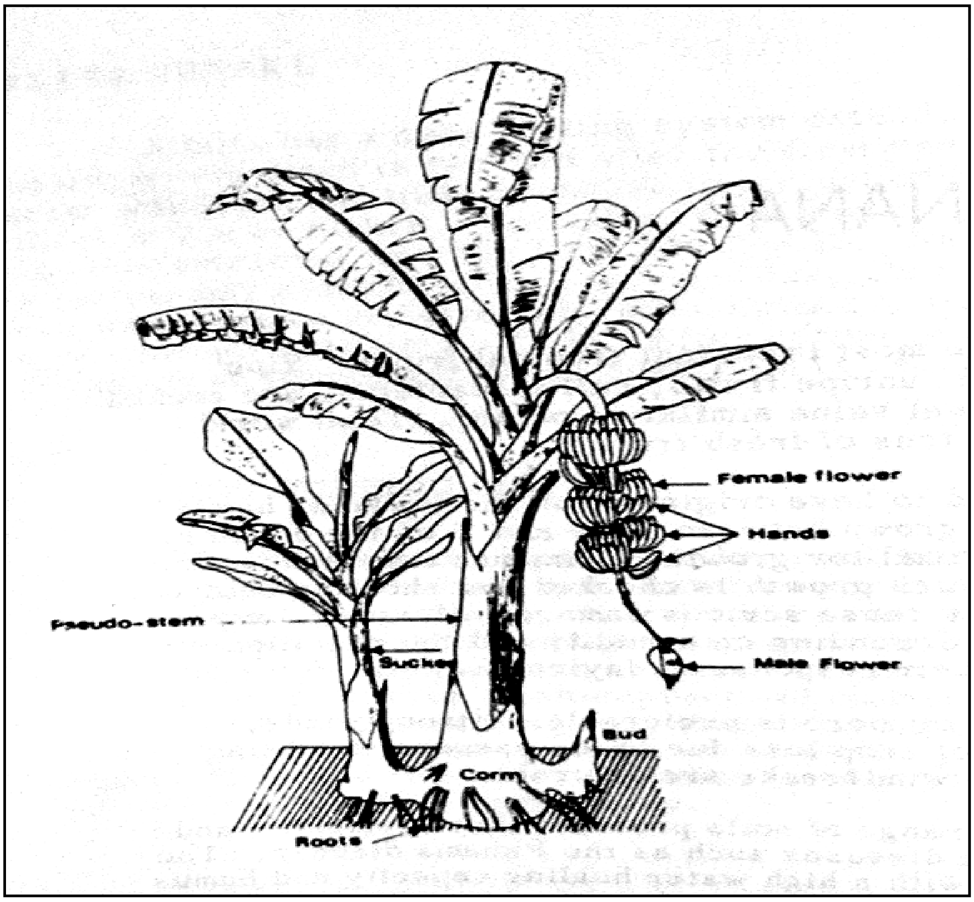
5.5.1 General

Banana is the most important cash crop in Wadi Zabid, where the area being cropped is estimated at between 3,000 and 4,000 ha.

Banana grows best under the following conditions:

- Temperatures of about 27^{0}C (25^{0}C to 30^{0}C ideal);
- Humidity of at least 60%;
- Wind speeds less than 4m/s (or provision of wind beaks);
- Well drained soils;
- Low salinity (Ece less than 1 mmho/cm)

The soil and climatic conditions at Zabid (and at Tuban) are therefore well suited to banana. However, disadvantages are the high water requirements of banana, the fact that they are shallow rooted and require frequent irrigations using pumped well water, and the resulting inequitable water use.



Banana bears leaves on a pseudostem consisting of leaf stalks. The flowering stalk emerges from the pseudostem and produces a hanging bunch of flowers. Fruits are formed on "hands" with about 12 fingers (bananas); each bunch contains up to 150 fingers (bananas). After harvest the pseudostem is cut. The underground stem (corm or rhizome) bears several buds, which, after sprouting, form new pseudostems, or suckers. These are removed except for one or two, which provide the ratoon crop.

Banana is normally multiplied vegetatively. Several types of suckers can be used. The development of a plant is as follows:

- Vegetative phase (planting to shooting), taking about 7 to 9 months;
- Flowering phase (shooting, yield formation to harvest) taking about 3 months.

The time to harvest of the next ratoon crop is about six months. The number of ratoons varies. The average life of a commercial plantation can be from 3 to 20 years.

5.5.2 *Crop Water Requirements, ETm*

The water requirements of banana are high. Using the reference evapotranspiration values calculated for Wadi Zabid, the annual crop water requirements have been calculated for a newly planted crop, and for a mature (ratoon) crop.

In relation to reference evapotranspiration (ETo) the maximum water requirements (ETm) are given by:

ETm = kc ETo

Where kc is the crop co-efficient.

Values for kc for a newly planted banana crop for the first year, and thereafter for mature banana (ratoon crop) are as follows:

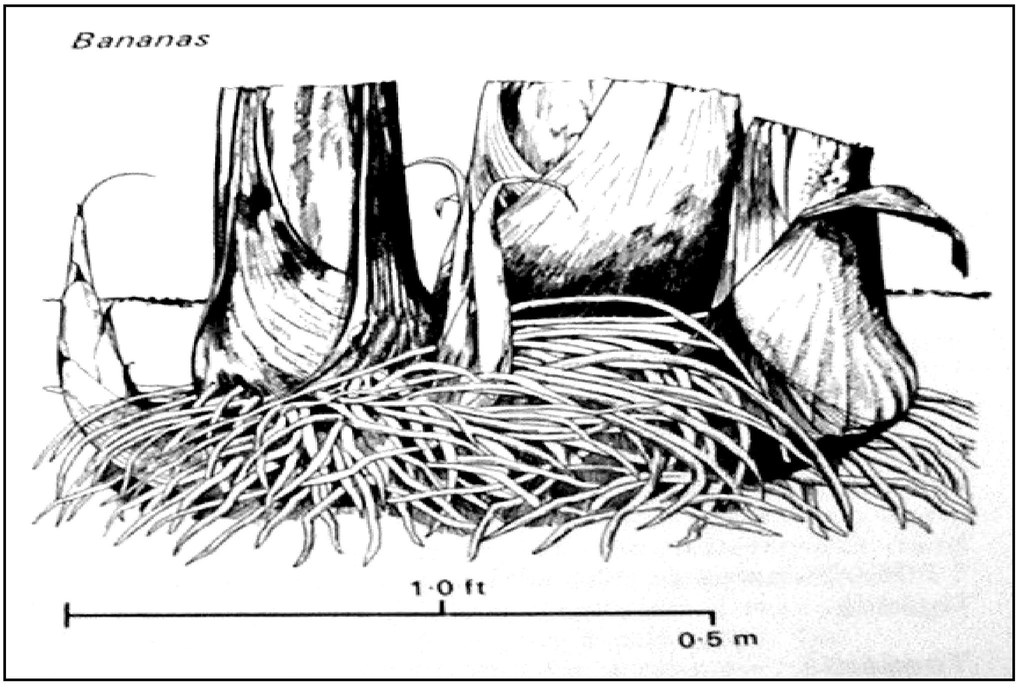
Table 5.6 Kc values for Banana	Year 1				Year 2
Months following planting	1 to 4	5 to 8	9 to 10	11 to 12	Months 1 to 12
Period	Vegetative growth		Flowering & yield formation		Mature banana & Ratoon Cropping
Kc	0.5	0.5 to 1.10	1.10	0.90	Values vary from 0.9 to 1.0

Monthly crop water requirements, ETm, for banana planted in January peak in July and August at about 5.5mm/d. The total requirement for the year is about 1,422mm. If effective rain is taken into account, then for an average year, net annual irrigation requirements would be about 1,135mm (see **Table 5.7**).

For mature banana, crop water requirements, ETm, peak in May, June and July at about 5.5mm/d. The total requirement for the year is about 1,709mm. If effective rain is taken into account, then for an average year, net annual irrigation requirements would be about 1,422mm (see **Table 5.8**).

5.5.3 *Water Uptake*

The banana plant has a sparse, shallow root system. Most feeding roots are spread laterally near the surface. Rooting depth, D, will generally not exceed 0.75m. A rooting depth, D, of 0.45m for young banana, and 0.75m for mature banana has been adopted.



For the "typical" soil adopted in this study, with 180mm/m available water, Sa, the total soil water available (or TAM – total available moisture), to mature banana is 135mm (D.Sa)

With maximum evapotranspiration (ETm) of about 5 to 6mm/d, a 35% depletion of the total available soil water should not be exceeded (ie p = 0.35). In other words, the readily available moisture (RAM) is just 47mm (p.D.Sa).

5.5.4 Water Supply and Crop Yield

Banana requires an ample and frequent supply of water. Water deficits adversely affect crop growth and yields. The establishment period and early phase of the vegetative period determine the potential for growth and fruiting, and adequate water and sufficient nutrient supply is essential during this period. Water deficits in the vegetative period affect the rate of leaf development, which in turn can influence the number of flowers, in addition to the number of hands and bunches.

Wadi Zabid: Young Banana & Well

The flowering period starts at flower differentiation, although vegetative development can still continue. Water deficits in this period limit leaf growth and number of fruits.

Water deficits in the yield formation period affect both the fruit size and quality. A reduce leaf area will reduce the rate of fruit filling; this leads, at harvest time, to bunches being older than they appear to be and consequently the fruits are liable to premature ripening during storage.

The ratio between relative yield decrease and relative evapotranspiration deficit (ky) is high, 1.2 to 1.35, with little difference between different growth periods. In the following analyses an overall ky value of 1.30 has been adopted, with appropriate values for the different stages of crop development.

5.5.5 Irrigation Scheduling and Yield Loss

Since depletion of more than about 35% of the available soil water will be harmful to growth and fruit production, frequent irrigations are required. Using CropWat, the effect of varying irrigation depths and intervals on yield has been assessed.

Given that the readily available moisture (RAM) is only about 50mm, clearly irrigations application depths should be small, but regular enough to keep the soil near field capacity.

Table 5.9 gives the results of various irrigation applications and intervals for newly planted banana (year 1), and **Table 10** gives the results for mature banana (year 2+).

Table 5.9 Irrigation of Banana (Year 1) and Yield Loss	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**
Irrigation Interval (days)	15	20	25	45
Irrigation application depths (mm)	50	70	85	160
Irrigation applied (mm/year)	1,217	1,278	1,241	1,298
Net CWR (ETm – Eff. rainfall) (mm/year)	1,135	1,135	1,135	1,135
Water loss to deep percolation (mm/year)	82	143	106	163
Yield reduction (%)	5	6	9	27

Table 5.10 Irrigation of Mature Banana (Year 2+) and Yield Loss	**Trial 1**	**Trial 2**	**Trial 3**	**Trial 4**
Irrigation Interval (days)	15	20	25	45
Irrigation application depths (mm)	60	80	100	180
Irrigation applied (mm/year)	1,460	1,460	1,460	1,460
Net CWR (ETm – Eff. rainfall) (mm/year)	1,422	1,422	1,422	1,422
Water loss to deep percolation (mm/year)	38	38	38	38
Yield reduction (%)	6	9	15	40

The results clearly show that to keep banana yield losses less than 10%, irrigation intervals should be less than every 20 days; ranging from say 20 days during the cooler months to 15days or less in the summer (June to October). Applications depths of more than about 80mm result in deep percolation below the root zone for banana. Tables and figures showing these results are given in **Appendix C-1** (Year 1 banana), and **Appendix C-2** (Year 2+ banana).

5.5.6 *Yields*

Yields of banana can vary enormously. Good commercial yields range from 40ton/ha to 60ton/ha.

Yields in Wadi Zabid are reported to range from just 20t/ha to 28t/ha, which is modest. Substantial increases are therefore possible, and demonstrations encouraging the use of fertilisers and improved water management practices are required.

5.6 Cotton

5.6.1 General

Cotton is the major cash crop in Wadi Tuban, and the second most important cash crop, after banana, in Wadi Zabid. It is grown for fibre and seed.

The length of the total growing period is about 150 to 180 days. Depending on temperature, 50 to 85 days are required from planting to first bud formation, 25 to 30 days for flower formation, and 50 to 60days from flower opening to mature boll. No clear distinction can be made in crop growth periods since vegetative growth continues during flowering and boll formation, and flowering continues during boll formation.

Establishment Vegetative Flowering Field Formation Ripening

Growth of Cotton

The development of the crop is sensitive to temperature. Germination is optimum at temperatures of 18^0C to 30^0C. Delayed germination exposes seeds to fungus infections in the soil. For early vegetative growth, temperatures must exceed 20^0C with 30^0C desirable. For proper bud formation and flowering, daytime temperatures should be higher than 20^0C and night temperatures higher than 12^0C. For boll development and maturation temperatures between 27^0C and 32^0C are optimum.

Cotton is resistant to short periods of water logging, and tolerant to soil salinity. There is no yield decrease for salinities less than 7.7mmhos/cm; with 10% yield decrease for salinities of 9.67mmhos/cm.

The recommended planting period for cotton is from 1st August to 30th September. Later planting will lead to yield loss and quality decrease. A planting date of 1st September has been assumed in determining crop water requirements and analysing irrigation options.

5.6.2 *Crop Water Requirements, ETm*

The water requirements of cotton have been calculated using the reference evapotranspiration values calculated for Wadi Tuban.

In relation to reference evapotranspiration (ETo) the maximum water requirements (ETm) are given by:

ETm = kc ETo

Where kc is the crop co-efficient.

Values for kc for cotton are as follows:

- Initial stage (30 days): 0.35;
- Development stage (50 days): 0.35 to 1.20;
- Mid-season stage (60 days): 1.20;
- Late-season stage (55 days): 1.20 to 0.60.

The total cultivation period is 195 days (6.4 months).

Monthly crop water requirements, ETm, for cotton planted in early September are high from the end of October to January. The peak requirement in November/December is about 4.5mm/d. The total requirement for cotton is about 710mm. If effective rain in Wadi Tuban is taken into account then, for average rainfall, the net irrigation requirement would be about 693mm (see **Table 5.11**).

5.6.3 *Water Uptake*

From emergence to early flowering, the taproot may extend in deep soils to a depth of 1.8m. Under favourable soil conditions, with restricted water during the later stages of development, roots have been found as deep as 4.5m. During the flowering period, additional root development occurs in the upper part of the root zone. In this analysis of crop water requirements and irrigation scheduling options, a rooting depth, D, of 0.3m is assumed for initial stages of development, increasing to 1.8m by the mid stage (ie 80 days after planting).

For the "typical" soil adopted in this study, with 180mm/m available water, Sa, the total soil water available (or TAM – total available moisture), to mature cotton is 324mm (D.Sa)

Under conditions when ETm is about 5 mm/day water uptake starts to be reduced when soil water depletion exceeds 60% (p = 0.60) for the initial and development stages, 65% in the mid stage (p=0.65), and 90% for the late stage (p=0.90). The readily available moisture (RAM) for cotton therefore varies from 194mm to 292mm (p.D.Sa).

5.6.4 *Water Supply and Crop Yield*

Water supply for high production must be adjusted to the requirements of each growth period. Optimum use of available water can be made by fully wetting the entire root zone up to 1.8m at sowing, and with subsequent wetting of the upper part (0.5 to 1m) of the root zone only. Root activity may be increased, and full utilization of the available soil water over the entire root zone is made, with little or no soil water left at the end of the total growing period.

The ratio between relative yield decrease and relative evapotranspiration deficit (ky) is low, 0.85 over the whole growing period. In the following analyses appropriate values for the different stages of crop development are adopted.

5.6.5 *Irrigation Scheduling and Yield Loss*

Three irrigation scenarios for cotton have been considered:

- Pre-wetting of the entire root zone at sowing with no further irrigation supply;
- Pre-wetting at sowing and one irrigation of 270mm after 100 days, in late November;
- Pre-wetting at sowing and two irrigations, each of 210mm, in early November and early January.

Table 5.12 gives the results for these irrigation scenarios.

Table 5.12 **Irrigation of Cotton and Yield Loss**	**Trial 1**	**Trial 2**	**Trial 3**
Pre-irrigation of 324mm before Planting Date (ie before 1st September)	324 mm	324mm	324mm
First irrigation (mm)	None	270mm in late November	210mm in early November
Second Irrigation (mm)	None	None	210mm in early January
Total Irrigation applied (mm)	324mm	594mm	744mm
Net CWR (ETm – Eff. rainfall) (mm)	692mm	692mm	692mm
Water loss to deep percolation (mm/year)	0 (crop stressed)	0 (crop slightly	52

		stressed)	
Yield reduction (%)	44	13	0

The results show the clear advantage of an irrigation about 100days after sowing, in addition to pre-wetting of the root zone to 1.8m. Tables and figures showing these results are given in **Appendix C-3.**

5.6.6 Yields

The average yield of cotton is about 1,100kg/ha in Wadi Tuban and 1,200kg/ha in Wadi Zabid. A good yield with irrigation is about 1,500kg/ha. This should be attainable with good seed, use of fertilisers and with an irrigation about 100 days after planting.

5.7 Sorghum

5.7.1 General

Sorghum is the most important cereal crop in both Wadi Tuban and Wadi Zabid. It is growth for both grain and fodder. Sorghum is grown in kharif (summer) mainly for grain, and in seif (winter) mainly for fodder. Spate flows are used. However, some farmers used well water to supplement spate supply. For example is Wadi Tuban well water is used by some farmers to allow them to plant kharif fodder before the first spate flow, thereby getting a head start.

Wadi Tuban, Beizag CA
Sorghum started with Well Water

Two traditional varieties are cultivated which produce low yields but have good quality grain and palatable forage.

The growth periods for (grain) sorghum are:

• Establishment, from sowing to head initiation:	15-20 days;
• Vegetative, from head initiation to head emergence:	20-30 days;
• Flowering, from emergence to seed set:	15-20 days;
• Yield formation, from seed set to maturity:	35-40 days;
• Ripening, from maturity to harvest:	10-15 days.
	95-125 days

5.7.2 Crop Water Requirements, ETm

The water requirements of kharif sorghum producing grain have been calculated using the reference evapotranspiration values calculated for Wadi Tuban.

In relation to reference evapotranspiration (ETo) the maximum water requirements (ETm) are given by:

ETm = kc ETo

Where kc is the crop co-efficient.

Values for kc for (grain) sorghum are as follows:

- Initial stage (20 days): 0.30;
- Development stage (35 days): 0.3 to 1.0;
- Mid-season stage (40 days): 1.0;
- Late-season stage (30 days): 0.55.

The total cultivation period is about 125 days (4 months).

Monthly crop water requirements, ETm, for sorghum planted in mid August are high from the end of September to mid November. The peak requirement in October is about 4.5mm/d. The total requirement for sorghum is about 420mm. If effective rain in Wadi Tuban is taken into account then, for average rainfall, the net irrigation requirement would be about 400mm (see **Table 5.13**).

5.7.3 *Water Uptake*

The Primary root system, with little branching, grows rapidly in deep soils to 1.0 to 1.5m. The secondary system starts several weeks after emergence and extends rapidly up to 2m, depending on depth of soil wetting. The maximum root system is generally reached at the time of heading.

In this analysis of crop water requirements and irrigation scheduling options, a rooting depth, D, of 0.3m is assumed for the initial stage of development, increasing to 1.6m by the mid-development stage (ie about 55 days after planting).

For the "typical" soil adopted in this study, with 180mm/m available water, Sa, the total soil water available (or TAM – total available moisture), to sorghum is 288mm (D.Sa)

For sorghum, water uptake starts to be reduced when soil water depletion exceeds 50% (p = 0.5). However, during ripening (late development stage), this increases to 80% (p=0.80). The readily available moisture (RAM) for sorghum therefore varies from 144mm to 230mm (p.D.Sa).

5.7.4 *Water Supply and Crop Yield*

Sorghum is relatively more drought resistant than many other crops (such as maize), due to an extensive root system, effective control of evaporation, and an ability to withstand desiccation.

The timing of water supply should reduce water deficit during the establishment (initial stage), and flowering and early yield formation periods (mid season stage). Severe water stress at theses times will affect yield.

The ratio between relative yield decrease and relative evapotranspiration deficit (yield factor, ky) is medium-low, 0.90 over the whole growing period. In the following analyses appropriate values for the different stages of crop development are adopted.

5.7.5 *Irrigation Scheduling and Yield Loss*

Three irrigation scenarios for kharif sorghum cultivated for grain have been considered:

- Pre-wetting of the entire root zone at sowing (in mid August) with no further irrigation supply;
- Pre-wetting at sowing and one irrigation of 170mm after 71 days, in late October;
- Pre-wetting at sowing and two irrigations, each of 146mm, in early/mid October and in early/mid November.

Table 5.14 gives the results for these irrigation scenarios.

Table 5.14 Irrigation of Sorghum and Yield Loss	**Trial 1**	**Trial 2**	**Trial 3**
Pre-irrigation of 288mm before Planting Date (ie before 15th August)	288 mm	288mm	288mm
First irrigation (mm)	None	170mm in late October	146mm in early October
Second Irrigation (mm)	None	None	146mm in early November
Total Irrigation applied (mm)	288mm	458mm	580mm
Net CWR (ETm – Eff. rainfall) (mm)	398mm	398mm	398mm
Water loss to deep percolation (mm/year)	0 (crop stressed)	60 (crop very slightly stressed)	182
Yield reduction (%)	27	2	0

The results show that, with pre-wetting and one irrigation of 170mm (excluding losses), applied about 70 days after planting, soil moisture only drops slightly below that readily available to the crop, and yield loss is not significant. However, the timing of this second irrigation is important. Applying two irrigations in addition to pre-wetting is wasteful of water. Tables and figures showing these results are given in **Appendix C-4.**

5.7.6 *Yields*

Grain yield under spate irrigation with a net irrigation applied of about 300mm typically varies from 800kg/ha to 1300kg/ha. These yields can be increased by about 30% with one irrigation about 70days after planting.

5.8 Tomato

5.8.1 General

Tomato is a rapidly growing crop, with a growing period of about 130 days (depending on variety). Tomato is grown in both Wadi Tuban and Wadi Zabid using pumped groundwater. There are many varieties grown depending on time of growing and marketing requirements. Private companies and the Agricultural Service Cooperation are responsible for introducing varieties.

Wadi Tuban
Tomato cultivated using Ground Water

Typical growth periods for tomato (for the first harvest) are:

- Establishment: 20-35 days;
- Vegetative: 20-25 days;
- Flowering: 20-30 days;
- Yield formation: 20-30 days;
- Ripening, from maturity to harvest: 15-20 days.

100-140 days

5.8.2 Crop Water Requirements, ETm

The water requirements of tomato have been calculated using the reference evapotranspiration values calculated for Wadi Tuban.

In relation to reference evapotranspiration (ETo) the maximum water requirements (ETm) are given by:

ETm = kc ETo

Where kc is the crop co-efficient.

Values for kc for tomato are typically as follows:

- Initial stage (25 days): 0.60;
- Development stage (35 days): 0.6 to 1.15;
- Mid-season stage (40 days): 1.15;
- Late-season stage (30 days): 0.80.

The total cultivation period is about 130 days (4.3 months).

Monthly crop water requirements, ETm, for tomato planted in mid August peak in October and early November at about 5mm/d. The total requirement for tomato is about 550mm. If effective rain in Wadi Tuban is taken into account then, for average rainfall, the net irrigation requirement would be about 530mm (see **Table 5.15**).

5.8.3 *Water Uptake*

The crop has a fairly deep root system and in deep soils roots can penetrate up to 1.5m. The maximum rooting depth is reached about 60days after planting.

Wadi Tuban: Planting Tomato

In this analysis of crop water requirements and irrigation scheduling options, a rooting depth, D, of 0.25m is assumed for the initial stage of development, increasing to 1.0m by the mid-development stage (ie about 60 days after planting).

For the "typical" soil adopted in this study, with 180mm/m available water, Sa, the total soil water available (or TAM – total available moisture), to tomato is 180mm (D.Sa)

For tomato, water uptake starts to be reduced when soil water depletion exceeds 30% (p=0.3) in the initial stage of development, increasing to 40% (p = 0.4) at mid stage, and 50% (p=0.50) in the late stage. The readily available moisture (RAM) for tomato therefore varies from 54mm to 90mm (p.D.Sa).

5.8.4 *Water Supply and Crop Yield*

Tomato is most sensitive to water deficit during flowering and yield formation. Water for quick seed germination is also necessary. Moderate water deficit during the vegetative period enhances root development.

The ratio between relative yield decrease and relative evapotranspiration deficit (yield factor, ky) is medium-high, 1.05 over the whole growing period. In the following analyses appropriate values for the different stages of development are adopted.

5.8.5 *Irrigation Scheduling and Yield Loss*

Tomato is typically grown using pumped ground water without prewetting of the soil by spate flows.

Three alternative irrigation scheduling scenarios have been analysed for tomato planted in Wadi Tuban in mid-August.

- Application of the amount of water needed to keep the soil moisture between field capacity and the readily available moisture (RAM) limit.
- An application of 60mm (net) every 15 days
- An application of 120mm (net) every 30 days.

The results are given in **Table 5.16.**

Table 5.16 **Irrigation of Tomato and Yield Loss**	**Trial 1**	**Trial 2**	**Trial 3**
Pre-irrigation before Planting Date (ie before 15th August)	0mm	0mm	0mm
Irrigation interval	Variable	15 days	30 days
Total (net) Irrigation applied (mm)	490mm	540mm	540mm
Net CWR (ETm – Eff. rainfall) (mm)	528mm	528mm	528mm
Water loss to deep percolation (mm/year)	0	12+ (crop very slightly stressed)	12+ (crop stressed)
Yield reduction (%)	0	4	14

The first trial represents the optimum, and farmers will need to have a good understanding of tomato water requirements and soil moisture conditions to approach this. This trial indicates that the best use of water is to apply irrigations every 15days or so, with the applications depths gradually increasing as the tomato grows, from about 20mm to 90mm. Trials 2 and 3, which both apply the same amount of water, indicate the need for regular irrigations, about every 15 days. 30 day irrigation intervals results in considerable (14%) yield reduction. Tables and figures showing these results are given in **Appendix C-5.**

5.8.6 Yields

Frequent light irrigations improve the size, shape, juiciness and colour of fruit, but the total solids (dry matter content) and acid content will be reduced. This will lower the fruit quality for processing.

Prolonged water deficits during yield formation, interrupted by heavy irrigation leads to fruit cracking. A good commercial yield is 45 to 65 ton/ha fresh fruit.

Table 5.3 Climatic, Soil and Water Requirements for Crops	Banana	Citrus	Cotton	Maize	Onion	Sorghum	Tomato
Total growing period (days)	300 to 365	240 to 365	150 to 180	100 to 140 +	100 to 140+ (30 to 35 in nursery)	100 to 140+	90 to 140 (25 to 35 in nursery)
Temperature requirements for growth, optimum mean daily temperatures (^{0}C)	25 to 30	23 to 30	20 to 30	24 to 30	15 to 20	24 to 30	18 to 25
Temperature requirements for growth, range (^{0}C)	15 to 35	13 to 35	16 to 35	15 to 35	10 to 25	15 to 35	15 to 28
Daylight requirements for flowering	Day neutral	Day neutral	Short day/Day neutral	Day neutral / short day	Long day / day neutral	Short day / day neutral	Day neutral
Specific climatic constraints / requirements	Sensitive to frost; temperatures < 8^{0}C cause serious damage; Require high RH; Winds < 4m/s	Sensitive to frost (dormant trees less), strong wind, high humidity Cool winter or short dry period preferred	Sensitive to frost, strong or cold winds; temperature required for boil development 27 to 30^{0}C (18 to 38^{0}C); dry ripening period required	Sensitive to frost; for germination temperature > 10^{0}C; cool temperatures causes problems for ripening	Tolerant to frost; low temperature (<16^{0}C) required for flower initiation; No extreme temperature or excessive rain	Sensitive to frost; for germination temperature > 10^{0}C; cool temperatures cause head sterility	Sensitive to frost, high RH & strong winds; optimum night temperatures 10 to 20^{0}C
Soil requirements	Deep, well drained loam without stagnant water:	Deep, well aerated, light to medium textured soils,	Deep, medium to heavy textured soils; pH 5.5 to 8	Well drained and aerated soils with deep water table	Medium texture soil; pH 6 to 7	Light to medium heavy soils; relatively tolerant to	Light loam; well drained without water logging;

	pH 5 to 7	free from stagnant water, PH 5 to 8		and without water logging; PH 5 to 7		periodic water logging; PH 6 to 8	PH 5 to 7
Sensitivity to salinity	Sensitive	Sensitive	Tolerant	Moderately sensitive	Sensitive	Moderately tolerant	Moderately sensitive
Fertilizer requirements N (kg/ha/growing period)	200 to 400	100 to 200	100 to 180	100 to 200	60 to 100	100 to 180	100 to 150
Fertilizer requirements P (kg/ha/growing period)	45 to 60	35 to 45	20 to 60	50 to 80	25 to 45	20 to 45	65 to 110
Fertilizer requirements K (kg/ha/growing period)	240 to 480	50 to 160	50 to 80	60 to 100	45 to 80	35 to 80	160 to 240
Water Requirements (mm/growing period)	1200 to 2200	900 to 1200	700 to 1300	500 to 800	350 to 550	450 to 650	400 to 600
Sensitivity to water supply (yield response factor), (ky)	High (1.2 to 1.35)	Low to medium-high (0.8 to 1.1)	Medium to low (0.85)	High (1.25)	Medium to High (1.1)	Medium to low (0.9)	Medium to high (1.05)
Water utilisation efficiency for harvested yield, Ey (kg/m└)	Plant crop: 2.5 to 4 Ratoon: 3.5 to 6	2 to 5	0.4 to 0.6	0.8 to 1.6	8 to 10	0.6 to 1.0	10 to 12
Harvested yield: percentage moisture (%)	Fruit: 70%	Fruit: 85% Lime: 70%	Seed cotton: 10%	Grain: 10 to 13%	Bulb: 85 to 90%	Grain: 12 to 15%	Fresh fruit: 80 to 90%
Good yields of high producing varieties adapted to climatic conditions, with adequate water supply and high level of agricultural inputs, Ym (ton/ha)	40 to 60 (banana fruit)	25 to 30 (lemon fruit)	3 to 4 (seed cotton)	6 to 8 (grain)	35 to 45 (bulb)	3.5 to 5 (grain)	45 to 65 (fruit)
	Banana	**Citrus**	**Cotton**	**Maize**	**Onion**	**Sorghum**	**Tomato**

6 Water Management in Wadi Tuban

6.1 Scheme Layout

A schematic layout of the Wadi Tuban Spate Irrigation Scheme is shown on **Figure 6.1.** As shown on this figure, and in the photo below, Wadi Tuban branches into two at the Ras Al Wadi weir, into Wadi Saghir to the east and Wadi Kabir to the west. At Ras Al Wadi Weir, the weir crest lengths for each wadi are both 80m and (as the crest heights are the same?) large spate flows in Wadi Tuban divide equally into Wadis Kabir and Saghir. For small spates, flow is directed to each wadi in turn using a bulldozer to construct temporary earthen guide bunds in the wadi bed.

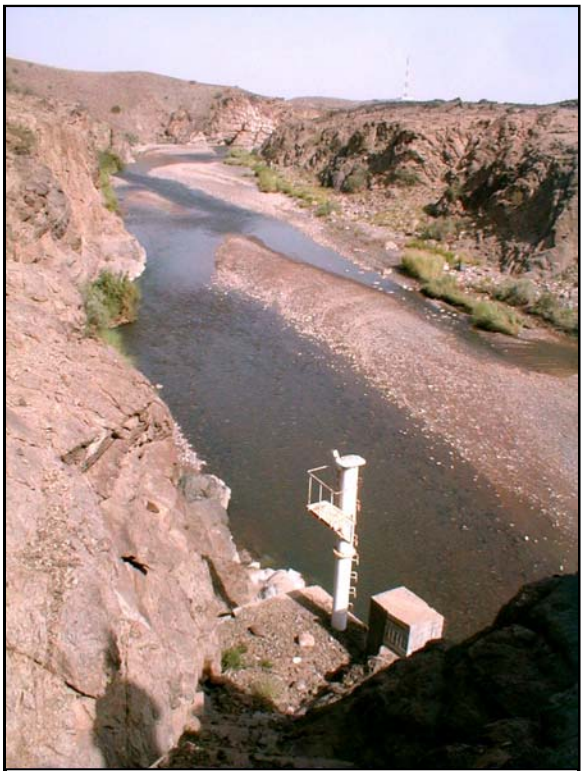
Ras Al Wadi weir showing arrangement for division of Wadi Tuban flow into Wadi Kabir and Wadi Saghir.
Photo shows flow of about $4m^3/s$ being diverted through the right side scour sluice gates

Of the total command area of about 12,000 ha, less than half is reported to be irrigated annually by spate flows. Annual variations are very high. Ground water is used to supplement spate irrigation, and also to cultivate vegetables.

6.2 Surface Water Resources

6.2.1 Data Sources

Water resources data are given in Annex B of the Project Preparation Report, 2000, and in Annex IV (Tuban Delta) of the Wadi Hadramaut Agricultural Development Project, 1987.



Dukame Automatic Water Level Gauging Station

Data is available in these reports for flows at Dukeim (9km upstream of Al Arais Weir) in Wadi Tuban from 1973 to 1980. It is not known how representative these data are of the long term flows.

In 1995, the National Water Resources Authority (NWRA) was established with overall responsibility for water resources sector coordination and planning, including the creation and management of the water resources data base, regional and basis wide water resources planning and regulation, monitoring, conduct of studies and provision of public information. The NWRA offices in Aden were visited (see **Appendix A**). It appears that they only have data in their data base from 1996.

6.2.2 *Available Surface Water*

The mean, maximum and minimum monthly and annual flow volumes at Dukeim are given in **Table 6.1**.

Table 6.1
Mean, Maximum and Minimum Monthly Flows at Dukeim (Mcm)

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Mean	Seif 23.98						Kharif 85.5						109.48
Mean	.89	.56	.25	4.58	8.83	8.87	12.37	27.67	31.00	9.53	3.24	1.69	109.48
Max	1.91	1.65	.52	19.7	27.6	26.5	33.6	58.9	57.1	30.7	7.76	3.77	222.85
Min	.19	.08	.07	.19	.42	1.58	4.67	7.28	6.79	.58	.34	.2	45.82

As shown in the Table, August and September are by far the wettest months.

The mean seasonal flows, and the 80% probability of exceedance flows (ie flow available 4 years out of 5) for Kharif (July to December) and Seif (January to June) are given below in **Table 6.2**.

Table 6.2
Mean and 80% Exceedqnce Seasonal Flows (Mcm)

	Seif	Kharif	Annual
Mean Flow (Mcm)	24.0	85.5	109.5
80% Exceedence Flows (Mcm)	12.0	45.0	73

6.2.3 Wadi Bila

Wadi Bila joins Wadi Tuban between Al Arais Weir and Rais Al Wadi weir. The catchment of this wadi may be small but flows are reported to be significant. No gauging data are available to assess how much this wadi contributes to flows in Wadi Tuban. The IIP hydrology study will address this.

Wadi Bila Joining Wadi Tuban
(looking d/s)

6.2.4 Flood Magnitudes and Frequencies

Floods with various return periods as estimated by two previous studies using the 12 year data record for Dukeim from 1968 to 1979 are given in **Table 6.3.** There is a large difference between the estimates. Under IIP, hydrology studies will be carried out to improve the estimate, using additional data to be collected from the NWRA since 1996, and correlating the rainfall run off relationship.

Table 6.3
Flood Magnitudes and Frequencies

Return Period (years)	Peak Flow Discharge (m^3/s)	
	Binnie's (1987)	SYIP, 1982
Mean Annual Flood	656	340
5	850	-
10	1350	1430
20	2100	1980
50	3650	2800
100	-	3500

The total diversion capacity of the permanent weirs and ogmas is about 550 m^3/s. The size of the spate flood required to meet this diversion capacity, allowing for wadi losses of 1% per km (see **Section 6.2.6**), between Dukeim and the median point of all the offtakes (estimated as a distance of 26km), is 710 m^3/s. A flood greater than this would result in some flow escaping towards the sea from the last diversion structures on the two wadis.

It is reported that spate flows reach the sea every 5-6 years, indicating that wadi losses during peak flows are about 1%/km and that the Binnie flood estimates are in the right order of magnitude.

6.2.5 *Travel Times of Floods*

From wadi cross section and slope dimensions, and bed friction estimates, the flow velocities for the wadis were estimated by Binnies (1987) for floods with return periods of 10 and 50 years. These were as follows:

Table 6.4
Flow Velocities

	Max. Flow Velocities (m/s)	
	20 year flood	**50 year flood**
Wadi Tuban	3.5	4.8
Wadi Kabir	3.8	5.2
Wadi Saghir	4.3	6.0

Adopting theses flow velocities the travel times of the flood peaks are as given in **Table 6.5.**

Table 6.5
Travel Times of Flood Peak

	20 Year Flood		**50 Year Flood**	
	Flow Velocity (m/s)	**Travel Time (hrs)**	**Flow Velocity (m/s)**	**Travel Time (hrs)**
Wadi Tuban				
Dukeim to Al Arais Weir (9.0 km)	3.5	0.7	4.8	0.5
Dukeim to Ras Al Wadi Weir (18.9 km)	3.5	1.5	4.8	1.1
Wadi Kabir				
Ras Al Wadi Weir to Al Waht Weir (18.7km)	3.8	1.4	5.2	1.0
Dukeim to to Al Waht Weir (37.6km)	Varies	2.9	Varies	2.1
Wadi Saghir				
Ras Al Wadi Weir to Manasira Weir (22.4km)	4.3	1.4	6.0	1.0
Dukeim to Manasira Weir (41.3km)	Varies	2.9	Varies	2.1

6.2.6 *Wadi Bed Seepage and Canal Conveyance Losses*

Seepage losses in the Wadi Bed downstream of Dukeim gauging station, and conveyance losses in the canals will reduce the volume of water that can reach farmers fields.

Wadi bed losses have been estimated as follows (refer PPR, Annex B, Water Resources):

Table 6.6 Wadi Bed Seepage Losses		
Average Discharge During Spate Flow (m^3/s)	**Water Loss per km length of Wadi**	
	(%)	**(m^3/s)**
5	4.0	0.2
10	3.3	0.33
30	2.45	0.74
50	1.6	0.8
80	1.0	0.8

Canal conveyance losses have been assumed to be about 20% of the diversion capacity.

6.2.7 *Crop and Command Deltas*

Command deltas from spate irrigation for the whole Tuban scheme have been estimated for Kharif and Seif using the average runoff volumes as measured at Dukeim and allowing for wadi bed and canal conveyance losses. Crop deltas have been calculated using estimated crop areas.

Wadi bed losses in Kharif are estimated assuming 1.6%/km water loss, while losses in Seif are based on 3.3%/km water loss. Assuming a median length of wadi bed of 26km, means that the Kharif wadi flow losses will be 34%, and the Seif wadi flow losses will be 58%.

Only a portion of the command area is irrigated in an average year (this should be confirmed by the high resolution (1m) satellite imagery to be procured under IIP). The Tuban cropping intensities for field crops (excluding horticultural crops grown using ground water) as given in the PPR (refer **Table 5.1**) are as follows:

- Kharif (cotton, grain soghum, sesame): 30%
- Seif (fodder sorghum): 14%
- Annual: 44%

Table 6.7 gives the command and crop deltas for the whole scheme.

Table 6.7 **Command and Crop Deltas for Wadi Tuban Scheme**			
	Kharif	**Seif**	**Annual**
Average runoff volume at Dukeim (Mcm)	85.5	24.0	109.5
Wadi Losses (Mcm)	29.1 (34%)	13.9 (58%)	43.0
Flow Diverted fromWadis (Mcm)	56.4	10.1	66.5
Conveyance losses (say 20%) (Mcm)	11.3	2.0	13.3
Water Reaching Fields (Mcm)	45.1	8.1	53.2
Command Area (ha)	12,000	12,000	12,000
Command Deltas (m)	**0.38**	**0.07**	**0.44**
Cropped Area of Field Crops (ha)	3,600 (30%)	1,680 (14%)	5,280 (44%)
Crop Deltas (m)	**1.25**	**0.48**	**1.01**

The above table indicates that wadi and conveyance losses total 56.3 Mcm, or 51% of the annual average flow. This volume largely percolates to recharge ground water.

The small command deltas confirm that, for an average year, the command area cannot be fully irrigated. Considering kharif, for cotton and grain sorghum, net crop water requirements (ETm-effective rainfall) are 0.69m and 0.4m respectively. Allowing for 20% application losses, indicates an overall delta of about 0.7m. This would indicate that the potential kharif cropped area is about 6,500 ha for an average year.

The areas of field crops grown are less than this, and total just 3,600 ha in Kharif, and 1,680ha in Seif. This gives crop deltas of 1.25m in Kharif and 0.48m in Seif. The crop deltas, particularly the Kharif crop delta, are larger than required to meet crop water requirements, and indicate that a significant quantity of water (about half that applied) is percolating to the water table.

6.3 Ground Water

6.3.1 General

The number of wells in the command area has increased from about 26 irrigation wells in 1961 to about 2000 dug wells or boreholes in 1999. Data are available for the Monitoring Section of the National Water Resources Agency, and/or from the Soil and Water Conservation Project.

Pumped well in Al Arais Command Area

6.3.2 Depths to Water Table

From 36 monitoring wells, which vary in depth from 18m to 92 m, with most being about 60 deep, the following may be concluded:

View down Well in Al-Arais Command Area

- Static water levels are between 10m and 50 m below ground level;
- Draw down water levels are between 20 and 60m below ground level;
- Salinity levels are between 2000 and 5000 micromhos/cm, with the higher salinity values nearer the coast;
- pH values are between about 6.5 and 7.2

The depths to the static water level for the years 1998, 1999 and 2000 had increased for 23 wells, and decreased for 13 wells. For three wells it remained unchanged. The data base is too short to draw firm conclusions.

6.3.3 Aden Water Supply

Aden currently has a population of about 800,000, and this is expected to increase to about 3 million by 2030. The present demand for water is about 50,000 m^3/d. The number of tubewells abstracting water from the Wadi Tuban area is 19, with other well fields in Abyan and Bir Nassan. The wells in Wadi Tuban have been estimated to export 21.5Mcm of water to Aden annually for domestic and industrial use. With the growing demand for water for Aden, this may increase dramatically over the next 30 years, reducing the water available for agriculture.

With improved technology, the cost of desalinated water is likely to continue to decrease, and may become as low as YRs 100 /m^3 (presently about YRs 180/m^3).

6.3.4 Implications

Groundwater monitoring indicates that mining of groundwater <u>may</u> now be taking place. As the growth of Aden's population is likely to mean that more water will be pumped from the Wadi Tuban (and other) areas to Aden, the amount of ground water available for agriculture will decrease.

No crops provide a return to water that is greater than the cost of desalinated water. Tomato and onion provide the highest return at about YRs 50/m^3. Cotton provides a return of about YRs 10/m^3, and sorghum provides a return of YRs 7/m^3 (grain) and YRs 3/m^3 (fodder) (see **Section 5.4**).

6.4 Water Balance

6.4.1 Water Balance and Overall Water Use Efficiency

The construction of ten permanent diversion weirs along the wadis from 1958 to 1973, in addition to the traditional earthen diversion bunds (ogmas), and the rapid increase in wells for irrigation, from 26 in 1961 to about 2000 in 1999, has had the following affects:

- Water only flows to sea every 5 to 6 years;
- Water "lost" to deep percolation is largely available for reuse by pumping;
- Increased cropping of high value vegetables.

Water balance calculations allow an understanding of water use, and an estimate of water use efficiency to be made. **Table 6.8** presents the estimated seasonal and annual water balances for average flows.

Table 6.8 Wadi Tuban Water Balance (Mcm)			
	Kharif (Jul-Dec)	**Seif (Jan-Jun)**	**Annual**
Water into Command Area (CA)			
Surface Inflow at Dukeim	85.5	24.0	109.5
Direct Rainfall on CA of 12,000 ha	3.4 (28 mm)	4.0 (34 mm)	7.4 (62 mm)
Total water into CA (=1)	**88.9**	**28.0**	**116.9**
Water Leaving Command Area			
Surface Outflow to the Sea	0	0	0
Aden water supply	10.8	10.8	21.6
ETm from Field Crops (delta & CI): -Cotton (0.71m; 15%) -Sorghum: grain (0.42m; 7%) -Sorghum: fodder (0.24m; 14%) -Sesame (0.41m; 5%) -Other (0.5m say; 3%) Subtotals:	 12.8 3.5 - 2.5 1.8 20.6	 - - 4.0 - - 4.0	 12.8 3.5 4.0 2.5 1.8 24.6
ETm from other crops: - Tomato, etc (0.55; 19%)	12.5	0.0	12.5
Trees: banana, papaya; mango (1.2 m; 5% say)	3.6	3.6	7.2
Evaporation & ET from non-productive land, wadi bed, etc (Kharif: 0.20m say; 46% of CA. Seif: 0.20m say; 81% of CA)	11.0	19.4	30.4
IMBALANCE	**10.3**	**10.3**	**20.6**
Total Water Out (=2)	**68.8**	**48.1**	**116.9**
Net Inflow (1-2 = 3)	**20.1**	**-20.1**	**0**

The water balance assumes no net recharge or mining of groundwater for an average year, and no out flow to the sea. Using the cropping data from the PPR (see **Section 5.2**), maximum crop evapotranspiration values (ETm), and including for tree crops over 5% of the command area results in an imbalance of 20.6 Mcm over the year.

This could be annual recharge to groundwater; however data and discussions with farmers indicate that the groundwater table is (slowly) declining. The most likely explanation includes:

- Cropping, particularly of vegetables using well water is much higher than reported in the PPR. (It is likely that farmers with wells are pumping and cropping through out the year).
- Average annual spate water inflows, which are based on only 8 years of data (from 1973 to 1980), may be less than 109.5 Mcm.
- Lateral groundwater outflow to wells & land located outside the command area of 12,000 ha may be significant.

The efficiency of water use being achieved depends on how this imbalance of 20.6 Mcm is being used. Assuming it is "wasted" gives an efficiency of just 47% (44.3 / (116.9 – 21.6)). Assuming it is being used productively, for example cropping is higher than reported in the PPR, the efficiency may be about 68% ((44.3+20.6)/(116.9 – 21.6)).

Land Preparation for TW Irrigation
Al Arais CA, 12 August 2002

6.4.2 Use of Groundwater

Water balance indicates that spate flows recharge groundwater in kharif and that water is abstracted in Seif. Assuming no net change in groundwater for an average year, the seasonal and annual recharge and abstraction of groundwater is calculated in **Table 6.9.**

Table 6.9 **Groundwater Balance**			
	Kharif	**Seif**	**Annual**
Recharge to Groundwater			
- from wadi bed:	29.1	13.9	43.0
- conveyance losses (20%):	11.3	2.0	13.3
- application losses (20%):	9.0	1.6	10.6
Total recharge to Groundwater (4)	**49.4**	**17.5**	**66.9**
Abstraction from Groundwater			
Aden Water Supply	10.8	10.8	21.6
Net Abstraction for Irrigation of vegetables in CA (= ETm from **Table 6.8**)	12.5	0.0	12.5
IMBALANCE	16.4	16.4	32.8
Total Abstraction (5)	**39.7.4**	**27.2**	**66.9**
Net increase in Groundwater (4-5)	**9.9**	**-9.7**	**0**

In an average year, about 67Mcm is recharged to the ground table. About 22 Mcm of this water is abstracted for Aden's water supply, and some of the rest is pumped from the 2000 or so wells in the command area. As for the overall water balance, there is a large amount of water unaccounted for.

Assuming the 2000 wells in the command area are pumping 8 hours a day, for 260 days in the year, and that their average discharge is about 2 l/s, this indicates that the annual volume pumped is 30 Mcm. About 40% of this will be loss to evaporation and seepage back to ground water, leaving about 18 Mcm for crop ET. This is rather more than the 12.5 Mcm estimated based on the area of vegetables cropped. However, the accuracy of such calculations renders them inconclusive. Nevertheless, some of the imbalance is likely to be the result of underestimation of the area of crops irrigated using well water.

6.5 Irrigation Infrastructure

6.5.1 Headworks, Diversion Capacities and Diversion Periods

Permanent Weirs

Irrigation in Wadi Tuban has been transformed by the construction of permanent weirs to divert spate flow, and the installation (mainly by farmers) of a large number or wells to exploit water than percolates to groundwater.

Many of the weirs and associated infrastructure are to be rehabilitated under the IIP.

Faleg Weir Head Regulator & Scour Sluice Wadi Kabid

The diversion capacity, area commanded and water duty for each of the permanent weirs are shown in **Table 6.10**.

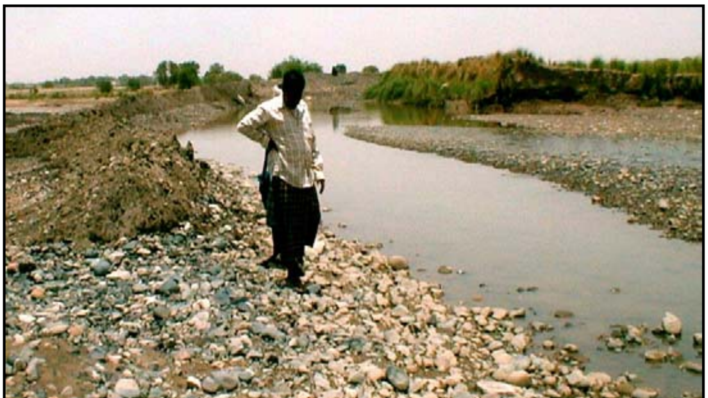
The permanent weir structures can divert a total of 304 m^3/s, and have a combined command area of 9,528ha. This equates to a "duty" of 31.3 ha per m^3/s (32 l/s/ha). The duty for the two weirs along Wadi Tuban averages 41 ha per m^3/s (24 l/s/ha), while for the weirs downstream in both Wadi Kabir and Wadi Saghir, the duty is about 28ha per m^3/s (36 l/s/ha). The smaller duty (capacity of canal per ha) for the upstream weirs is easily explained by the upstream weirs having the right to base flow, as well as small floods.

On the basis of applying a sufficient water to wet the ground to field capacity to rooting depth for cotton, a depth of water of 324 mm is required (see **Section 5.6**). Allowing for 20% conveyance losses and 40% application losses, a gross delta of about 520mm has to be provided to the command area. To provide this amount of water, flow must be diverted to each canal for the periods given in **Table 6.11**. The time taken to irrigate each command area, assuming the canal flows full, varies from just 13 hours for the canals offtaking from Bustan weir, to 96 hours for the Manasira weir. The Manasira weir is the last permanent diversion structure along Wadi Saghir, and in most years its command area is only partially irrigated with spate flow.

Table 6.11 Time Water to be Diverted to Pre-Irrigate for Cotton (gross delta of 520mm)				
Canal	Canal Duty		Time Water to be Diverted for Canal flowing full (hours)	Canal Command Area (ha)
	(ha per m³/s)	(l/s/ha)		
Wadi Tuban				
Al Arais Weir, 1972	38.3	26	56	958
Ras Al Wadi Weir, 1958: Right	55.8	18	80	1394
Ras Al Wadi Weir, 1958: Center	11.0	91	16	110
Wadi Kabir				
Faleg Weir, 1971	47.6	21	69	1191
Fakih Lifiah Weir: Right	26.2	38	38	131
Fakih Lifiah Weir: Left	16.6	60	24	449
Mujahed Weir, 1971	26.3	38	38	657
Al Waht Weir, 1962	25.9	39	37	1037
Wadi Saghir				
Beizag Weir, 1964	43.7	23	63	1093
Al Khadaram Weir, 1972: Left	15.0	67	22	225
Al Khadaram Weir, 1972: Right	12.7	79	18	318
Bustan Weir, 1973: Left	8.8	114	13	105
Bustan Weir, 1973: Right	9.0	111	13	180
Manasira Weir, 1960	67.2	15	96	1680
			463	**9528**

Earthen Diversion Weirs (Ogmas)

The diversion capacity, area commanded and water duty for the earthen diversion bunds (ogmas) are shown in **Table 6.12**.



Ogma Al Abab in Wadi Tuban
Discharge 7m³/s, 17.6km downstream of Dukame

The ogmas can divert a total of 246 m³/s (assuming they can all divert at the same time), and have a combined command area of just

2,532ha. This equates to a "duty" of 10.3 ha per m^3/s (97 l/s/ha). The duty for these ogmas is much higher than for the diversion weirs, as during a typical high spate flow they would be washed away during the rising flood. They therefore have to divert a large volume of water quickly.

The combined diversion capacity of the ogmas (assuming they are not quickly washed away) and the permanent weir structures is 550 m^3/s.

On the basis of applying a sufficient water to wet the ground to field capacity to rooting depth for cotton, a depth of water of 324 mm is required (see **Section 5.4**). Allowing for 20% conveyance losses, and 40% application losses a gross delta of about 520mm has to be provided to the command area. For the typical ogma with a duty of 97 l/s/ha, the time required to irrigate its command area would be 13 hours.

Table 6.10
Offtaking Capacity and Design Duties for Permanent Weirs

Structure	Distance from Dukeim (km)	Weir Width (m)	Offtaking Canal				Remarks
			Left/Right	Design Flow (m^3/s)	Command Area (ha)	Design Duty ($ha/m^3/s$)	
Wadi Tuban							
Al Arais Weir, 1972	9.0	200	Right	25	958	38.3	These upstream weirs have the first right to use base flow, as well as the first use of spate flow.
Ras Al Wadi Weir, 1958	18.9	2 x 80	Right	25	1394	55.8	
			Centre	10	110	11.0	
				60	**2462**	**41.0**	
Wadi Kabir							
Faleg Weir, 1971	27.1	130	Left	25	1191	47.6	In general, less area is irrigated per m^3/s as one progresses downstream.
Fakih Lifiah Weir	-	-	Right	5	131	26.2	
			Left	27	449	16.6	
Mujahed Weir, 1971	34.8	200	Left	25	657	26.3	
Al Waht Weir, 1962	37.6	175	Left	40	1037	25.9	
				122	**3465**	**28.4**	
Wadi Saghir							
Beizag Weir, 1964	25.7	90	Right	25	1093	43.7	In general, less area is irrigated per m^3/s as one progresses downstream. This command area of the Manasira weir is rarely fully irrigated.
Al Khadaram Weir, 1972	31.6	95	Left	15	225	15.0	
			Right	25	318	12.7	
Bustan Weir, 1973	35.2	75	Left	12	105	8.8	
			Right	20	180	9.0	
Manasira Weir, 41.3	41.3	-	Left	25	1680	67.2	
				122	**3601**	**29.5**	
				304	**9528**	**31.3**	

Table 6.12
Offtaking Capacity and Design Duties for Earthen Diversion (Ogmas)

	Distance from Dukeim (km)	Weir Width (m)	Offtaking Canal				Remarks
			Left/Right	Design Flow (m^3/s)	Command Area (ha)	Design Duty ($ha/m^3/s$)	
Wadi Tuban							
Moqaytir	-	-	Left	3	10	3.3	
Obar Shamia	10.1	-	Left	6	27	4.5	
Garaib Al-Wadi	13.3	-	Right	4	16	4.0	
Obar Shakaa	14.1	-	Left	10	108	10.8	
Obar Al-Sahloula	17.0	-	Left	6	31	5.1	
Rod Al-Abab	17.6	-	Right	7	16	2.3	
				36	**208**	**5.8**	
Wadi Kabir							
Al-Mukharaj	21.5	-	Right	16	30	1.9	
Obar Al-Sadain	25.1	-	Right	17	71	4.2	
Faleg Al-Nino	-	0	Left	12	172	14.3	
Obar Ba Nagail	-	-	Left	8	38	4.8	
Obar Al Sada	-	-	Right	7	22	3.1	
Ruwad	-	-	Right	6	20	3.3	
				66	**353**	**5.3**	

Table 6.12 (cont.) **Offtaking Capacity and Design Duties for Earthen Diversion (Ogmas)**							
	Distance from Dukeim (km)	**Weir Width (m)**	**Offtaking Canal**				**Remarks**
			Left/Right	**Design Flow (m^3/s)**	**Command Area (ha)**	**Design Duty ($ha/m^3/s$)**	
Wadi Saghir							
Lihsan	22.1	-	Right	11	231	21.0	
Ath Thalab	28.5	-	Left	15	280	18.7	
Bert Salam	38.2	-	Right	15	250	16.7	
Obar Mansori	38.7	-	Left	10	60	6.0	
Oberali	39.4	-	Left	15	300	20.0	
Al Bert	39.8	-	Right	8	80	10.0	
Habeil	39.8	-	Right	10	100	10.0	
Gadeid	39.8	-	Left	10	190	19.0	
Mahagif	40.2	-	Right	10	60	6.0	
Obar Rihadh	43.3	-	Left	40	420	10.5	
				144	**1971**	**13.7**	
				246	**2532**	**10.3**	

6.5.2 Distribution Systems

Modern Systems

The works for the modern irrigation systems were implemented by Yemeni-Soviet projects. Along with the weirs, comprehensive distribution systems and other structures were constructed including:

Al Arais Main Canal & Cross regulator at P26 Turnout, 12 August 2002

- Primary canals
- Distributary canals
- Minor Distributary canals
- Gated Cross Regulators and Head Regulators
- Turnouts
- Drop structures
- Road bridges
- Access Roads
- Large, levelled rectangular fields,
- Gated structures between fields.

Ras Al Wadi Distributary Canal (P4)

In the modern systems, water from the Primary canal is supplied directly to the Distributary canals, either through an orifice turnout, or a gated regulator. Distributary canals offtaking from the right side of a Primary canal are given even numbers (P2, P4, P6, etc), while those offtaking from the left side are given odd numbers (P1, P3, P5, etc). Some of the Distributaries command large areas, and are subdivided into two or more Minor Distributaries. In contrast, some of the Distributaries command such small areas, that they only extend a few meters from the Primary canal.

The area commanded by each Distributary canal varies for each scheme. For Al Arais the command area is about 958ha and there are about 28 Distributaries canals, giving an average command area of 34ha. For Ras Al Wadi (Right), the command area is about 1,394 ha, and there are only about 18 Distributaries canals, giving an average command area of 77ha. Ras Al Wadi has considerably more Minor Distributaries.

Water is supplied to the fields directly from the Distributaries or Minor Distributaries.

The distribution systems of the modern systems are functioning, but now require rehabilitation to ensure a design life for another 30+ years. Rehabilitation and improvement works are part of the IIP.

The gates are in especially poor condition, and most need replacing.

Cross Regulator, Beizag Main Canal 14 August 2002

Drop structures in both the main and secondary canals are inclined drop designs, made of mass concrete. It is likely that to last for 30+ more years that they will need strengthening, for example by placing a protective layer of concrete on top, with steel to prevent cracking, and flexible stone protection downstream.

Ras Al Wadi, Secondary Canal Check Drop and Turnout, August 2002

Distribution Systems in the Traditional Irrigation Schemes

In contrast to the modern systems, the traditional systems have winding main canals with few structures. There are few Distributary canals (if any), and irrigation is from field to field. Conveyance losses to groundwater are much higher than for the modern systems, and control of large flows is difficult.

Small Traditional System, Primary Canal with "Stick & Earth" Check

6.5.3 *Discharge Measurement, Sedimentation & Canal Capacity*

Gauges are provided at weirs and head regulators to allow flow depths to be measured, and discharges along the wadis to be estimated. Structures for (automatic) water level recorders are also provided in the wadis upstream of the weirs. It is understood that the two automatic water level gauges are in the store of the Land & Water Conservation project (LWCP). They should be installed, and provision made for their security. There are little data of flows along the wadis downstream of Dukame.

View upstream of Al-Arais Head Regulator showing (disused) Gauging Structure

Sedimentation in the canal system did not appear to be too severe. However, the scour sluice channels were full of sediment, and the sluice channel may be failing to flush sediment through the structure to the wadi downstream. The provision of hydro-mechanical (automatic) gates to the scour sluices could be considered.

Faleg Weir Head Reg. & Scour Sluice

The purpose of the upstream guide wall dividing flow to the two gates of the scour sluice was not apparent. The skimming platform's geometry could be improved, with a smooth curve.

The capacity of the canals to divert the design flows needs to be checked by surveying levels of structures and taking (a few) canal cross sections. If capacity is insufficient it may be preferable to increase the command of the canal (field levels are reported to have increased due to silt accumulation over the years) by increasing structure and embankment heights, rather than removing sediment.

6.5.4 *Field Arrangements and Access Roads*

For the "modern" schemes, fields are large and generally rectangular. This, and good access, facilitates the use of tractors for ploughing and seed drilling.

In contrast, access to fields in the traditional systems is often difficult, and only possible across other farmers' plots.

Ras Al Wadi Command Area
Rectangular Field Typical of the Modern Schemes

6.6 Water Rights, Institutions and Spate Water Distribution

6.6.1 Water Rights

The principal of Ala'ala Fala'ala or Rada'ah applies throughout Wadi Tuban, and gives precedence to upstream users both between and within diversion structures and canal systems. This means that upstream users have the right to a single full irrigation before their downstream neighbours. The entitlement is traditionally defined as the height of a man's ankle, about 150mm. However, application depths are largely acknowledged and accepted to be deeper than this.

A draft Water Resources law has been under elaboration since 1992, to cover for river basin management, protection of groundwater against depletion and pollution, etc, consistent with the Articles 8 & 18 of the Constitution. The draft law distinguishes between spate and groundwater rights as follows (refer Annex F, Legal Framework Development of the PPR, 2000):

- Rights to groundwater shall be authorized by the National Water Resources Authority's (NWRA) Public Awareness and Implementation Section.
- Traditional rights to spate water for irrigation shall be exercised according to regional tradition and custom, without any administration interference. These rights are not subject to prior authorisation.

The Constitution vests ownership of all natural resources, including groundwater with the State. Nevertheless, under Article 1366 of the Civil Code, a groundwater right may be acquired by simply purchasing land and drilling a well. The rules governing drilling are:

- observance of minimum distances between neighbouring wells (Civil Code, Article 1181); and
- the establishment of protection zones (harim) around wells (Civil Code, Articles 1185 & 1152).

These rules do not appear to be enforced in Wadi Tuban.

6.6.2 Institutions

The Lahej Irrigation & Agriculture Department is assisted in the management of Wadi Tuban spate irrigation scheme by an Irrigation Council (IC) comprising the District Commissioner as Chairman, and Directors of Agriculture and Irrigation acting as Deputy and Secretary respectively, and a further 14 members. The 10 farmer members are selected by the Irrigation Section of the I&A Department. Appointments are permanent.

The IC provides top-level management for matters concerned with the distribution of spate water in Tuban, and maintenance of infrastructure. It provides a high level interface between farmers and government and delegates tasks to members. For example, the Agriculture & Irrigation General Manager, the Co-operative Union Head and the Irrigation Manager would be required to have meetings with Water Masters and Irrigation Supervisors, while the Agriculture Manager could be required to report on any lands which did not receive irrigation in the previous year, and which should receive priority. Typically the IC meets in May, before the main spate flow season. The IC would prepare an (overall) seasonal irrigation plan, supervise its implementation, investigate violations and mediate disputes. The statutes of the IC provide for sanctions against infringers that are enforceable by the police who may impose fines or imprisonment.

The irrigation Water Master (Sheik al Obar) is responsible for water distribution and organising communal O&M at the village level below the jurisdiction of the ID. They are formally appointed by the ID, or by the Tuban District Council in the case of traditional schemes. The appointments are permanent. Most Water Masters have strong ties of allegiance to the Village Chief (Sheik al Qaria) and other local elites. There are a total of 43 Water Masters in Wadi Tuban.

The Water Masters are assisted/supervised by Irrigation Supervisors who are permanent employees of the Irrigation Section, within the Ministry of Agriculture and Irrigation. There are a total of 15 supervisors, (one for each of the 10 permanent weirs and five for the traditional schemes), and each works with about 3 Water Masters. Also involved are the Agricultural Extension workers.

Within each Primary canal command there are farmer groups responsible for O&M. They work under the direction of the Water Masters. For example, when an earthen diversion bund in the wadi (ogma) has been washed away by a spate flow, the irrigation Water Master will usually arrange, with the ID, for a bulldozer to rebuilt it. The farmer group responsible for O&M will then ensure that water is conveyed towards farmers' fields, by cleaning the canals, etc. The farmers whose fields are being irrigated will be present in their fields to manage water applications.

Under the Project, farmer institutions are to be strengthened to take over more O&M responsibilities. It is envisaged in the first four years that:

- Water User Groups (WUGs) will be formed at the end of Year 1 for each (tertiary and) secondary canal command to take over of O&M within that command;
- Water User Associations would be formed at the end of Year 4 for each Primary canal command to take over O&M within their canal commands.

The IC would be reformed, and the number of professional staff engaged by the Irrigation Department would be reduced as O&M responsibilities are transferred.

6.6.3 Spate Water Distribution

The IC has established rules to provide equity for downstream users; the concept being that spate water will not be diverted into fields that have already received surface flows (either from base flow or a spate). It is reported that water distribution is based on the following overall plan:

- When a spate flow is low (5-15 m^3/s), distribution priority is given to schemes in the upper part of the command area (the Al-Arais and Ras Al Wadi systems);
- When spate flow is of medium size (15-25m^3/s), priority is given to schemes in the middle part of the delta (including the Beizag and Faleg systems);
- When spate flows are high (25-40om^3/s) the flow is directed, according to turn, to either Wadi Khabir or Wadi Saghir. This is done by constructing an earthen bund at the Ras Al Wadi weir bifurcation point;
- When spate flows exceed 40m^3/s, flow is allowed to divide equally between the two wadis.

Water joining the Al-Arais Main Canal just upstream of the P19 and P22 turnouts, 12 August 2002

It is not know to what extent this overall plan is adhered to. During site visits from 11 to 14 August 2002 flows remained less than 5m^3/s, and this base flow was largely being diverted by ogmas along Wadi Tuban.

The poor condition of the scour sluice gates at Al Arais Weir prevented diversion of flow into the main canal at this weir. However, an ogma downstream was diverting water which joined the Al Arais main canal at the P19 & P22 outlets. Similarly, at Ras al Wadi, flow (3-4m^3/s) was flowing through the scour sluice gates into Wadi Kabir and being diverted by ogmas downstream. There was no flow into Wadi Saghir.

6.7 Method of Irrigation and On-Farm Water Management Practices

6.7.1 General

Farming practices in Wadi Tuban have changed over the past 30 years due to the construction of the 10 permanent weir structures and the modern irrigation schemes, and the rapid increase in the number of wells to about 2000 resulting in increased use of groundwater.

Of the average annual surface inflow at Dukeim of 110 Mcm, about 72 Mcm (65%) is thought to be recharging the water table. About 22 Mcm is then pumped from the area for Aden water supply, leaving a considerable volume available for abstraction for agriculture.

Ground water is used to irrigate vegetable crops, such as tomato and onions. It is also being used to provide supplementary irrigation to grain crops, such as sorghum grown for grain, and also for the small areas of tree orchards such as papaya, banana and mango.

Using the cropped data from the PPR, which may under estimate the area cropped to vegetables, evapotranspiration from field crops is about 25 Mcm, and from vegetables is about 13Mcm. The return to water is about YRs 8/m^3 for field crops, and YRs 45/m^3 for vegetables. This clearly shows the high returns being achieved by those with wells, and therefore well numbers are likely to go on increasing.

One of the great advantages of using ground water is that water can be supplied to the crop when it needs it.

In this section, irrigation methods and water management practices for both spate flows and groundwater are discussed.

6.7.2 Irrigation Practices Using Spate Flows

Spate flows are used primarily for field crops, including fodder sorghum in April-May, and grain sorghum, cotton, and sesame in August-December.

In the modern schemes Distributary canals distribute water from the Primary canals to the fields. The fields are generally rectangular in

Al Arais CA showing Field Bund & Field Drop structure, 11 August 2002

shape. Field drop structures have been provided between some of the fields, to allow surplus water to drain off to an adjacent lower field. The field sizes commanded by each turnout from the Distributary canal are large, typically about 400m x 200m (8ha) in size. The height of the bunds around each field is typically 1.0 to 1.3m high. Within each field are smaller bunds which divide the fields into smaller units, typically 100m x 50m (0.5ha). These smaller field units can be irrigated quite efficiently with stream sizes of about 100l/s.

Ras Al Wadi Command Area, Field Unit of about 0.5ha recently Irrigated (11 August 2002)

During the site visit on 11 and 12 August, irrigation practices were observed. With less than $0.5m^3/s$ in a Primary canal, water was typically being diverted into one or two Distributaries. Stream flow size to each field unit of about 0.5ha was about 100l/s and field units were being irrigated in turn. About 0.4m to 0.6m depths of water were being applied to each field unit. Farmers present reported that the fields would take 3-4 days to become surface-dry, and that after about 21 days the fields would be ploughed, and then planted to sorghum and cotton. No land preparation prior to applying water was usually carried out.

AL Arais CA, Distributary P19 Flow about 200l/s, 12 August 2002

Some of the fields were quite level, others sloped or were uneven, so that application depths varied by 0.3m or more.

Al Arais, P19 CA, Uneven Field being Irrigated
12 August 2002

The soils were silty or clay loam, and for cotton or sorghum with a rooting depth of about 1.8m, the maximum water that could be stored in the root zone is about 324mm (D.Sa). Field application depths were therefore rather more than necessary, and uneven fields, meant that about 40% to 50% of the water applied was percolating down to the water table.

Uneven Germination of Sorghum in Traditional Scheme due to Uneven Water Application

Percolation water recharges the water table and may not be considered as water lost. However, poor levelling of the fields often results in crops either getting more or less than they require, particularly in subsequent irrigations for growing crops. The result is uneven germination and growth of crops.

It was observed that the fields in the modern schemes were rather better levelled than those in the traditional schemes. This may be due to lack of tractor access within the traditional schemes, and/or due to the traditional schemes diverting less silt to the fields (silt settles out and tends to fill up low spots in a field).

6.7.3 Irrigation Practices Using Tubewells

Vegetable crops are grown using well water. Well water is also used to some extent to provide supplementary water for field crops and tree orchards.

Al Arais CA, P22, Furrows Prepared for Well Irrigation, 12 August 2002

It was evident from site observations, that in August farmers at the head of the Tuban system were receiving spate flows and irrigating their lands. About 10-12 days after irrigation, the land would be ploughed and seed drill used to plant sorghum and/or cotton. Other farmers, particularly further downstream, were preparing land to be furrow irrigated using pumped ground water. Most of these farmers reported that when spate flow was available, it would be used to supplement pumped ground water.

Land near Fakih Lifiah Weir
Furrows Prepared and Irrigated using Well Water. Tomato Seed Sown (13 August 2002)

Furrows were prepared manually. Ridge widths were typically 1.2m wide, while the furrow widths were typically 0.8m wide. The length of the furrows was about 7m. Tomato seed were sown at 20cm spacings near the edges of the ridges (ie on both sides of the ridge), in soil dampened by capillary rise. Water was conveyed to a header furrow, in the high side of the field, from the well using 100mm diameter blue, flexible hose. This hose was seen all over the Tuban area, and clearly preferred by farmers to the uPVC buried pipelines adopted and installed by the Land & Water Conservation project, except where the latter was provided free or very cheaply. The flexible hose was cheap, and could be moved to convey water to fields all around the well, up to a distance of about 1,000m. Farmers reported that after sowing (tomato) seed, they would irrigate every 2-6 days initially, increasing the irrigation interval to 8-10 days as the crop developed. This is slightly more frequently than necessary; 15 day irrigation intervals after germination would result in little yield loss. The area irrigated by one well was stated by farmers there, to total 40 feddans (about 17 ha). As the flow from the well was about 2-3l/s, this must be a considerable overestimate, depending on the extent to which well water was supplemented by spate flows.

Manasira CA, Well Irrigated Crop

Quality USA seed packaged in tins was being used. No fertiliser or pesticides were apparently applied.

The observed irrigation practice and furrows used for well irrigation of vegetables appeared suited to stream size and soil type. Slightly narrower widths would reduce water use slightly. However, in this case the seed planting spacing should be increased to 30cm, giving little benefit. Overall, farmers were taking considerable care to optimise water use for vegetables, perhaps because of the cost of pumping. Greater yields are likely to stem from use of other inputs (fertilisers, etc). However, it should be emphasised that overuse of agro-chemicals could quickly result in aquifer contamination, with negative results, particularly for Aden water supply.

At the tail of the irrigation system, to the Masasira command area along Wadi Saghir, the only crops being grown at this time (August) were being irrigated by wells.

Manasira Primary canal with wind blown sand accumulation, 14 August 2002

From the number of empty but formed fields it was appreciated that spate irrigation of field crops occurs to some extent most years. However, it was understood that the full command area of 1,680 ha rarely received water. Many of the Distributary canals appeared to have accumulated a significant amount of wind blown sediment.

6.8 Sediment

There did not appear to be a great accumulation of sediment in the canals inspected. However the need to remove sediment, or increase canal bank elevations, to restore canal capacities to (near) the original design discharge needs to be confirmed.

7 Water Management in Wadi Zabid

7.1 Scheme Layout

A schematic layout of the Wadi Zabid Spate Irrigation Scheme is shown on **Figure 7.1.**

Wadi Zabid bifurcates just upstream of Weir 4 into Wadi Nasery and Wadi Ain. Guide bunds/bed bars to stabilise flood flows and channel flood flow (equally) into the two wadis form part of the IIP. Weir 4 consists of two weirs and extends to cover both Wadi Ain and Wadi Nasery with an earthen bund in between.

Weir 4 Left (Wadi Ain) Side with offtakes to Bira (L) & Gerab (R) Canals. Weir 4 Right (Wadi Nasery) side is located to the right of the earthen bund out of the picture. 8th August 2002

Of the total command area of about 15,215 ha, 67% is reported to be irrigated in Kharif, and 37% in Seif. Cropping data are, however, clearly out of date. For example, from observations during the field visits on 7 & 8th August 2002, and from a perusal of low resolution (10-15m) satellite imagery, the area of banana is estimated at 3,500 ha (23% of the total command area of about 15,215ha) (see **Section 5.2**).

Ground water is used to supplement spate irrigation, and to cultivate banana and vegetables.

Rainfall in Wadi Zabid allows some rain fed cropping, particularly of millet and cowpea.

7.2 Surface Water Resources

7.2.1 Data Sources

Water resources data are given in Annex B of the Project Preparation Report, 2000. The record is from 1970 to 1997.

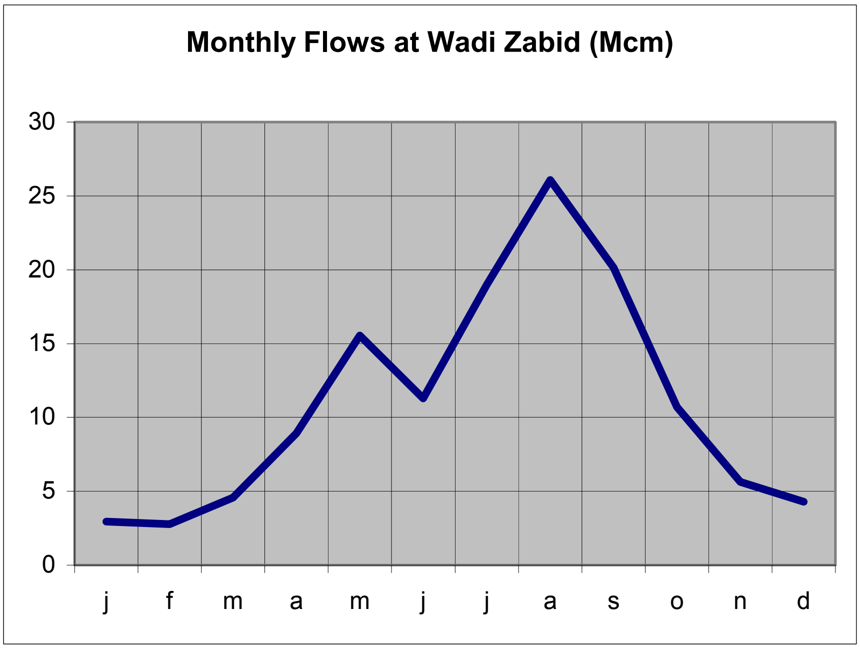
7.2.2 *Available Surface Water*

The mean, maximum and minimum monthly and annual flow volumes at the gauging station at Al Kohla collected by the Tihama Development Authority (TDA) are given in **Table 7.1**. Al Khola is reported in the PPR to be located 20km upstream of Weir 1, and this distance has been adopted in this Paper. However, perusal of maps indicates that the distance may only be about 10km. The exact distance will be confirmed for use in the Spate Management Model, to firm up wadi losses, etc.

Table 7.1
Mean, Maximum and Minimum Monthly Flows at Dukeim (Mcm)

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Mean	Seif 46.1						Kharif 85.8						131.9
Mean	2.9	2.8	4.6	8.9	15.6	11.3	19.0	26.1	20.1	10.7	5.6	4.3	131.9
Max	10.1	11.1	26.9	46.8	59.9	23.3	55.6	83.5	50.3	48.1	36.2	27.7	237.6
Min	.46	.29	.17	.81	.78	2.49	6.29	8.41	5.29	1.54	.03	0	59.4

As shown in the Table and Figure most runoff occurs from May to October.



The mean seasonal flows, and the 80% probability of exceedance flows (ie flow available 4 years out of 5) for Kharif (July to December) and Seif (January to June) are given in **Table 7.2**.

Table 7.2 **Mean and 80% Exceedance Seasonal Flows (Mcm)**			
	Seif	**Kharif**	**Annual**
Mean Flow (Mcm)	46.1	85.8	131.9
80% Exceedence Flows (Mcm)	30.7	57.2	88

7.2.3 *Flood Magnitudes and Frequencies*

The return periods associated with various flood events computed using the data for Al Kohla are given in **Table 7.3.**

Table 7.3 **Flood Magnitudes and Frequencies**	
Return Period (years)	**Peak Flow Discharge (m^3/s)**
2.33 (Mean Annual Flood)	580
5	980
10	1350
20	1800
50	2200
100	2500

The total diversion capacity of the permanent weirs is about 236m³/s. There are also about eight ogmas on Wadi Nasery (which may be replaced by two link canals offtaking from Weir 4 if this is economic given the short time that this area has water rights, and the large discharge capacities required), and about four ogmas on Wadi Ain downstream of Weir 5. The diversion capacities of these ogmas are not known, but are likely to total about 100m³/s, giving a total diversion capacity of about 336m³/s.

The size of the spate flood required to meet this diversion capacity, allowing for wadi losses of 1% per km (see **Section 7.2.5**), between Al Khola and the median point of all the offtakes (say Weir 4 located 31km downstream), is 454 m³/s. A flood greater than this would result in some flow escaping from the command area.

This crude estimate indicates that some flood flow may pass downstream of the Wadi command area most years.

7.2.4 *Travel Times of Floods*

Travel times of floods at Wadi Zabid are not known, but are likely to be about 3-4m/s for the 20 year flood. Assuming this in the case, the time for a flood peak at the Al Khola gauging station to reach Weir 1, 20km downstream, is likely to be about 1.5-2 hours.

7.2.5 *Wadi Bed Seepage and Canal Conveyance Losses*

Seepage losses in the Wadi Bed downstream of Al Khola gauging station, and conveyance losses in the canals will reduce the volume of water that can reach farmers fields.

No proper assessment of Wadi bed losses for Zabid has been carried out. A rough estimate of $0.16m^3/s$ is mentioned in the PPR. Assuming this is applicable for small flows (of about $5m^3/s$) gives a water loss of about 3% of the flood flow per km.

Wadi Zabid is generally wider than Wadi Tuban, with finer bed material (generally sand), and a tendency to meander and braid: several (low) flow channels are apparent. Bank stability appears to be more of a problem than in Wadi Tuban, exacerbated by a few farmers reclaiming land from the wadi bed for cultivation.

Wadi Zabid viewed from Weir 2 looking upstream, 7 August 2002

Assuming that wadi bed losses from Wadi Zabid are similar to those in Wadi Tuban, bed losses of 1% of the flow/km are assumed for major floods.

Canal conveyance losses have been assumed to be about 20% of the diversion capacity.

7.2.6 Crop and Command Deltas

Command deltas from spate irrigation for the whole Zabid scheme have been estimated for Kharif and Seif using the average runoff volumes as measured at Al Khola and allowing for wadi bed and canal conveyance losses. It has been assumed that in an average year, the flow volume passing downstream of the command area is negligible. This needs to be confirmed or otherwise. Crop deltas have been estimated using crop areas reported in the PPR.

Similar to Wadi Tuban, wadi bed losses in Kharif are estimated assuming 1.6%/km water loss, while losses in Seif assume 2.5%/km water loss. Assuming a median length of wadi bed of 31km, means that the Kharif wadi flow losses will be 39%, and the Seif wadi flow losses will be 54%.

Mawi-Yusfi Canal, Looking Upstream to Weir 3, 7 August 2002

Only a portion of the command area is irrigated in an average year (this may be confirmed by the high resolution (1m) satellite imagery to be procured under IIP). The Zabid cropping intensities for field crops (excluding horticultural crops grown only ground water), but including banana grown using both spate and groundwater, as given in the PPR (refer **Table 5.1**) are as follows:

- Kharif (banana, cotton, grain soghum, sesame): 60%
- Seif (banana, fodder sorghum): 28%
- Annual: 88%

Note: Banana as an annual is included in both Kharif and Seif.

However, the area of banana is almost certainly under reported in the PPR at 8%, with a more likely value being 23%. Assuming annual cropping intensities have remained at 88%, gives the following:

- Kharif (banana, cotton, grain soghum, sesame): 55%
- Seif (banana, fodder sorghum): 33%
- Annual: 88%

Table 7.4 gives the command and crop deltas for the whole scheme.

Table 7.4 **Command and Crop Deltas for Wadi Zabid Scheme**			
	Kharif	**Seif**	**Annual**
Average runoff volume at Al Khola (Mcm)	85.8	46.1	131.9
Wadi Losses (Mcm)	33.5 (39%)	24.9 (54%)	58.4
Flow Diverted from Wadis (Mcm)	52.3	21.2	73.5
Conveyance losses (say 20%) (Mcm)	10.5	4.2	14.7
Water Reaching Fields (Mcm)	41.8	17.0	58.8
Command Area (ha)	15,215	15,215	15,215
Command Deltas (m)	**0.27**	**0.11**	**0.38**
Cropped Area of Field Crops (ha)	8,368 (55%)	5,021 (33%)	
Crop Deltas (m)	**0.50**	**0.39**	**0.59**

The above table indicates that wadi and conveyance losses total 73.1 Mcm, or 55% of the annual average flow. This volume largely percolates to recharge ground water.

The small command deltas confirm that, for an average year, the full command area cannot be fully irrigated, even if banana was not being grown.

Considering kharif, for cotton and grain sorghum, net crop water requirements (ETm-effective rainfall) are 0.69m and 0.4m respectively. Allowing for 20% application losses, indicates that an overall delta of about 0.7m is required. This would indicate that the potential kharif cropped area, even if only traditional spate irrigated crops were grown, is only about 6,000 ha for an average year.

Crop data in the PPR, corrected to allow for 3,500ha (23%) of banana, indicates that the areas field and banana crops grown are more than this, and total about 8,000 ha (53%) in Kharif, and 5,000ha (33%) in Seif.

7.3 Ground Water

Tubewell in Yusfi Command Area

The number of wells (in the command area) has increased from about 263 irrigation wells in 1973 to about 1900 dug wells or boreholes in 1987. A Study in 1987 (DHV Tihama Basin Water Resources Study) concluded that the water table was dropping at a rate of about 1m/year. It is likely that, as the area under banana has increased since 1987, the rate of decline of the water table has also increased.

7.4 Water Balance

7.4.1 *Water Balance and Overall Water Use Efficiency*

The construction of the five permanent diversion weirs along the wadis was completed in 1985. These, in addition to the traditional earthen diversion bunds (ogmas), and the large number of irrigation wells, have had the following affects:

- Less water flows downstream of the command area;
- Increased cropping of banana. Water lost to deep percolation is (largely) available for reuse by pumping.

Water balance calculations allow an understanding of water use, and an estimate of water use efficiency to be made. **Table 7.5** presents the estimated seasonal and annual water balances for average flows. Rainfall data are available for two climatic stations in the command area, and indicate that annual rainfall declines from about 352mm in the East, to about 191mm in Zabid town and even less East towards the coast. For the whole command area an annual quantity of 250mm has been assumed. Crop statistics have been adjusted, keeping the total cropping intensity at 103% (88% excluding vegetables), but increasing the cropping intensity for banana to 46% (ie 2 x 23%).

Table 7.5 Wadi Tuban Water Balance (Mcm)			
	Kharif (Jul-Dec)	**Seif (Jan-Jun)**	**Annual**
Water into Command Area (CA)			
Surface Inflow at Al Khola	85.8	46.1	131.9
Direct Rainfall on CA of 15,215 ha	30.4 (200 mm)	7.6 (50 mm)	38.0 (250 mm)
Total water into CA (=1)	**116.2**	**53.7**	**169.9**
Water Leaving Command Area			
Surface Outflow	0	0	0
ETm from Field Crops (delta & CI): -Cotton (0.71m; 6% say) -Sorghum: grain (0.42m; 18% say) -Sorghum: fodder (0.24m; 10% say) -Sesame (0.41m; 6% say) -Other (0.5m say; 2% say) Subtotals:	 6.5 11.5 - 3.7 1.5 23.2	 - - 3.7 - - 3.7	 6.5 11.5 3.7 3.7 1.5 26.9
ETm from other crops: - Tomato, etc (0.55; 15%)	12.6	0.0	12.6
ETm for Banana, etc (1.72 m/year; 23% of area)	30.1	30.1	60.2
Evaporation & ET from non-irrigated land, wadi bed, etc (Kharif: 0.30m say; 37% of CA. Seif: 0.30m say; 60% of CA)	17.0	27.5	44.5
IMBALANCE	**12.9**	**12.8**	**25.7**
Total Water Out (=2)	**95.8**	**74.1**	**169.9**
Net Inflow (1-2 = 3)	**20.4**	**-20.4**	**0**

The water balance assumes no net recharge or mining of groundwater for an average year, and no surface out flow downstream of the command area.

The water balance indicates a surplus of water over the year of 25.7 Mcm.

This surplus could be annual recharge to groundwater. However the DHV 1987 study, and discussions from farmers indicate that the groundwater table is declining. The most likely explanations, therefore, are that:

- Surface flows flow downstream of the Tuban command area most years.
- Cropping using ground water is higher than estimated.
- Average annual spate water inflows may be less than 131.9 Mcm.
- Lateral groundwater outflow to wells & land located outside the command area of 15,215 ha may be significant.

The efficiency of water use being achieved depends on how this imbalance of 25.7 Mcm is being used. Assuming it is "wasted" gives an efficiency of 59% (99.7 / 169.9). Assuming it is being used productively for crops, gives an efficiency of 74% ((99.7+25.7)/169.9).

7.4.2 *Use of Groundwater*

Water balance indicates that water recharges groundwater in Kharif (July to December) and is abstracted in Seif. Assuming no net change in groundwater for an average year, the seasonal and annual recharge and abstraction of groundwater is calculated in **Table 7.6.** Application losses are taken at 40% (higher than the 20% used for Wadi Tuban) as farmers are largely using ground water for banana planted in basins, rather than for vegetables planted in rows/beds. None of the rainfall is considered to percolate to the water table.

Table 7.6 **Groundwater Balance**			
	Kharif	**Seif**	**Annual**
Recharge to Groundwater			
- from wadi bed:	33.5	24.9	58.4
- conveyance losses (20%):	10.5	4.2	14.7
- application losses (40%):	16.7	6.8	23.5
Total recharge to Groundwater (4)	**60.7**	**35.9**	**96.6**
Abstraction from Groundwater			
Net Abstraction for Irrigation of vegetables in CA (= ETm from **Table 7.5**)	12.6	0.0	12.6
Net Abstraction for Irrigation of banana in CA (= 90% of ETm from **Table 7.5.** Ie 10% from spate flow)	27.1	27.1	54.2
IMBALANCE	14.9	14.9	29.8
Total Abstraction (5)	**54.6**	**42.0**	**96.6**
Net increase in Groundwater (4-5)	**6.1**	**-6.1**	**0**

In an average year, about Mcm 96.6 is recharged to the ground table. About 66.8 Mcm of this water is pumped from the 2000+ wells in the command area, mostly to meet the crop water requirements of banana. As for the overall water balance, there is a large surplus amount of water unaccounted for.

7.5 Irrigation Infrastructure

7.5.1 Headworks, Diversion Capacities and Diversion Periods

Irrigation in Wadi Zabid has been transformed by the construction of permanent weirs to divert spate flow, and the installation of a large number or wells by farmers to exploit the water than percolates to groundwater.

Weir 3, Main Weir Crest, 7th August 2002

The diversion capacity, area commanded and water duties for each of the Primary canals are shown in **Table 7.7**.

The five permanent weir structures can divert a total of 237 m^3/s, and have a combined command area of 11,910ha. This equates to a "duty" of 50.3 ha per m^3/s (20 l/s/ha). However the duty varies for each main canal, from 113 ha per m^3/s (9 l/s/ha) for the Roda-Gerbeh canal offtaking from Weir 1, to 25 ha per m^3/s (40 l/s/ha) for the Mahraqi Harram canal offtaking from Weir 5.

The smaller duties are for the canals off-taking from Weir 1 and Weir 2 (in Canal Group 1). This makes sense as Canal Group 1 has the rights to water for a long period when spate flows are "low" from 19th October to 2nd August (288 days). The other two canal groups have water rights for short periods when spate flows are higher and therefore need higher duties.

On the basis of applying a sufficient water to wet the ground to field capacity to rooting depth for cotton, a depth of water of 324 mm is required (see **Section 5.6**). Allowing for 20% conveyance losses and 40% application losses, a gross delta of about 520mm has to be provided to the command area. To provide this amount of water, flow must be diverted to each canal for the periods given in **Table 7.8**.

The time taken to irrigate each command area, assuming the Primary canal flows full, varies from about 40 hours for the canals offtaking from Weir 5, to about 150 hours for the canals offtaking from Weir 1.

Table 7.8
Time Water to be Diverted to Pre-Irrigate for Cotton (gross delta of 520mm)

Canal	Canal Duty (ha per m^3/s)	Canal Duty (l/s/ha)	Time Water to be Diverted for Canal flowing full (hours)	Canal Command Area (ha)
Canal Group 1				
Weir 1: Bunay-Barry Canal	102	10	144	1125
Weir 1: Roda-Gerbeh Canal	113	9	160	565
Weir 2: Mansury-Rayyan Bagr	66	15	96	2635
Canal Group 2				
Weir 3: Mawi Yusufi Canal	55	18	80	3310
Weir 3: Ebry-Gerhazi Canal	47	21	68	1890
Weir 4: Proposed Link Canal	-	-	-	585
Weir 4: Gerab Canal (+ Ogmas)	-	-	-	2050
Weir 4: Bira Canal	33	30	48	1330
Canal Group 3				
Weir 5: Sharabi Canal	28	36	40	560
Weir 5: Mahraqi-Harram Canal	25	40	36	495
Ogmas	-	-	-	670

Table 7.7
Offtaking Capacity and Design Duties for Primary Canals

Canal System	Distance from Al Khola (km)	Wadi	Offtaking Canal				Remarks
			Left/Right	Design Flow (m^3/s)	Command Area (ha)	Design Duty ($ha/m^3/s$)	
Canal Group 1							
Weir 1: Bunay-Barry Canal	20.0	Zabid	Right	11	1125	102	Canal Group 1 has the right to water from 19th October to 2nd August (288 days).
Weir 1: Roda-Gerbeh Canal	20.0	Zabid	Left	5	565	113	
Weir 2: Mansury-Rayyan Bagr	22.5	Zabid	Right	40	2635	66	
				57	**4326**	**76**	
Canal Group 2							
Weir 3: Mawi Yusfi Canal	25.0	Zabid	Right	60	3310	55	Canal Group 2 has the right to water from 3rd August to 13th September (42 days).
Weir 3: Ebry-Gerhazi Canal	25.0	Zabid	Left	40	1890	47	
Weir 4: Proposed Link Canal to replace ogmas	(31.0)	Nasery	Right	To be decided	585	-	
Weir 3: Gerab Canal (to be expanded to replace ogmas)	(31)	Ain	Right	To be decided	2050 (1800+ 250)	-	
Weir 4: Bira Canal	(31)	Ain	Left	40	1330	33	
				140+	**9165**	**-**	
Canal Group 3							
Weir 5: Sharabi Canal (Area also supplied by 2 d/s Ogmas)	(34.5)	Ain	Right	20	560	28	Canal Group 3 has the right to water from 14th September to 18th October (35 days).
Weir 5: Mahraqi-Harram Canal	(34.5)	Ain	Left	20	495	25	
Ogmas	-	Ain	Left	-	670	-	
				40+	**1725**	**-**	
Whole Wadi System				**237+**	**15,215**	**-**	

7.5.2 Distribution Systems

The Primary canals leading from the five permanent weirs were constructed complete with drop structures, gated head regulators and/or pipe orifice outlets. However, Distributary canals leading from the Primary canals were not built, or only for a short distance, and irrigation is from field to field.

Mawi Canal, Temporary Earthen Check upstream of Drop Structure and Outlets, 8 August 2002

The absence of gated check structures in the Primary canals means that farmers construct earthen bunds in the canals just downstream of their outlets. These are breached when sufficient water has been diverted to their fields, allowing spate water to flow further downstream.

Some of the Primary canals have only been improved for the upper and middle portions, and thereafter discharge into old traditional spate canals, which meander between fields.

7.5.3 Sedimentation & Canal Capacity

In contrast to Wadi Tuban, sedimentation of the Primary canals is restricting flow capacity. The sediment appeared to comprise medium and coarse sands.

The scour sluices at the headworks are clearly not removing the sand fraction. This may be due in part to non-timely operation of the scour sluice gates. The provision of hydro-mechanical (automatic) gates to the scour sluices could be considered. However, it is likely that, during spates, sand is held in suspension, in which case scour sluices would not be very effective even if properly operated.

The capacity of many of the canals to carry the design flows is most likely insufficient. There may also be some locations where command is a problem.

Yusufi Canal showing Sediment & Bund to Divert Flows to Outets, 8th August 2002

Silt accumulation in fields adjacent to the Primary canals appears more acute in Wadi Zabid than in Wadi Tuban, possibly due to more sediment being carried by the Primary canals, but also because field to field irrigation results in silt/fine sand settling out in the first (upstream) fields.

7.5.4 Field Arrangements and Access Roads

Fields are largely irregular as they were originally shaped to minimise earth movement, and therefore boundaries tend to follow the land contour. There are several roads bisecting the command area, but access to many fields is only possible across other farmers' plots. Construction of Distributary canals with vehicle access on one embankment would allow ploughing, seed drilling of field crops, easier harvesting of banana and cutting out of old stems, etc.

7.6 Water Rights, Institutions and Spate Water Distribution

7.6.1 Water Rights

While the principal of Ala'ala Fala'ala applies below each diversion structure, spate flows are rotated between Diversion (Ogma and Weir) structures as follows:

- From 19th October to 2nd August (288 days) water is diverted to Canal Group 1 (Primary canals offtaking from Weir 1 and Weir 2);
- From 3rd August to 13th September (42 days) water is diverted to Canal Group 2 (Primary canals offtaking from Weir 3 and Weir 4) including the seven ogmas downstream in Wadi Nasery;
- From 14th September to 18th October (35 days) water is diverted to Canal Group 3 (Primary canals offtaking from Weir 5 and from four ogmas downstream in Wadi Ain).

Within each Group, the upstream (weir) structure diverts water first, then the downstream ones. At Weir 3, diversion is to the right side Primary canal first, the Mawi-Yusfi canal, and for the Mawi canal; then to the left side Primary canal, the Ebry-Gerhazi canal and the Ebry canal; then for the right side again for the Yusfi canal; finally for the left side for the Gerhazi canal. However, when spate flow is large, water may begin to be diverted to more than one of these canals at a time.

The details of water distribution priorities within each canal group need to be confirmed with the stakeholders.

This system does not appear to provide for equity of flow along the Wadi as shown in **Table 7.9** where flow volumes for each time period, and command areas and command deltas for each Canal Group are tabulated.

Table 7.9
Command Areas and Command Deltas for each Canal Group

	Command Area (ha)	Average Monthly Flow (Mcm)	Flow Volume (Mcm)	Command Delta (m)
Canal Group 1 (288 days)	4,325	8.6	83	1.92
Canal Group 2 (42 days)	9,165	22.9	32	0.35
Canal Group 3 (35 days)	1,725	14.6	17	0.98
	15,215		**132**	

Correcting for wadi losses to determine more accurate command deltas has been carried out assuming that wadi losses are as follows:

- Group 1: Wadi Losses of 3.0%/km over a distance of 22km, giving overall losses of 49% for the flows during this period;
- Group 2: Wadi Losses of 1.2%/km over a distance of 30km giving overall losses of 30% for the flows during this period
- Group 3: Wadi Losses of 1.6%/km over a distance of 36km giving overall losses of 44% for the flows during this period.

The distances are the approximate median distance to the offtakes in each canal group. The losses (%/km) are higher for the low flow periods than for the high flow periods.

Command deltas including for wadi losses are shown in **Table 7.10.**

Table 7.10 **Command Deltas Including for Wadi Losses for each Canal Group**			
	Canal Group 1 (288 days	**Canal Group 2 (42 days)**	**Canal Group 3 (35 days)**
Command Area (ha)	4,325	9,165	1,725
Water Right Period (days)	288	42	35
Flow Volume (Mcm)	83	32	17
Percentage of Flow Loss (%)	49	30	44
Wadi Losses (Mcm)	41	10	7
Flow Diverted to Primary Canal (Mcm)	42	22	10
Command Deltas (m)	**0.97**	**0.24**	**0.60**

Established water rights do not appear to provide for equity of water distribution, and increasing the time that water is provided to Group 2 is recommended. However, it is acknowledged that it may not be possible to get consensus agreement from stakeholder to this.

Inequity of distribution will be confirmed (or otherwise) using the spate management model for Wadi Tuban, and simulating a range of (historic) flood flows along the wadi. A better estimate of wadi losses is also required. The model would also take into account the extent to which (upstream) canals are unable to divert the water, and it becomes available to other (downstream) users.

Reallocating water rights of the low flow period from Group 1 to Group 3 would make it easier to avoid floods that cannot be fully diverted from leaving the command area; (an alternative would be for upstream users to start to divert water once the flood rises above a certain value). However, diverting low flows upstream (by Group 1) minimises wadi bed losses. No major change to traditional arrangements is therefore proposed.

As in Wadi Tuban, along each Primary canal precedence to divert flows is given to upstream users. This means that upstream users have the right to a single full irrigation before their downstream neighbours. The entitlement is traditionally defined as the height of a man's ankle, about 150mm. However, application depths are largely acknowledged and accepted to be deeper than this.

The laws/rules concerning the use of groundwater are presented in **Section 6.6**. They do not appear to be enforced in Wadi Zabid.

7.6.2 *Institutions*

The Tihama Development Authority (TDA) is responsible for the operation and maintenance of the irrigation systems. The recurrent budget for maintenance is appears insufficient. None the less the Authority carries out essential maintenance (for example gates were recently greased and painted), and operates the main system, particularly water diversions from the weirs.

The TDA convened an Irrigation Council for Wadi Zabid, similar to that set up at Wadi Tuban. It proved to be ineffective and lasted only a year. This may be because members were appointed directly, and did not properly represent the communities as well as those of influence.

The irrigation Water Masters (Shaykh al Sharej) are responsible for water distribution along and downstream of the Primary canals. They are largely hereditary positions, with close links to the large landowners and others in authority.

Under the project, farmer institutions are to be strengthened to take over more O&M responsibilities. It is envisaged in the first four years that:

- Water User Groups (WUGs) will be formed at the end of Year 1 for each (tertiary and) secondary (Distributary) canal command to take over of O&M within that command;
- Water User Associations would be formed at the end of Year 4 for each Primary canal command to take over of O&M within their canal commands.

The IC would be reformed, and the number of professional staff engaged by the TDA would be reduced as O&M responsibilities are transferred.

7.6.3 *Spate Water Distribution*

Spate water distribution is largely in accordance with the traditional water rights, and is supervised by the Water Masters and staff from the TDA.

Weir 3 Looking Upstream from Left Side Head Regulator

Water is being incorrectly diverted to left side by an earthen bund in the river

7th August 2002

Some Water Masters carry out their duties conscientiously, while a few may accept bribes to allocate water "out of turn". Also, some groups of farmers or landowners may try and abuse the system. However, once objections are raised by farmers being disadvantaged, the "correct traditional" distribution is adopted.

For example, during the site visit on 7th August, the head regulator gates in Group 1 were closed (as they should be), with flood water being diverted at Weir 3. However, initially the flood water was being deflected by an earthen bund in the river to the left side head regulator (to the Ebry-Gerhazi canal), although the right side had the water right. The Water Master and staff from TDA were present and a bulldozer was mobilised to divert the water back to the right side, to the Mawi-Yusfi canal. This took a few hours, with a large group of farmers present to "ensure" quick action.

7.7 Method of Irrigation and On-Farm Water Management Practices

7.7.1 *General*

Farming practices in Wadi Zabid have changed over the past 15-20 years following the construction of the five permanent weir structures, the rapid increase in the number of wells, which reached 1900 in 1987, and the introduction of banana as a cash crop.

Of the average annual surface inflow at Al Khola of 132 Mcm, about 97 Mcm (73%) is thought to be percolating to the water table. This is then (mostly) available for pumping through out the year.

Ground water is used to irrigate banana and some vegetable crops. It is also being used to provide supplementary irrigation to grain crops, such as sorghum grown for grain.

Using the same annual cropping intensity (103%) as given in the PPR, but increasing the area of banana to 2,300ha (2x23% cropping intensity), evapotranspiration from field crops is about 27 Mcm, from vegetables is about 13Mcm and from banana is about 60Mcm. The returns to water are about YRs 8/m^3 for field crops, YRs 45/m^3 for vegetables and about YRs 22/ m^3 for banana. This clearly shows the high returns being achieved by those with wells, and suggests that wells numbers are likely to go on increasing.

One of the great advantages of using ground water is that water can be supplied to the crop when it needs it.

In this section, irrigation methods and water management practices for both spate flows and groundwater are discussed.

7.7.2 Irrigation Practices Using Spate Flows

Spate flows are used for a pre-planting irrigation for field crops and for banana. The flow is diverted from a Primary canal by a temporary earthen bund built downstream of the outlet. Outlets generally comprise gated pipe orifices that extend under the Primary canal embankments.

Gated Pipe Culvert Outlet from Yusfi Canal

The area commanded by each outlet varies from about 15 ha to about 100 ha, and the number of and size of pipe orifices varies accordingly, from 1-3 in number and from about 0.3m to 0.6m in size.

Occasionally there are short (say 100m) lengths of Distributary canal leading from the pipe orifice, but mostly the water is discharged directly into the adjacent field, or into a winding channel along a field's edge.

Fields are irregular and vary greatly in size, from about 1-6 ha. Maps are available at 1:5,000 scale showing the hydraulic layout, field boundaries, and some field spot heights.

Ebry-Gerhazy CA. View of water distribution "channel" looking upstream. An earthen bund is diverting flow to upstream fields. Later, this bund will be cut releasing flow to downstream users.

Field to field irrigation makes it impossible to provide crops with the correct amount of water. Crops in fields adjacent to the Primary canal may receive too much, while those further away may receive too little. In either case yield is adversely affected.

Mawi CA. Spate Irrigation of Banana

Often the depth of water on a field exceeds 0.9m. Where banana is cropped, most of this percolates below the root zone to the water table.

Where field to field irrigation is practiced across many (say more than five fields), much of the ponded water may drain off to downstream fields when supply is cut off. The amount of water applied is then dependent on how long the water was standing in the field before draining away. In contrast, where there is a Distributary channel, supply to the field is blocked off when the depth of water impounded is sufficient, and this water slowly infiltrates the soil. Depths of application appear to be high, more than 0.6m. It is almost certain that farmers are aware that they are applying more than the crop needs, and are consciously trying to maximise recharge to the water table for subsequent reuse by pumping.

There are often large drops between fields. Field bund back slopes have to be flat enough to avoid being breached when water is applied. This apparently occurs quite frequently, with the result that water very rapidly drains from the field. When this happens, the farmer concerned will receive priority for water in the next spate. Meanwhile, considerable crop damage may have occurred. Canal breaches are reported to be largely due to animal (rat?), holes in the embankments. Farmers attempt to seal the embankments by ploughing

Mawi CA. Holes in field embankment & ploughed inner slope of bund to try and prevent bank failure by sealing holes. 8th August 2002 around the inner bunds of their fields prior to irrigating. This is why the inner slopes of the fields are very shallow, with poor crop yields around the edge of the fields.

7.7.3 *Irrigation Practices Using Tubewells*

In Zabid, the most important use being made of wells is to apply frequent small irrigations to banana. However, some farmers in Canal Group 2 who cultivate field crops (typically sorghum) with a single pre-irrigation using spate flow from 3rd August to 13th September, may also cultivate a second crop (usually also of sorghum) using pumped ground water.

Yusfi CA. Residue from the cultivation of sorghum in April-May using well water. Small earthen bunds formed small basins within the large field. In September, spate water will be used to flood the whole basin to a depth of about 0.9m for the main sorghumcrop. (8th August 2002)

To cultivate sorghum using groundwater, small bunds, typically about 0.3m high, are made to form small basins (typically 5m x 5m) within in a part of a large field. For farmers who do not own a well, the water is apparently usually purchased on a crop share arrangement.

A tenant farmer without land would give about a third of the crop to the landowner, and a second third to the owner of the well.

8 Water Management Plans

8.1 Clarification of Objectives

The ToR (page 53) states that a "*good water management plan will need to take account of components in optimising the crop returns on a delta wide basis. These components include:*

- *Land and water resources*
- *Water rights and the establishment of priorities for water use at the wadi level*
- *Water right contradiction with existing irrigation canals or offtakes*
- *Water retention capacity of the soils*
- *Cropping pattern and crop water requirements*
- *Root zone parameters*
- *Water application depth*
- *The irrigation distribution system and the operational protocols*
- *Irrigation efficiencies*
- *Social implications of alternative strategies*"

Over the last 30-40 years higher value vegetable crops and banana orchards have displaced traditional spate field crops such as sorgum (fodder and grain), cotton and sesame in importance. This became possible following the construction of permanent weirs across the wadis, and the investment by farmers in wells and pumped ground water irrigated agriculture. There are now more than 2000 wells in both Wadi Tuban and Wadi Zabid. Vegetables and banana require more labour and provide more employment (eg picking banana and cutting out old stems) than traditional field crops. However, due to their high value they provide higher returns to land and water than traditional field crops, and comparable returns to labour. To be sustainable, groundwater recharge must equal pumped volumes over the long term. The water table in both Wadi Tuban and Wadi Zabid may be declining due to over use of water.

The objectives of the Water Management Plans for both Wadi Tuban and Wadi Zabid should therefore be to:

- Improve yields of higher value vegetables and (banana) orchards and traditional spate irrigated field crops to get more "crop per drop".
- Encourage the cultivation of higher value vegetables, subject to market opportunities in both Wadi Tuban and Wadi Zabid, and of banana in Wadi Zabid. However, the interests of the poorer farmers should not be ignored (see below);
- Promote the sustainable use of the available surface and groundwater resource by determining and agreeing with farmers' areas for intensive cultivation.

These "*Intensive Command Areas*" are unlikely to be more than about 6,500ha in Wadi Tuban and about 8,000 ha in Wadi Zabid.

- Ensure that spate flows continue to be fully diverted during wet years, so that surface water does not escape to the sea. "P*eripheral Command Areas*" to absorb spate flows in wet years should be identified.

The project would therefore support the on-going trend to higher value cropping, while promoting improved and sustainable use of both spate and groundwater.

To address the danger that only farmers with wells would benefit, the project would have to support and expand water markets, whereby farmers without wells would have (secure) access to pumped water. This would likely in continue to be in the form of sharecropping with the well owners.

8.2 Cropping

The area under vegetables is likely to increase to meet demand, particularly in Wadi Tuban due to the proximity of Aden. Tomato, being perishable, and providing appropriate varieties were introduced, could be grown around the year. Similarly, for other perishable vegetable crops. Onion could be grown to a greater extent on residual soil moisture following spate floods in August and September.

8.3 Intensive and Peripheral Command Areas

8.3.1 Intensive Command Areas

Spate flows should be spread over sufficient area to ensure that all the available surface water is used for cropping with the balance percolating to the water table. This area will vary from year to year.

The project will determine (using the Spate Management Models) the size of Intensive Command Areas over which it would probably be economic to invest in improvements that will result in improved crop yield, including the construction of Distribution canals, roads for improved access, land levelling, etc. In these Intensive Command Areas water management (and hopefully agricultural extension activities) will promote the conjunctive use of spate and groundwater to maximise crop yields (ie more "crop per drop") and the cultivation of high value crops. The size of the Intensive Command Areas will be such that the conjunctive use of spate and groundwater is sustainable.

<u>Wadi Tuban Intensive Command Area</u>

For Wadi Tuban, allowing for wadi and conveyance losses, the volume of water that reaches the fields in an average kharif season is 45.1 Mcm. Assuming a Kharif delta of 0.7m gives an area of about 6,500ha.

For an average year, wadi and conveyance losses total about 56.1 Mcm. Application losses are about 11 Mcm (20% of water reaching the field). This indicates annual average recharge to the water table of about 67 Mcm. About 22 Mcm is pumped to

Aden for potable water supply, leaving about 45 Mcm. Much of this volume would be available for pumping, mostly within the Intensive Command Area, but also outside where wells are already installed.

It would appear that intensive cropping of an area of about 6,500ha would be sustainable in Wadi Tuban; the area needs to be smaller if a substantial increase in abstraction for water supply for Aden has to be allowed for. For now, the Intensive Command Area is provisionally set at 6,500ha, considerably less than the total command area of about 12,000ha.

Wadi Zabid Intensive Command Area

A similar exercise for Wadi Zabid, indicated an area of just 6,000ha. However, cropping data indicate that about 8,000ha may presently being cropped in Kharif. For now, the Intensive Command Area is provisionally set at 8,000ha, considerably less than the total command area of about 15,215ha.

Intensive Command Area Boundaries

Delineation of the boundaries for each Primary Canal will have to take the following into consideration:

- Land already abandoned (or which has not received water in recent years).
- Canal conveyance capacity, and areas where there has already been considerable investment in irrigation infrastructure, including distribution systems, etc.
- Areas where land is already under high value cropping (eg banana) and where there is considerable conjunctive use of spate and ground water;
- Farmers opinion (see **Section 8.6**).

8.3.2 Peripheral Command Areas

In wet years, water may be diverted over larger areas, with cropping occurring outside the Intensive Command Areas and in the Peripheral Command Areas. In the Peripheral Command Areas, it is not likely to be economic to improve infrastructure and cultivation of low value field crops would predominate. Installation of wells and the conjunctive use of spate and well water should be discouraged, as this would result in the overuse of the available groundwater resource.

In the Peripheral Command Areas infrastructure would essentially comprise the old spate irrigation canals with minimal improvement.

8.4 *Increasing Crop Production*

Water management activities would support increases in crop production per unit of water (ie more "crop per drop") within the Intensive Command Areas. Typical activities would include:

- Timing and amount of water applications to better meet crop water requirements, by conjunctive use of spate and groundwater.
- Improved land levelling, or land preparation, particularly where more than one irrigation is applied, so that yield losses due to over or under irrigation are minimised.
- Promotion of high value crops.
- Fostering more formal agreements within each WUG/WUA so that farmers without wells have access to well water, on a share cropping or cash basis.
- Allowing, on a rotational basis, several irrigations using spate flows, but at the same time enforcing a maximum depth of water to be applied per spate irrigation. This depth should be about 300mm.
- Encouraging farmers to seek advice on the use of agro-chemicals, improved seed, etc. However, care should be taken to ensure that the groundwater is not contaminated, particularly in Wadi Tuban where a considerable volume is pumped to help meet Aden's potable water supply requirements.

8.5 *Infrastructure*

Infrastructure to divert and distribute spate flows should be rehabilitated and improved to cover the Intensive Command Areas of about 6,500ha in Wadi Tuban and about 8,000ha in Wadi Zabid. The works should be carried out so that the design life of the rehabilitated infrastructure is 30+ years.

To ensure that head – tail inequity along the wadis does not result, the new Intensive Command Areas boundaries for each Primary canal system, should be delineated taking the following into consideration:

- Maintaining the existing status quo, ie: lands which have not in the past few years received spate flow should be excluded. This should be evident from the high resolution (1m) satellite imagery being obtained under the project.
- Discussions with farmers to obtain consensus on a reasonable head-tail distribution of spate flows along the wadis. In Wadi Zabid the possibility of increasing the period that water is provided to Group 2 canals, and reducing the period for Group 1 canals, could be considered and discussed to promote greater equity of spate flow distribution along the wadi.

In Wadi Zabid, and on the traditional schemes in Wadi Tuban, improved road access is required within the new Intensive Command Area boundaries, and also construction of Distributary canals. The absence of Distributary canals, so that irrigation is from field to field, means that crops near to the Primary canal receive too much water, while those further away may receive too little. Crop yields will be depressed for both extremes.

Gates are required in Wadi Zabid for check structures along the Primary canal. Extension of improved, properly aligned and shaped Primary canals should be carried out within the Intensive Command Areas. The suggested (in the PPR) new link canals along either side of Wadi Nasery to replace the traditional canals supplied from seven ogmas may not be economically justified given the short time that this area (in Group 2), has the right to divert spate flows (only 42 days at present), and the high design capacity therefore needed.

8.6 Wadi and Primary Canal Water Management Plans

8.6.1 Wadi Water Management Plans

It is suggested that consensus on a Wadi Water Management Plan be achieved with all stakeholders in both Wadi Tuban and Wadi Zabid, so that water is distributed reasonably equitably along the wadis to each of the Primary canal systems. Involving local influential landowners and gaining their support is vital for success. The Project will have to act, along with Government agencies, as a mediator between parties with conflicting interests. The Wadi Water Management Plan would:

- define the Intensive Command Area boundaries and areas for each Primary Canal.
- Agree spate water distribution rules.
- Agree command deltas (ie volumes to be applied over the Intensive Command Areas) to be diverted to each Primary canal before priority is given to another Primary canal.

8.6.2 Primary Canal Water Management Plans

For each Primary canal system, Primary Canal Water Management Plans should be formulated together with the Water User Associations. The decision to spread spate water widely along a Primary canal to grow traditional spate crops, or to use water over a smaller area for higher value crops requiring conjunctive pumping, should largely be left to the WUAs. Similarly, the application depths and whether to allow more than one applications using spate water will be their decision. They would however be strongly encouraged to maximise "crop per drop" by improving yields and growing high value crops with the conjunctive use of spate and groundwater.

The boundaries of the new Intensive Command Areas will be affected by the WUA's decision, and therefore may affect the extent of Distributary canals and access roads construction and/or improvement.

It is suggested that WUA construction contracts be used as the vehicle for construction works downstream of the Primary canal offtakes. These contracts would be managed by the WUAs, and they would be paid at lower rates for work carried out than would be paid to a commercial contractor; the difference being the WUA's contribution to construction works.

9 Spate Management Models

9.1 Purpose of Spate Management Model

In accordance with the TOR, "*spate management models will be prepared for Wadi Tuban and Wadi Zabid which, in conjunction with the spate warning systems, will allow decisions to be made promptly regarding:*

- *(i) Which command areas should be irrigated, as the model keeps a record of the depth of water application a particular command area has received, allowing the outstanding requirements to be estimated.*
- *(ii) How much water to divert to each ogma/weir on the wadi as, based on the calculated requirements, the model works out how far the forthcoming spate will supply needs, given canal capacities and restrictions, etc, and determines the quantity to be diverted and for how long.*
- *(iii) The spate waters to be diverted to (*from?*) the Wadi and in what quantity, as the model determines the peak spate discharge threshold at which the last ogma will be breached, and water will flow to the sea.*
- *(iv) For any required improvement works, it is possible to use the model to simulate the passage of floods down the wadi, using hydrographs developed for the wadi. This allows decisions to be made regarding the size of the supply canals to the traditional areas and possible improvement works in other areas.*
- *(v) The probability of irrigation of the areas commanded by each diversion weir, will assist in deciding on the type and value of any improvements that are required.*

Component (iv) is particularly relevant to Wadi Zabid, where only five permanent weirs have been constructed (compared to the ten operational in Wadi Tuban), and where the construction of additional permanent diversion capacity and link canals (from Weir 4) is under consideration.

Also in Wadi Zabid, the capacity of the Primary canals in Group 2 and Group 3 may be constraining the amount of water that can be diverted during the short periods (42 days and 35 days respectively), that these areas have the prior right to water.

Component (v) is relevant to both Wadi Tuban and Wadi Zabid, and will help determine the boundaries of the proposed Intensive Command Areas.

For the first three components, the Spate Management models will cover water flow along the wadi, including estimated wadi bed losses, diversions into Primary canals, command areas and depths of water supplied (over the Intensive Command Areas).

The Spate Management models should be easy to use by irrigation staff from the Agriculture and Irrigation Department for Wadi Tuban and from the TDA in Wadi Zabid. To be useful to those staff responsible for operation of the head regulator gates to the Primary canals, canal diversions and flood data will have to be entered into the models after each flood event. Also, information on the size and characteristics of coming spates floods will need to transmitted (by the spate early warning system) in a timely manner to allow decisions to be made and action taken.

The Spate Management models will then facilitate improved distribution of water according to the Wadi Water Management Plans agreed with stakeholders for Wadi Tuban and Wadi Zabid.

Training of Government irrigation staff to use the Spate Management models is essential, and will form part of the Water Management Specialist's future inputs. TDA in Zabid and the Irrigation Section of MAI in Tuban may need (new) computers.

Water distribution along the Primary canals will not form part of the Spate Management model, as this will be controlled by Water Masters who will be answerable to their respective Water User Associations. Extension and training to Water Masters is required but does not appear to form part of this phase of the IIP.

While at this stage the models are specific to Zabid and Turban, they should be easily adaptable for use on other wadi systems.

It is considered that a Planning Water Management model could be used as a planning and training aid, particularly for Government irrigation staff and planners to better understand the use of groundwater, and the yield response to water of crops. However, for this the scope of the model would have to be expanded beyond that considered in the ToR.

9.2 Previous Spate Management Model

The consultants have obtained details of the Spate Irrigation Model developed for Wadi Bana and Wadi Hassan in about 1986. This model was written in Fortran and ran on DOS. Some details of the model have been obtained from the developer, Mr D M McNamara:

- The program was specifically designed for the Abyan Delta Project (Wadi Bana and Wadi Hassan), South Yemen. Based on the estimated flood volume the flood peak and hydrograph shape was computed. At a sluice/ogma the program calculated the volume of irrigation water required by all the blocks/fields on the canal offtake. After distributing the water to the blocks any surplus water was returned to the wadi. The actual volume of water passed down a canal was then deducted from the hydrograph volume and the flood was routed down the wadi, taking account of wadi bed losses. The process was then repeated.

- The program also took account of the water requirements of different crops. Once the full water requirements allocation of an upstream crop had been satisfied, no more water was given to that crop. The programs output gave, for each canal, a summary of each crops required volume, actual volume to date, command area and irrigated area. The output included a summary of each crops total area and its area irrigated to date. Cumulative flood, irrigation, bed loss and surplus volumes were also given.
- The relationship between the hydrograph volume and its flood peak and shape was obtained from previous hydrological studies.
- The model did not use wadi cross sections.

The model software was written in1986 and is, by current standards, not user friendly. It requires a lengthy pre-prepared data file and produces an output file which takes time to interpret.

9.3 Description of Proposed Spate Management Model

9.3.1 General

The Spate Management models for both Wadi Tuban and Wadi Zabid will be user friendly, with data input and output on easily understood menu screens, with optional printouts. The models will allow prompt decisions all as required by the ToR (see **Section 9.1)**.

9.3.2 Data Requirements

The data requirements for the models are envisaged to comprise: (a) fixed data which will not change regularly, at least within a single irrigation season; and (b) variable data which has to entered by the operators throughout the irrigation season.

Fixed data which will not change regularly include the following:

- Irrigation network and hydraulic properties (ie locations of structures, capacities of offtaking Primary canals, weir and head regulator discharge characteristics, etc).
- Intensive Command Areas for each Primary Canal.
- Priorities for water distribution based on traditional water rights, and agreed refinements, all as incorporated in the Wadi Water Management Plan.
- Volumes of spate water (= Command Deltas over Intensive Command Areas) to be supplied to each Primary canal before priority for spate water is given to another Primary canal.
- Estimated wadi bed loss – spate flow relationships.

Defining the Intensive Command Area boundaries will be determined by the consultants using high resolution (about 1m) imagery, taking into consideration areas which are presently cropped, where good infrastructure has been provided, consensus of stakeholder (farmer) wishes, etc. This activity will take a considerable time.

The spate water distribution rules will be firmed up by discussions with stakeholders. These are expected to be largely in accordance with the existing rules, but with refinements.

Application depths (command deltas) for the Intensive Command Areas will need to be agreed by all parties. The Project will recommend command deltas which are compatible with the Intensive Command Areas so that the total volume of water required, allowing for wadi and conveyance losses, does not exceed the average annual spate volume.

Agreement on these parameters and data will allow the formal agreement of Wadi Water Management Plans (see **Section ****).

Variable data which will need to be entered by the models operators throughout the season include:

- Spate characteristics (ie discharge over time data) as measured upstream at the gauging stations, and transmitted by the early warning system
- Flow volumes provided to each Primary canal along the wadi in previous spates.

For the gated Primary canals from permanent weirs, discharges may be estimated, for free flow conditions, by gate opening and upstream depth of flow data. If submerged flow conditions usually apply, then discharge is more difficult to estimate. Alternatives should then be considered, including measuring discharges at an existing drop structure, constructing a stage-discharge relationship for the first reach of the Primary canal, or even the construction of a discharge measurement structure.

For the ogmas, a discharge measurement structure will have to be provided if a canal rating curve cannot be developed. A further complication is that most ogmas are washed away by floods, so division of water cannot be assumed to be taking place for the duration of the flood. Providing gabion protection to ogmas should be considered.

9.3.3 Output

Output from models will comprise:

- the incremental and cumulative amount of water (delta and volume) provided to each Primary canal command area in previous spate flows.
- the quantity of water (volume and delta) still due to each Primary canal.
- the duration of time water is still to be diverted to each Primary canal, assuming full flow, for the next incoming spate.

By running each model using the spate runoff characteristics for its wadi, the ability of the canal system to divert the required volume to each Primary canal's Intensive

Command Area can be determined. Similarly, the probability of any Primary canal's Intensive Command Area not receiving its due share of spate flow can be determined.

The model will also allow future scenarios to be planned in advance, by entering various incoming spate flows. This will allow operators to know how many Primary canals will be able to divert the incoming spate water at the same time, thus minimising the quantity of spate water that escapes downstream.

By planning in advance, alternative action plans, depending on the size of the next spate, can be formulated, and disseminated to system operators and stakeholders.

In "wet" years when each Primary canal Intensive Command Area has had its due allocation, the model will allow each Primary canal to receive more water, in turn according to water right.

In "dry" years, the Primary canal commands last in line to receive water, may not receive their due volumes. If the Wadi Water Management Plan allows carry over from year to year, these commands will receive priority in the next season. If not, the model will be reset to start afresh.

9.3.4 Operators of the Spate Management Model

The operators of the spate management model, including those responsible for collection and input of data, need to be trained. They should therefore be identified from an early stage. Also, necessary equipment and computers need to be procured.

9.4 Planning Water Management Model

A Planning Water Management Model could be developed as a planning and training aid to allow managers to understand better the conjunctive use being made of water in both Wadi Tuban and Wadi Zabid.

Such a model would not use scheme specific data, but would allow the crop production implications of various water distribution scenarios to be understood. Such a model would need to be more sophisticated. It could include climate data, soil data, cropping data, crop yield response to water relationships, and test various options for the conjunctive use of spate and groundwater for irrigation. Such a model is beyond the scope of the ToR.

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Appendix A

National Water Resources Agency

Appendix A National Water Resources Agency

The NWRA was established in 1995 and became operational in 1996 with overall responsibility for water resources sector coordination and planning, including the creation and management of the water resources data base, regional and basis wide water resources planning and regulation, monitoring, conduct of studies and provision of public information.

Key sections of NWRA in Aden include:

- Public Awareness and Implementation: including subsections concerning with issuing "permits" for ground water abstraction (not yet effective?), (ground) water regulation, and public awareness. This last sub-section is concerned with changing farmer attitudes to use of water;
- Studies and Information: including sub-sections for Studies, Monitoring and Data Base Management;
- Finance

Discussions were held with the Director of NWRA, Aden, and the Heads of the Public Awareness and Studies and Information Sections.

From these discussions the following was understood:

- A socio-economic study (in the Tuban area) was carried out by NWRA with 40 days of field work in early 2002. The Director suggested we obtain a copy of this study from NWRA, Aden where the report was being completed.

- The data base contains (only) data collected by NWRA staff; ie from 1996/97.

Data collected by NWRA, Aden (of relevance to IIP) includes:

- Rainfall data at five stations within the Tuban catchment area of 5,393 km^2 (ie at Harad, Oraisama, Al-Dala, Waruzan, and Bulan)

- Stream gauge data (at Dukame, located in Wadi Tuban about 9.0km upstream of El Arais weir).

- Climatic data from Lahej

- Ground water data (depth to SWL, EC, pH, etc) from wells within the Tuban delta area. These show increasing salinity from wells near to the sea.

Appendix B

Low Resolution (10-15m) Satellite Imagery for Wadi Zabid

Appendix C-1

Irrigation Scheduling for Banana (Year 1)

Appendix C-2

Irrigation Scheduling for Banana (Year 2+)

Appendix C-3

Irrigation Scheduling for Cotton

Appendix C-4

Irrigation Scheduling for Sorghum (Grain)

Appendix C-5

Irrigation Scheduling for Tomato