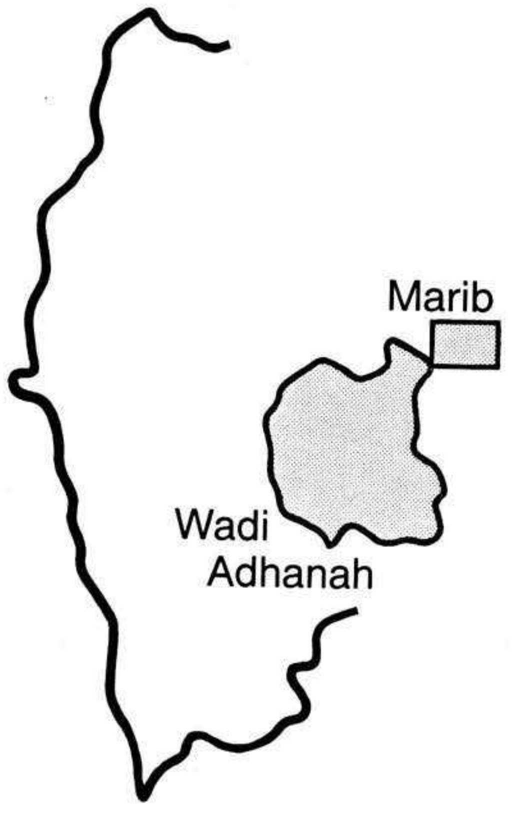
WATER RESOURCES ASSESSMENT YEMEN ARAB REPUBLIC

WATER RESOURCES
Wadi Adhanah and Marib Area



main report

REPORT WRAY 15

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MINERAL RESOURCES

GENERAL DEPARTMENT OF
WATER RESOURCES STUDIES

TNO - DGV

INSTITUTE OF APPLIED GEOSCIENCE

WATER RESOURCES ASSESSMENT YEMEN ARAB REPUBLIC

Yemen Arab Republic
Ministry of Oil
and Mineral Resources

Kingdom of the Netherlands
Ministry of Foreign Affairs
Directorate General of
International Cooperation

WATER RESOURCES
WADI ADHANAH AND MARIB AREA

MAIN REPORT

by

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in co-operation with the staff of
the General Department of Water Resources Studies

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General Department of Water Resources Studies
Sana'a, Yemen Arab Republic

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SUMMARY

A water resources assessment study of the Wadi Adhanah and Marib area was carried out by the General Department of Water Resources Studies of the Ministry of Oil and Mineral Resources (Yemen Arab Republic), in collaboration with the TNO Institute of Applied Geoscience (The Netherlands), as part of the project: Water Resources Assessment Yemen Arab Republic, phase III (WRAY III project). The project started in 1982 and the third phase lasted from September 1986 to December 1989. Valuable information on the area's water resources is now available. Some important general characteristics are outlined below.

The Marib and Wadi Adhanah area is located in the catchment area of the Wadi Hadramawt. The area consists of two very distinct geographical zones: the eastern 'Marib plain area' that forms part of the Wadi Jawf-Marib Basin (near the south western boundary of the 'Rub Al Khali', the extensive Arabian desert) and the mountainous 'catchment area' of the Wadi Adhanah to the west of the Marib area. This subdivision is relevant to the water resources, because it is strongly associated with differences in climate, surface water availability and groundwater conditions.
The WRAY project focused its investigations on the surface water and groundwater resources available to the Marib plain area.

The catchment is characterized by low rainfall in the main part of the area and is drained by the Wadi Adhanah's tributary system. The higher plains (Central Highland) in the western part of the catchment receive moderate amounts of rainfall. However, under 'normal' rainfall conditions they do not contribute to the discharge of the Wadi Adhanah because of their internal drainage system. Groundwater resources are available in aquifers on the Central Highland plains, in the Tawilah sandstones outcropping east of the Central Highlands and in some local basins (Rahabah) and valley-fill deposits.

Before the construction of the new Marib Dam, the intermittent streamflows (floods) of the Wadi Adhanah could pass unhindered into the Marib plain. Flows became gradually less downstream because of diversion for spate irrigation and infiltration into the subsoil of the wadi beds and subsequent percolation to the groundwater. Since 1986 the discharge of the Wadi Adhanah has been stored in the Marib Dam Reservoir. At the time of writing, the secondary canals of the irrigation system were still under construction and implementation of a Marib Scheme was still pending. During the period of hydrological observation (Jan. 1986-April 1989), the total discharge was 360 million m^3 and the average annual discharge into the Marib Dam Reservoir is estimated at 90 million m^3. This amount is considerably less than the "corrected" average long term annual discharge of 148 million m^3 expected by Electrowatt (1978). These new data have to be taken in account when developing rules for the operation for the Marib Dam. However it has to be stressed that much longer records are needed to acquire a more accurate mean annual flow and better knowledge of the variability of annual flow.

A special study was done to ascertain the depositional system and sedimentation rate in the Wadi Adhanah catchment area and Marib Reservoir. The total measured volume of sediment that had accumulated after the reservoir was first flooded in April 1986 until Februari 1989 was 4.5 million m^3, a reduction of the storage capacity by 1.12% This amount of sedimentation rate (originating from mainly low floods) would not be an immediate course of concern. However, for a more realistic prediction of the storage reduction also high floods should be included.
The major accumulation of sediments has occurred near the dam and this could hamper a normal operation of the intake in future.

Under present conditions, the Marib plain area receives the water that drains from the Wadi Adhanah catchment and that has been released from the Marib Dam reservoir after being temporarily stored there. This water partly replenishes the groundwater reservoir and partly feeds the irrigation distribution system. Very little water is currently diverted into the irrigation canals because the secondary irrigation canals are still under construction. Besides receiving water from the Marib Dam reservoir, the Marib plain receives water from some minor catchments and directly from the rare rainfall events. However the amounts are small compared with the total contributed by the catchment of the Wadi Adhanah.

The evaporation losses from the water in the Marib Dam reservoir are considerable. During the observation period from January 1986 to April 1989 a total of 93 million m^3 was lost by evaporation, i.e. about 26% of the total inflow into the lake in that period. Only 123 million m^3 was released. Hence the replenishment of the groundwater reservoir is considerably reduced compared with the situation before the construction of the Marib Dam.
During the WRAY III project information was collected on the characteristics of surface flow, and the Marib plain area was explored to define the most relevant properties of the groundwater reservoir. Furthermore, a clear picture was obtained of the current water use in the Marib project area.

In the future, the availability and use of surface water will depend on the operation of the Marib Dam and irrigation canals (Marib Scheme). ERADA, the Eastern Region Agricultural Development Authority (Ministry of Agriculture and Fisheries) will be responsible for this scheme. Recently (September 1989), the small southern branch of the irrigation system was completed (primary and secondary canals) and its command area (about 350 ha) can be supplied by surface water. The gross irrigated area initially planned in the Marib Scheme included about 6890 ha to be supplied by surface water and groundwater. However, the recently obtained data that are presented in this report suggest that much less surface water is available than previously assumed; therefore the effective size of the area to be irrigated may be drastically altered.

Groundwater abstraction has increased dramatically during the last ten years and was approximately 136 million m^3 in 1987. The annual increase of abstraction during the period 1986 to 1988 is estimated at some 20 million m^3. At present almost all the irrigated land is supplied from groundwater. During the past 3 years, groundwater abstraction has largely exceeded recharge and groundwater storage has been depleted.

If the demand for water in the future is at least equivalent to the present demand, and if as much surface water is available to meet that demand as was available during the period 1986-1989, then the groundwater reservoir will be overexploited. Consequently certain zones of the currently exploited shallow part of the aquifer will become exhausted in the next 20 to 40 years. The subsurface outflow from the Marib water resources system under consideration is estimated to be about 60 million m^3 per year for the present situation. If, as is very likely the present subsurface outflow is not sustained by sufficient recharge, groundwater levels will decline in the long run because hydraulic gradients will decrease as consequence of decreasing groundwater flow.

The total storage of groundwater is difficult to assess because the distribution of fresh groundwater, especially vertically is not yet well known. A rough estimation indicates a volume of 10^{10} m^3 which could potentially be drained by gravity from zones of sufficient permeability. This volume is approximately 90 times the annual (1987) depletion of groundwater.

In the Wadi Adhanah and Marib plain area the development of groundwater is at present almost entirely in private hands. The gross irrigated area was approximately 10,000 ha in February 1989. Using a systems approach the relevant flow and storage components of the water resources of the Marib area were estimated for the observation period 1986-1989. The average annual depletion of the groundwater reservoir was estimated to be approximately 107 million m^3 for this period. In future, after implementation of the Marib Dam and Irrigation System, the various elements of the system will be strongly influenced by the rules governing the operation of the Marib

Dam and Irrigation system. This is why it is crucial that this scheme is part of an integrated water resources management plan.

The following two important aspects, related to groundwater flow must be considered in such a water resources management plan:

- the possibilities of reducing groundwater flow. In that respect the influence of the probably impermeable Azal shale layer on the groundwater flow system (a "subsurface barrier") should be ascertained.

- the possibilities of controlling the recharge and abstraction of groundwater in quantity, time and space.

1. INTRODUCTION

1.1 The WRAY programme

The Water Resources Assessment Yemen Arab Republic (WRAY) is a bilateral programme for technical cooperation between the Yemen Arab Republic and the Kingdom of the Netherlands, which is being executed under the aegis of the Ministry of Oil and Mineral Resources (until November 1985: Yemen Oil and Mineral Corporation) of the Yemen Arab Republic and the Dutch Minister of Development Cooperation. The executive authorities are the Ministry of Oil and Mineral Resources (MOMR) and the Directorate General of International Cooperation (DGIS). The executing agencies are the General Department of Water Resources Studies (GDWRS) of MOMR and the TNO Institute of Applied Geoscience.

The long-term objectives of the WRAY -programme are:

- to strengthen the General Department of Water Resources Studies
- to execute a systematic regional water resources assessment programme
- to disseminate water resources data and advisory services through GDWRS

The first phase of the programme (WRAY I) started in April 1982. All available hydrological and hydrogeological information on the Yemen Arab Republic were compiled and regional water resources studies were carried out in the Sadah and Wadi Surdud areas. Work was started on organizing implementing a water resources data base/information centre.

The second phase (WRAY II), a bridging operation lasting for only one year, started in September 1985. The programme included the operation of the hydrological networks in Sadah and Wadi Surdud, the drilling of two exploratory boreholes in the coastal area of Wadi Surdud, and the preparation and start of the Wadi Adhana - Marib studies.

The third phase (WRAY III) of the programme started in September 1986 and was planned for a period of three years. However, in December 1988 it was agreed to extend this phase until 1 January 1990. The Wadi Adhana - Marib water resources assessment study was the most important activity during this third phase. This report presents the major outcomes of the Water Resources Assessment Study of the Wadi Adhanah and Marib Area. The area is indicated in Figure 1.1.

The allocations made for this phase (WRAY III) are respectively YER 18 million to be contributed by the Yemen Arab Republic and NLG 7.5 million to be contributed by the Kingdom of the Netherlands.

1.2 The Wadi Adhanah-Marib Water Resources Assessment Study

By 1983-1984 the rapid economic development and related increase of water use in the Marib area had led to the government becoming concerned about the possible repercussions on the area's water reserves. Therefore, during the preparation of the proposal for phase 2 of the WRAY project (March 1985), both the Central Planning Organization and the Yemen Oil and Mineral Corporation requested that the water resources of the Marib area be investigated within the framework of the WRAY programme.

The main objective of this investigation was to assess the total available fresh groundwater and surface water resources, taking into account the new Marib Dam and Irrigation Scheme.

The field investigations started with the geo-electrical and well inventory surveys in June 1986. The final field activity related to the subsurface investigations i.e. the pumping test in borehole WRAY-9 took place in March 1989; network operations are continuing.

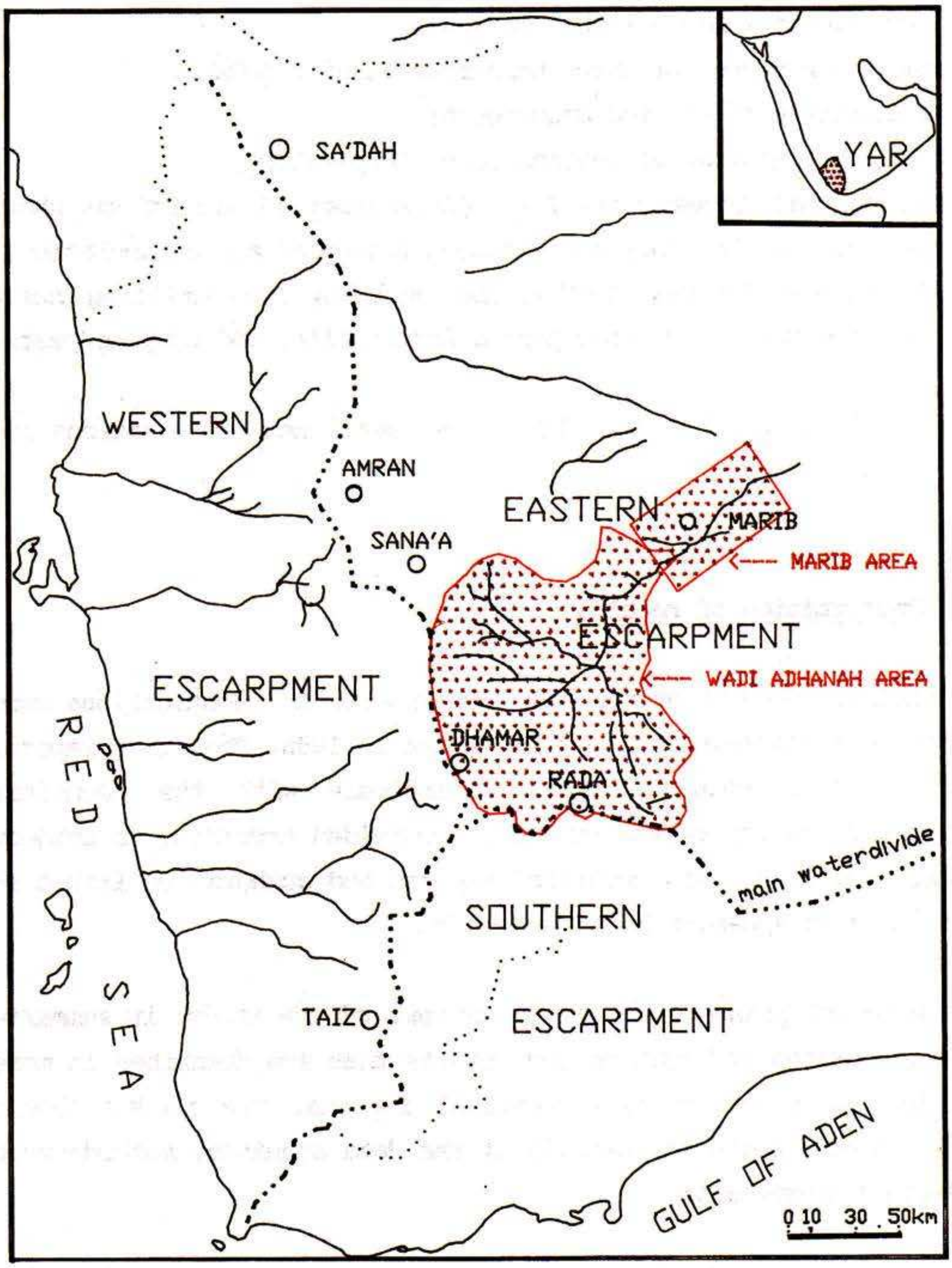


FIGURE 1.1
LOCATION OF THE WADI ADHANAH AND MARIB AREA

1.3 Participating organizations, companies and persons

The following organizations participated in the technical activities of the Wadi Adhana - Marib investigations:

- General Department of Water Resources Studies (MOMR);
- TNO Institute of Applied Geoscience;
- Directorate General of International Cooperation;
- International Geoservices B.V. (Intergeos) (1 expert on short term missions, to study the sediment transport and accumulation);
- Alkohali for General Trading and Drilling (one drilling crew, plus two crews for shorter period for drilling and pumping tests.

The personnel employed by the three first mentioned organizations are specified in Appendix 1.

1.4 Presentation of results

The preliminary results of the Wadi Adhana - Marib investigations were presented in a three-volume interim report in 1988. The final report, consisting of 8 volumes, deals extensively with the technical execution and results of the studies, subdivided according to subject or specific activity. The technical reports and authors are listed in Chapter 8 and in Appendix 2, respectively.

This main report presents the major outcomes of the study; it summarizes and integrates information and results that are described in more detail in the abovementioned technical reports. The reader should refer to these reports for details of the data acquired, methods used and interpretations made.

The results already have been presented in a preliminary and summarizing way in five lectures during the symposium on "Water Resources Assessment in the Yemen Arab Republic" organized by the WRAY project in Sana'a on 8 and 9 October 1989.

1.5 Acknowledgements

The successful completion of the project was only possible through the dedicated attention and co-operation of his excellency Mr. Ahmed Ali Mohanny, the Minister of Oil and Mineral Resources, and his supporting departments. In particular the support the project received from the Deputy Minister Mr. Ali Jabr Alawi was of great value.

The authors gratefully acknowledge the contribution of their Yemeni counterparts of the General Department of Water Resources Studies. Especially we want to mention the enthousiastic involvement of the co-managers of the project Mr. Ahmed Wahib and Mr. Mahmood Al Udaini. We are also very grateful for the contribution of our co-directors Mr. Ali Ahmed Athari, Mr. Abdullatif Hassan Saeed, Mr. Mohamed Danikh, Mr. Ali Saad Atroos and Mr. Noori Gamal for their contribution in the organisation and execution of fieldwork, data processing, data interpretation and report writing.

The dedicated care of the technical staff, especially concerning the execution of the fieldwork has been a major contribution to a successful completion of the investigation.

The extensive computer facilities of the Data Base Section made rapid dataprocessing, data interpretation and presentation possible. Special thanks go to the staff of the Data Base Section for the excellent computerized draughting of figures and plates.

The successful completion of the project has been made possible through important contributions from other institutions.
We are especially grateful for the support received from the staff of the Electrowatt Engineering Services Ltd in Marib, from the staff of the General Directorate of Irrigation and the Eastern Region Agricultural Development Authority of the Ministry of Agriculture and Fisheries, from the General Department of Exploration and Production of the Ministry of Oil and Mineral Resources, and from the Yemen Exploration and Production Information Centre.

The field surveys would not have been possible without the understanding and co-operation of the governmental authorities in the Marib area. Especially we like to mention the support from the Governor and his staff.

Finally we like to express our gratitude for the hospitality and understanding the WRAY-project staff members received from the local farmers in the Marib region.

2. REVIEW OF TECHNICAL ACTIVITIES

2.1 General aspects

2.1.1 Approach

The Wadi Adhanah and Marib Area water resources assessment study was not intended to study all hydrological and hydrogeological aspects of the areas in full detail. Instead, the following major aspects were dealt with:

- exploration and quantification of the groundwater resources in the Marib plain area, where the area's most important groundwater reservoir is situated, and where most of the area's water use is concentrated;
- observation and analysis of the surface water resources generated in the Wadi Adhanah catchment and recharging the Marib Dam reservoir;
- influence of the Marib Scheme (Marib Dam and Irrigation Project) on the available water resources;

This approach led to intensive surveys of various types in the Marib plain area and to only limited activities in the mountainous Wadi Adhanah catchment area where the area's water resources largely originate. The study is expected to be a major contribution to the development and management of the water resources in the Marib plain area.

2.1.2 Operational constraints

Within the investigation period of three years the project faced a number of problems or conditions that either required modifications of the standard methodological approach or limited the data collection and analysis to some extent. The most important ones are listed below:

a) The inaccessability of the catchment area of the Wadi Adhana. This problem was partly solved by using fully automatic monitoring equipment, but it is one of the reasons why reliable rating curves of the Wadi Adhana stream gauging stations could not be established.

b) Limited length of the investigation period: as a result, time series of wadi flow and rainfall are too short to make reliable estimates of the long-term annual means.

c) Soil conditions unfavourable for the execution of geo-electrical field investigations. This was compensated for by doing additional EM surveys in the drier zones, and in particular by the extensive use and re-interpretation of geophysical data previously collected during oil exploration.

d) The lack of detailed and reliable topographical maps and of salient topographical landmarks. This was solved by using sophisticated topographical positioning systems and SPOT satellite imagery.

e) Difficult conditions for the execution of the well inventory drilling and aquifer tests, because of the lack of cooperation from the local population. This hampered field observations, particularly the posterior checks.

f) The limited time available for modelling groundwater flow. As a consequence, only one of the modelling objectives could be met.

2.2 Inventory of available information

2.2.1 Topographical information

The following topographical information was available at the beginning of the investigations or became available during the period concerned:

- all available sheets scale 1:50 000, 1:250 000 and 1:500 000 covering the Wadi Adhanah and Marib area. Topographical maps from the Survey Department of the Ministry of Public Works, Sana'a; scale 1:50 000, sheets 1545 A4 and 1545 C2;
- Air photos R.A.F. 1973; scale 1:52 000 (Wadi Adhana and Marib area);
- Air photos B.K.S. Surveys Ltd., 1989; scale 1:25 000 (Marib area);
- Satellite images; scale 1 : 100 000 (specified in Appendix 3).

2.2.2 Hydrological and hydrogeological information

The report by Electrowatt Engineering Services Ltd. and Hunting Technical Services Ltd., 1978, contains a wealth of reliable and relevant information. When combined with the data presented in the WRAY reports the development of groundwater abstractions during the period 1977 - 1987 can clearly be seen.

Information about the water level of the Marib Reservoir was received from the Marib Branch of Electrowatt Engineering Services Ltd. and from the Eastern Region Agricultural Development Authority (ERADA) of the Ministry of Agriculture and Fisheries (MAF). These data were used to calibrate of the data collected by the WRAY project.

2.2.3 Meteorological information

Meteorological data from stations belonging to the network of the Civil Aviation and Meteorological Authority (CAMA) were made available to the project. Useful data form 1968 onwards were received from the Sana'a station. The station at Marib Airport supplied reliable data from 1985 onwards and intermittend, less reliable data prior to 1985.

The meteorological data for two project areas contributed significant information on the climate in the Yemen Highlands at the western fringe of the Wadi Adhana catchment. The two projects concerned are the Central Highland Rural Development Project at Risabah (Dhamar area) and the Rada Integrated Rural Development Project at Rada, (Al Bayda Province).

2.2.4 Geological information

The following maps and reports were available at the start of the investigations (1986): Geukens, 1966; Grolier et al., 1978; Kruck, 1983; Van Enk et al., 1984.

During the execution period of the project two reports by Maycock (1987 and 1988) became available.

The following confidential reports were prepared for hydrocarbon exploration: Exxon Company International, Exxon Production Research Company, 1987; Robertson Research International Ltd., 1988; Trollinger - Marsh Resources Inc., 1987; Yemen Hunt Oil Company, 1986. The WRAY project had no direct access to these reports.

2.2.5 Geophysical information

A wealth of geophysical data was collected from 1982 onwards during the intensive exploiration for oil and gas in the area. These data are confidential and the WRAY project had only very restricted access to them.

The General Department of Exploration and Production of the Ministry of Oil and Mineral Resources, and the Yemen Exploration and Production Information Centre kindly made the following geophysical information available:

- 10 seismic reflection sections; total length of 296 km
- geophysical logs run in two exploration boreholes

- one vertical seismic profile run in one borehole
- lithological description of these exploration boreholes

The WRAY project had access to the upper (shallow) part of the data only. The information received pertained to maximum depths of 1400-1700 m below surface.

These geophysical data were of vital importance in elucidating of the geological (stratigraphical and structural) development of the area under investigation. They enabled a proper interpretation of the geo-electrical resistivity and electro-magnetic surveys to be made.

2.3 Geo-electrical resistivity survey

The geo-electrical method was used to ascertain the resistivity distribution of the sub-surface. Knowledge of the resistivity distribution leads to hydrogeological information on the:

- depth to the saturated zone;
- vertical and lateral distribution of formations with higher resistivity (e.g. sand) and formations with lower resistivity (e.g. clay);
- spatial distribution of fresh, brackish and saline groundwater.

The geo-electrical investigations were executed with a GEA-51, manufactured by TNO Institute of Applied Geoscience, Delft, the Netherlands. This equipment consists of a direct current resistivity instrument with a maximum power output of 250 Watt. The universal Schlumberger configuration was applied. The software used for the interpretation was the VES computer program, version 4.20-S, developed by H.M. Pars, TNO Institute of Applied Geoscience Delft, the Netherlands.

In all, 201 geo-electrical soundings were carried out from June 1986-May 1987 in the Marib region over an area of 1100 km², extending outside the present area of agricultural development.

In view of the extremely high surface resistivities, especially in those areas covered by sand dunes the field measurements were limited to 700 m; this limited the depth of the interpretation. Other information i.e. seismic data, borehole data and an electro-magnetic survey had to be used as well, to obtain and interpret a spatial model of the sub-surface.

The geo-electrical survey contributed considerable information about the depth of the distribution of fresh and brackish groundwater and of the depth of the top of the Azal (clay) Formation, the depth of the top of the Safer Formation and the depth of the top of the Amran Group in the southwestern part of the area.

The results are presented in 29 profiles and 4 maps (1:100 000) in Report WRAY 15.1, Kool et al., 1990.

2.4 Electro-magnetic survey

The electro-magnetic induction method was applied in the Marib area with the following objectives:

- to determine the resistivity distribution of the sub-surface in those areas where the geo-electrical resistivity method could not be applied successfully because of the high resistivity of the top layer;
- to supply the necessary additional geophysical data to be able to improve the interpretation of the geo-electrical resistivity method.

The frequency domain EM method applied is capable of detecting lateral trends and discontinuities (qualitative information). However, in the Marib field investigations EM was applied in a vertical (in situ) electric sounding as well, which enabled a quantitative interpretation to be made. The data were collected with an APEX MaxMin-I-9 EM system, manufactured by APEX Parametrics Ltd. Uxbridge, Ontario, Canada. In the Marib study the so-called horizontal coplanar configuration was used, to obtain the deepest penetration of the EM field in the sub-surface.

J.P. Kool of the WRAY project developed the software necessary to process, interpret and present the EM data on an IBM (compatible) AT or XT micro computer.

Eleven electro-magnetic profiles were executed; 8 were obtained with a coil separation of 200 m and a station interval of 50 m; 3 profiles were obtained with a coil separation of 400 m and a station interval of 100 m. The total length of the EM profiles executed is 98 km.

The most important hydrogeological information that the EM method yielded was the spatial (lateral) extent of fresh groundwater in the area.

During the geo-electrical field survey and the EM field survey problems related to positioning were solved by using a Wild T-1000 theodolite with a Distomat 15S positioning system manufactured by Wild, Heerbrugg, Switzerland.

The results are presented in 11 profiles and one map (scale 1:100 000) in Report WRAY 15.1, Kool et al., 1990.

2.5 Geophysical well logging

To acquire in situ geophysical information on the subsoil in the Marib area, logs were run in 5 boreholes drilled by the WRAY project at four locations. Samples were taken and quantitative lithological and hydrological information was obtained. The WRAY logging programme included:

- for the uncased open hole, prior to completion:
    * resistivity LN and SN
    * spontaneous potential
    * natural gamma radiation
    * caliper

- for the borehole after completion, during pumping:
    * flow
    * fluid resistivity

As well as logging in these five boreholes, the project ran logs in 60 privately drilled wells prior to the installation of a pump. In all wells a natural gamma log was run. Since most of the wells had been drilled by the percussion cable-tool method, casing was present. Hence, resistivity logs could be run in 35 wells over the deepest 20 m only. In 9 wells a caliper log was run and in 3 wells a spontaneous potential log was run.

As well as yielding in situ data, logging enabled the applied resistivity and electro-magnetic methods to be calibrated. The natural gamma logs were used to correlate formations in scattered boreholes. The flow logs gave information on the hydraulic permeability of different parts (horizons) of the aquifer.

The logging was executed with B-1000 geophysical well logging equipment, manufactured by TNO Institute of Applied Geoscience, Delft, the Netherlands.

The results were published in 5 logs and in a "lithology cross-section". The gamma recordings were published in a gamma correlation diagram. Report WRAY 15.1, Kool et al., 1990.

2.6 Exploratory drilling

An exploratory drilling programme executed in the Marib area with the general ains of obtaining detailed in situ hydrogeological and geophysical information at locations selected by the WRAY project.

The main purposes of the drilling programme were:

1) to find out more about the lithology and hydrology at a specific location;

2) to ascertain geohydrological parameters;
3) to collect additional data in situ on water level and water quality.

The techniques applied were:
- collection of subsoil samples
- geophysical logging
- aquifer tests
- installation of automatic groundwater level recorders

The boreholes were sited with the aim of obtaining accurate data on the depth, lithology and lateral extent of the Azal Formation. One location (WRAY-7) was selected to investigate the phenomena related to the considerably lower water table in the northeastern part of the Marib area. In all, 8 boreholes were drilled in the period February 1988 - March 1989 at 4 locations. At each location a deep production well and a shallow observation well were drilled. The contractor Abdulla Ahmed Alkohali (for general trading & drilling), Zubeiri Street, Sana'a, YAR, executed the drilling, completed the wells and supplied the pump for the aquifer tests as well.

The final depth to be reached was either related to the top of the Azal Formation (WRAY-6 and -8) or to the full penetration of the upper aquifer (WRAY-7 and -9). For technical reasons, i.e. loss of circulation (WRAY-7 and -9) and collapse of the walls of the upper part of the borehole (WRAY-9A), it became very difficult and time consuming to reach these required depths. Therefore at these locations the design for the completion had to be revised.

The maximum depth reached was 330 m (WRAY-7B). The total length drilled in the 8 boreholes was 1368 m.

Three production wells (WRAY 6, 7 and 8) were completed with genuine Johnson screens. In WRAY-9 a locally made perforated steel screen was installed.

The execution and the results of the WRAY exploratory borehole drilling programme are presented in Report WRAY 15.5, Noori Gamal et al., 1990.

2.7 Hydrological networks

The hydrological network in the Wadi Adhanah catchment and Marib area supplies data on rainfall, runoff towards the Marib Reservoir, storage in the reservoir and release from the reservoir.

The rainfall recording network consists of:

- 6 automatic stations installed in November 1986
- 4 automatic stations installed in July 1987

The surface water recording network consists of:

- 1 stream gauge station installed in April 1987
- 1 auxiliary stream gauge station installed in December 1987
- 1 lake level station installed in November 1988
- 1 gate-opening station installed in October 1987

The groundwater level recording network consists of:

- 4 groundwater level stations installed in private wells in April - May 1987
- 6 groundwater level stations installed in WRAY exploratory boreholes in October 1988 - March 1989
- 133 observation wells in the Marib area were selected for manually recording the groundwater level.

All automatic stations are equipped with Omnidata electronic data recording systems manufactured by Omnidata International Inc., Logan, Utah, U.S.A..

The network operation consists of:

- visits to the automatic recording stations every 4 months for data collection, control and maintenance;
- regular visits to the wadi flow runoff stations in the Wadi Adhana for stream flow measurements and cross-section surveys;
- monthly measurements in the Marib observation wells;
- processing and interpretation of the data in the computerized data base of the GDWRS in Sana'a.

The most important results are:

- reliable data on rainfall and runoff from 1987 onwards;
- a permanent network enabling the Marib Reservoir to be manitored and managed in the future;
- a permanent network to monitor the groundwater level fluctuations before and during the operation of the Marib Irrigation Scheme. The data obtained will enable the Eastern Region Agricultural Development Authority to manage the future irrigation scheme responsibly.

The hydrological networks are presented in Report WRAY 15.3, Heynert, 1990.

2.8 Well inventory

The main purpose of the well inventory was to collect relevant data on:

- construction of each well
- groundwater abstraction
- groundwater quality
- groundwater levels

The well inventory in the Marib area yielded information on 1513 wells in an area of approximately 500 km^2. The inventory was executed by a field crew from the department of hydrogeology of GDWRS in the period June 1986 - May 1987. Groundwater levels were measured by SEBA electrical contact meters. The most reliable information collected was on directly measurable and observable parameters e.g. depth to groundwater level, electrical conductivity, water temperature and instantaneous yield. The data were processed at the GDWRS office in Sana'a.

The information on the execution of the well inventory and the data acquired data are presented in Report WRAY 15.2 Uil et al., 1990.

2.9 Aquifer tests

The main purpose of the aquifer tests was to acquire geohydrological characteristics for the hydraulic calibration of data acquired by the geophysical and geological investigations.

Single-well tests were executed in 21 private wells. Pumping tests were executed in the WRAY exploratory boreholes at 4 locations in the study area by the department of hydrogeology of GDWRS. The single-well tests, carried out with the well owner's pump, took place during the period April - June 1988. The pumping tests, performed by using the pump and handling equipment of Alkohali for general trading and drilling, took place during the period October 1988 - March 1989. Both types of aquifer test were followed by a recovery phase. After the pump had stopped, the rising water level was recorded over a certain period of time.

For the single-well tests the variations in groundwater level were recorded manually with SEBA electric tapes. During the pumping tests the variations in groundwater level were recorded with Omnidata fully automatic solid state recorders, as well as manually with the electric tape instruments.

The collected data were analysed and interpreted with the Well Hydraulics Interpretation Program (WHIP), a computer program developed by Hydro Geo Chem Inc. Groundwater Consultants, Arizona, U.S.A.. This enabled the hydraulic conductivity and transmissivity of the upper aquifer to be estimated.

The aquifer tests, execution and interpretation are presented in Report WRAY 15.4, Verbeek, 1990.

2.10 Groundwater modelling

There were three main potential objectives of numerically modelling the groundwater-flow system in the Marib area:

1) so that information on geohydrological parameters (i.e. transmissivity and storage coefficient) could be obtained by application of 'inverse modelling';
2) to simulate groundwater flow in a regional context;
3) to apply modelling to qualitatively evaluate alternative strategies for groundwater resources management in the Marib area.

Lack of time made it necessary to limit objective 1).

The USGS modular three-dimensional finite-difference groundwater flow model (MODFLOW) developed by M.G. McDonald and A.W. Harbough, Scientific Software Group, Washington D.C., 1988 was used to construct a model that simulates the groundwater flow system in the Marib area. The model was implemented on an IBM AT PC microprocessor equipped with 640 k RAM and a DOS 3.0 operating system.

The first modelling stage, the application of 'inverse' use of modelling, concentrated on an area of 24 * 18 km^2 bordering the new Marib Dam to the east, roughly described as the area between the new dam and Diversion Structure B of the Irrigation Scheme. Water was released from the Marib Reservoir during the period March-November 1988, resulting in considerable groundwater recharge in the area. The reactions of the groundwater level were carefully monitored by the WRAY project. These observations were used to calibrate the model simulation.

The following results were obtained:

- values for the subsurface hydraulic parameters (in particular for the hydraulic conductivity);
- confirmation of the modified conceptual model of the geohydrology.

Because of restrictions in the time available the modelling was restricted to these limited results.

The modelling process and its results are presented in Report WRAY 15.7, Verbeek et al., 1990.

2.11 Sediment transport and accumulation

In response to growing interest and concern regarding the sediment accumulation in the Marib Reservoir it was decided to include a study of the sedimentation pattern within the Wadi Adhana in WRAY phase 3. The aim was to elucidate the sediment transport in the Wadi Adhana, explain the present situation and predict the sediment accumulation in the Marib Reservoir.

The WRAY project invited Professor S.D. Nio of International Geoservices B.V. Leiderdorp, the Netherlands, to execute this study.

The study was subdivided into three parts:

- delineation of major sediment supply areas
- study of the transport process in the main wadi and tributaries during different types of flood
- sediment infill and storage characteristics of the Marib Reservoir

A first field survey focusing on the geology, sediment supply and topography of the Wadi Adhana catchment took place in the period 3-22 July 1988.

A second field survey focused on a survey of the sediment accumulation in the Marib Reservoir and on a study of the sediment transport in the lower (eastern) part of the catchment. This survey took place in the period 19 February-10 March 1989.

During the latter survey a "sediment echo recorder" manufactured by Fahrentholz, Kiel, Federal Republic Germany, was used to measure the thickness of sediment in the reservoir. The echo recorder was equipped with two simultaneously operating transducers with frequencies of 15 and 100 kHz. More than 20 echo-sounding profiles were taken. The total sediment volume within the Marib Reservoir was calculated using these data. Storage reduction of the reservoir was calculated based on 4 modules related to 4 different types of floods and related to yearly runoff into the lake.

The execution of the study and the results obtained are presented in Report WRAY 15.6, Nio, 1990.

2.12 Technical reporting

Three interim reports on the investigations in the Wadi Adhana - Marib area were issued during the period following the main field investigations i.e. the period November 1987-February 1988:

- Well inventory results WRAY-8.1
- Hydrological networks WRAY-8.2
- Geophysical investigations WRAY-8.3

The final reporting started in February 1989 with the first drafting of the report on the geophysical investigations. The technical reports dealing with various, relatively independent topics were started in the course of the following months. Generally speaking, the tasks were allocated as follows: the Yemeni colleagues focused on data processing and a modest contribution to certain chapters. The Dutch team members prepared the texts. Draughting was executed by the Yemeni counterparts solely using the Autocad computer program (versions 10 and 17).

The report on the drilling activities (Report WRAY 15.5) was written by Yemeni authors with some assistance from Dutch team members.

3. GENERAL CHARACTERISTICS OF THE PROJECT AREA

3.1 Location and topography

The locations of the Wadi Adhanah catchment and the Marib project area in the Yemen Arab Republic are shown in Figure 1.1. The catchment area of the Wadi Adhanah is situated on the Eastern Escarpment of the Yemen mountain ridges, which constitutes the eastern flank of the Red Sea Rift Valley. The Marib project area into which the Wadi Adhanah drains is a plain, located at the foot of the mountains northeast of the catchment. The plain forms part of the Wadi Jawf Basin, which is on the western edge of the extensive Arabian desert called the 'Rub Al Khali' or Empty Quarter. In addition to the Wadi Adhanah, several minor wadis discharge into the Marib plain area; they are shown in Figure 3.1. They include the Wadi Masil, Wadi As Saila, and Wadi Al Mil.

The total area involved is located between longitudes 44° 15′ and 45° 45′ east (420 and 575 km east, UTM) and latitudes 14° 15′ and 15° 45′ north (1575 and 1750 km north, UTM). The Marib project area lies within longitudes 45° 15′ and 45° 40′ east (525 and 575 km north, UTM) and the latitudes 15° 20′ and 15° 45′ north (1690 and 1750 km north, UTM).

The Wadi Adhanah catchment is approximately 11 500 km^2 in extent and covers the area between the cities of Marib, Rada, Dhamar and Sana'a. The minor catchments comprise approximately 1220 km^2. The area investigated in the project was about 1000 km^2.

From upstream to downstream the Wadi Adhanah catchment area comprises parts of the Central and Eastern Highlands and of the Eastern Midlands (Figure 3.1). The western and southwestern areas of the catchment belong to the Central Highlands of the Yemen Arab Republic and consist of the intermontane plains of Mabar, Dhamar and Rada. The elevations of the plains generally vary between 2100 and 2700 m; some peaks of

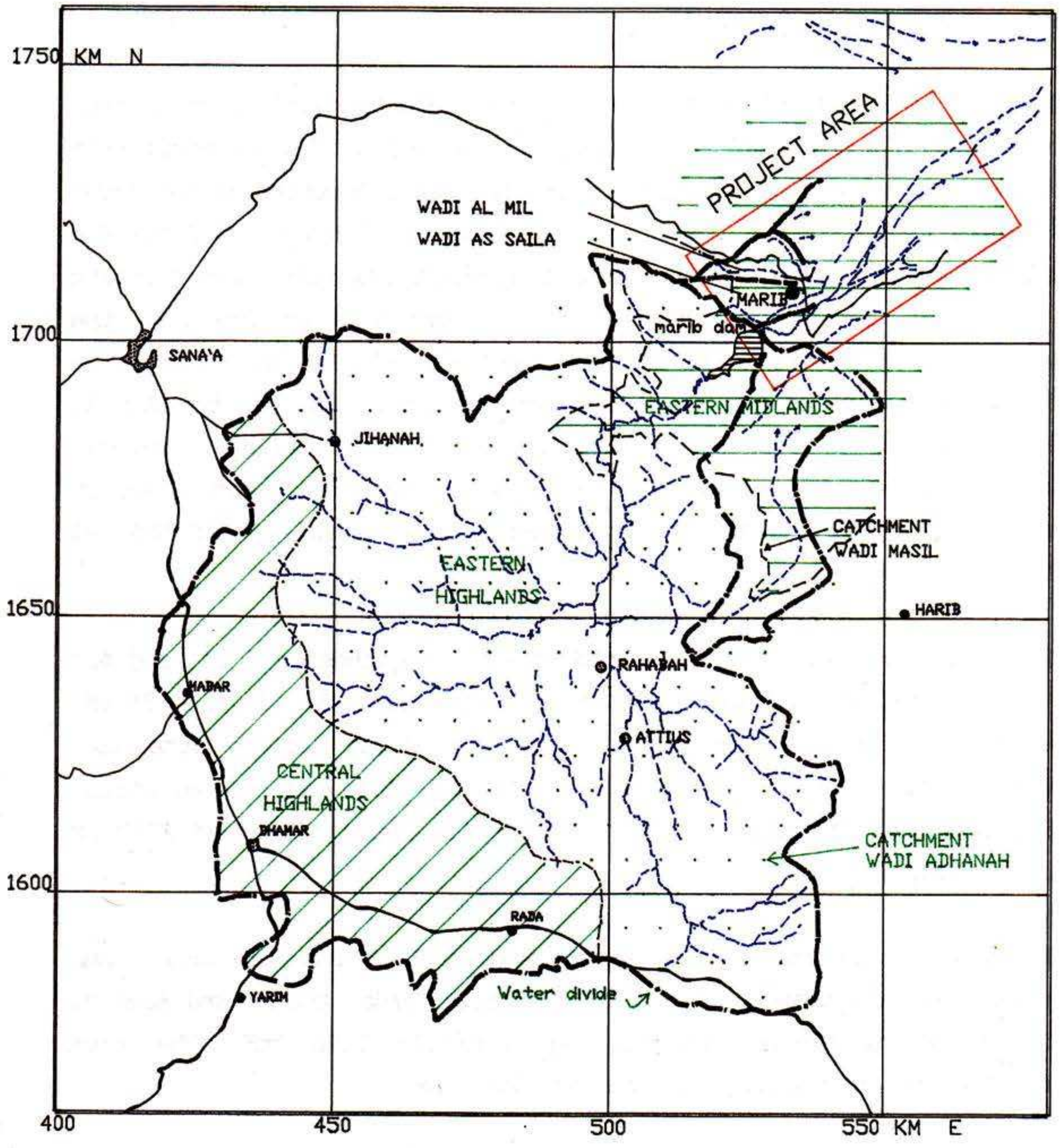


FIGURE 3.1

LOCATION OF CATCHMENT AREAS AND GEOGRAPHICAL UNITS the surrounding mountains reach altitudes above 3000 m. The boundary between the Central and the Eastern Highlands runs mainly along water divides, but locally this boundary is not well defined, especially where the plains have a stormflood outlet into the eastern catchments.

The Eastern Highlands with elevations between 1500 and 2000 m cover most of the catchment area. In the northeastern corner of the catchment, near where the Wadi Adhanah discharges into the Marib Dam reservoir the area lies below 1500 m and belong to the Eastern Midlands.

The area studied, the Marib plain, belongs to the Eastern Midlands, which extend as far eastward as the land along the wadi courses was periodically flooded before the construction of the Marib Dam. Where the Wadi Adhanah enters the plain (then it is called Wadi As Sudd), the elevation of the plain is about 1120 m above mean sea level. The plain gradually slopes northeastwards and reaches elevations of about 1000 m at the boundary of the area investigated.
The general slope is locally disturbed by sand dunes, which locally reach thicknesses of more than 100 m.

3.2 Geology

Figure 3.2 shows the geology of the Wadi Adhana catchment area according to Kruck, 1983 and Nio, 1990. The geology of this area was not very relevant because the WRAY project focused on the water resources in the Marib area. Nevertheless geological research was done to elucidate the sediment transport in the catchment and sedimentation accumulation in the Marib reservoir (Nio, 1990). This study was confined to the morphological setting and the type of weathering to be expected in relation with the surface geology (Nio, 1990).

However, in the Marib area the geology was studied in detail, to elucidate the hydrogeology. Almost the entire area of 1000 km² is covered by Quaternary basalt lava flows and alluvial or aeolian


WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
MOMR - GDWRS
TNO - DGY
MARIB AREA
GEOLOGICAL SKETCH MAP
OF THE WADI ADHANAH CATCHMENT AREA
after Kruck (1983) and Nio (1989)
Scale :
Date : 1989
Report WRAY - 15
Map :
MARIB
MARIB DAM
SANA'A
DHAMAR
GEOLOGICAL LEGEND
Recent and slightly older alluvial valley fill
Quaternary and Tertiary volcanic rocks
Jurassic limestone (Amran Series)
Cretaceous Tawilah Sandstone
Gneisses, schist
LEGEND
WATER DIVIDE
MAIN WADI CHANNEL
TRIBUTARY CHANNELS
BOUNDARIES OF TRIBUTARY SYSTEMS
0
10
20
30km

FIGURE 3.2

deposits, and therefore geophysical techniques and drilling were the only ways of obtaining sub-surface information. Figure 3.3 shows the geology of the Marib area.

The area studied is part of the Marib - Jawf Basin, which is a southeast trending structural trough. The basin is approximately 250 km long and 80 km wide (see Figure 3.4). The evolution of the basin started during the Lower and Middle Jurassic. Rifting started in Upper Jurassic, resulting in a rapid subsidence. This phase was controlled by southeast trending faults dividing the Marib - Jawf basin into several sub-basins. This period coincided with the deposition of the Amran Group (Figure 3.4). After the fault movements had stopped the basin area was involved in a subsidence phase coinciding with deposition of the Alif Formation followed by the Safer Formation during the Upper Jurassic (upper Tiltonian). A major transgression followed, depositing the Azal Formation in the Marib - Jawf basin during Lower Cretaceous.

During the following regression marginal marine to fluviatile circumstances were established. Under these circumstances the Unnamed Formation of the Tawilah Group was deposited.

The last stage in the development was of Quaternary volcanic activity resulting in basalt lava fields. Fluviatile deposits in the lower wadis and an extensive coverage of aeolian sand layers outside the wadis were deposited in recent time.

The research done during the WRAY project revealed that the following lithostratigraphic units are the most important hydrogeologically (see Table 3.1):

Amran Group

The Amran Group consists of sequences of shales and sandstones, covered by sequences of limestones, dolomites and minor shales.
The limestones form the distinctive hydrogeological lower boundary of the groundwater system at the southwestern fringe of the Marib area

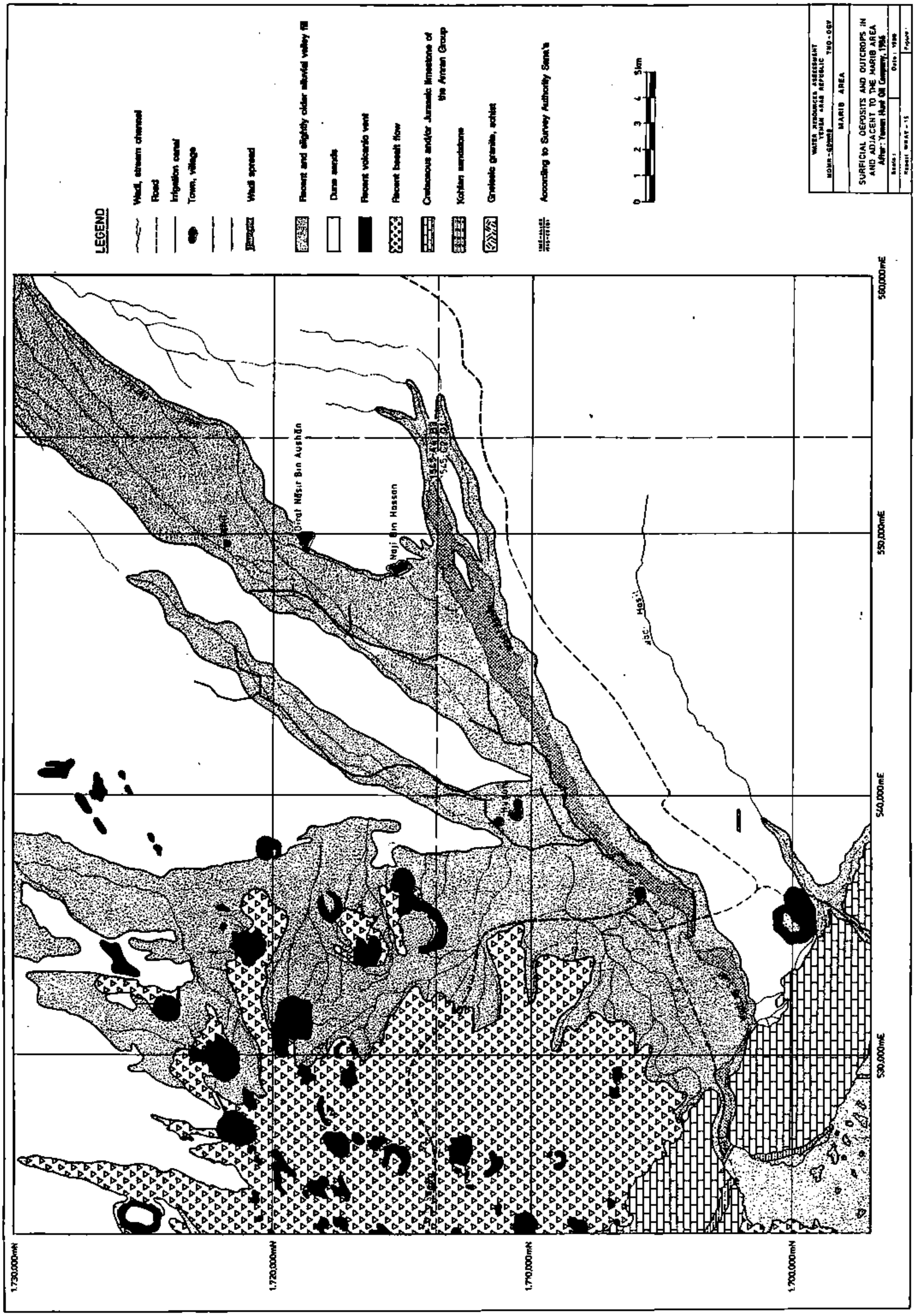

LEGEND
Wadi, stream channel
Road
Irrigation canal
Town, village
Wadi spread
Recent and slightly older alluvial valley fill
Dune sands
Recent volcanic vent
Recent basalt flow
Cretaceous and/or Jurassic limestone of the Amran Group
Kohlan sandstone
Gneissic granite, schist
According to Survey Authority Sana'a
0 1 2 3 4 5km
MARIB AREA
SURFICIAL DEPOSITS AND OUTCROPS IN AND ADJACENT TO THE MARIB AREA
After: Yemen Hunt Oil Company, 1986
Naji Bin Hassan
1,730,000mN
1,720,000mN
1,710,000mN
1,700,000mN
530,000mE
540,000mE
550,000mE
560,000mE

FIGURE 3.3

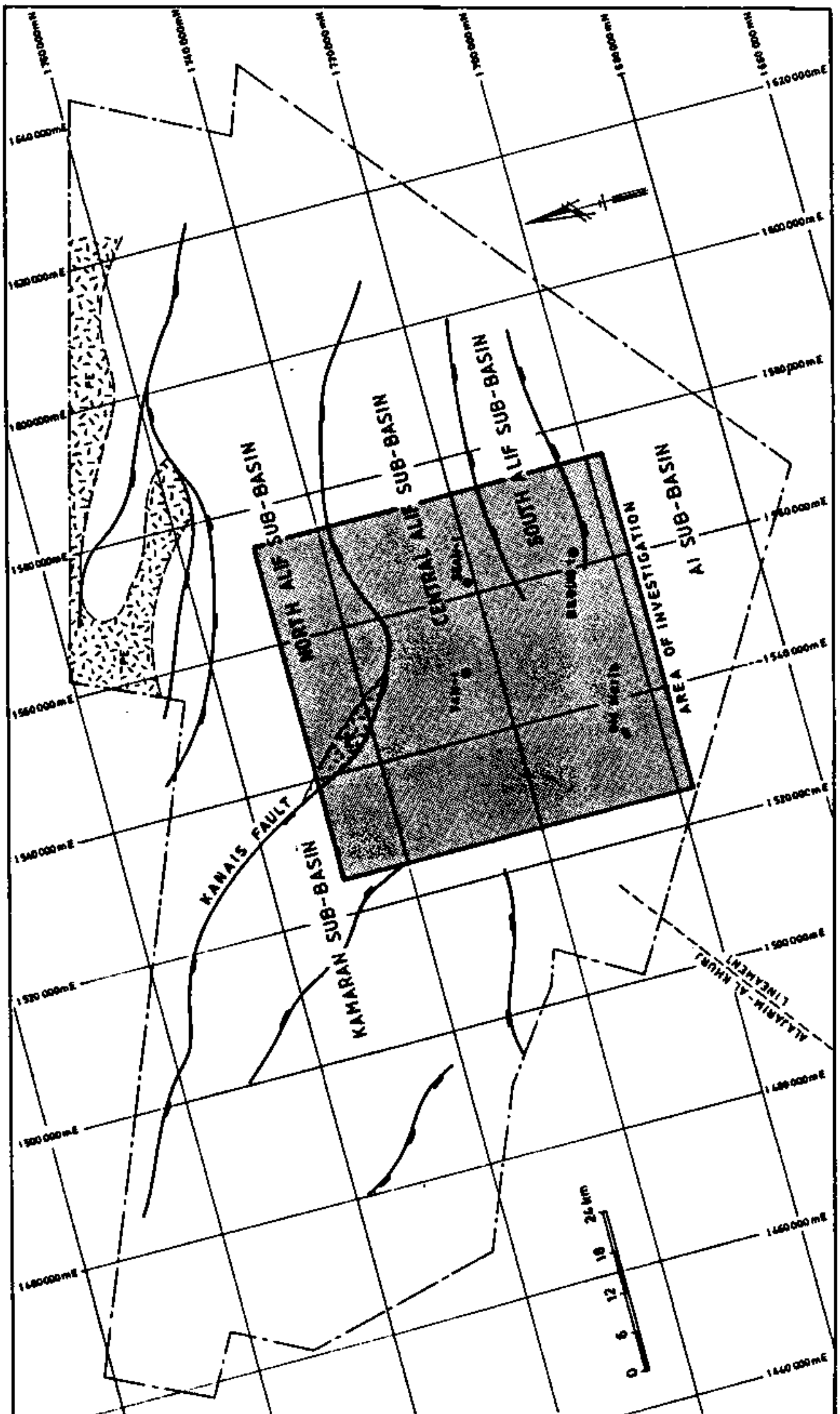


FIGURE 3.4
DISTRIBUTION OF SUB-BASINS WITHIN THE MARIB-JAWF BASIN

TABLE 3.1

Lithostratigraphic and geohydrological correlation chart

Geochronology		Lithostratigraphy			Lithology	Geohydrology	
Cainozoic	Quaternary				aeolian fine sands, alluvial gravels, sands and silts, irrigation silts, possibly evaporites	good to high hydraulic conductivity, intensively exploited aquifer, unknown whether aeolian sands are locally saturated and constitute part of aquifer.	Aquifer
					basaltic lava flows, pyroclastics	unknown hydraulic characteristics, could be source of poor water quality	
	Tertiary	Yemen Volcanics			probably absent in project area		
Mesozoic	Cretaceous	Tawilah Group	Unnamed Unit	Upper	coarse-grained sandstones separated by red or vericoloured shales	good hydraulic conductivity	Aquifer
				Middle	fine, sometimes coarse sandstones, alternating with green or red shales	medium hydraulic conductivity Aquitard	Aquifer/ Aquitard
				Lower	fine-grained sandstones, siltstones and shales	expected poor hydraulic conductivity, locally base of upper aquifer	Aquitard
			Azal Formation		massive, predominantly olive gray shales with minor limestones and rare sandstones	probably impermeable, considered as base of upper aquifer system	Aquiclude
	Jurassic	Amlah Group	Safer Formation	nine members	alternating evaporite and clastic units , mainly shales minor sandstones	minor sandstone layers have reservoir potential, source of high salinity of water	Potential Aquifer
			Alif Formation	Shale, Alif, Sean, Yah member	marine, coastal and deltaic shales and sandstones	sandstone layers, considerable reservoir potential, could belong to aquifer system in western part of project area	Potential Aquifer
		Amran Group	Lam	Dahfar, Noon, Raydan member	shales, sandstones and limestones	sandstone sections have reservoir potential and could take part of groundwater flow regime in South-western zone of project area	Potential Aquifers
			Maem		mainly shales and sandstones		
			Arwa		limestones, shales etc.		
			Saba		limestones and dolomites		
			Kohlan		shales and sandstones		
	Permian	Wajid			sandstone, minor shales, conglomerates		
Cambrian		Akbra			shales, argillite, sandstone, conglomerates		
Precambrian		basement rocks			northeast boundary: highly folded, faulted and metamorphosed schists and gneisses, intrusions of granites and dikes		

(see Figure 3.5). In the southwestern corner of the project area the limestone layers are underlain by Kohlan sandstone that could have local, probably minor, groundwater potential.

Alif Formation

The Alif Formation consists mainly of shales and sandstones. The Alif Formation (Amlah Group) was deposited in the Wadi Jawf-Marib Basin as a broad extensive sheet. The top is formed by the transgressive shale member. The sandstone layers of the Alif Formation contain considerable reservoir potential.

Safer Formation

The Safer Formation consists of alternating evaporates and clastic units. The Safer Formation is present over the entire area of investigation, its top located at depths of 75-1600 m below surface. In the southwestern part of the area the formation could not be distinguished from the overlying Unnamed Unit and/or Quaternary deposits. The sandstones of the Safer Formation, together with the sandstones of the Alif Formation, are considered to be the lower aquifer (see Figure 3.5).

Azal Formation

The Azal Formation consists of massive shales with minor inter-bedding of limestones. The Azal Formation is present in the northeastern part of the area (north of 1.710.000 m N.). The Azal Formation is considered to be an aquiclude dividing the upper aquifer from the lower aquifer (see Figure 3.5).

Unnamed Unit

The Unnamed Unit consists mainly of fine- to coarse-grained semi-consolidated sandstone, alternating with shale or clay layers. The Unnamed Unit is most probably present all over the area of investigation. Because the lithologies of the top of the formation and of the overlying Quaternary deposits are similar, it was not possible to distinguish any boundary between these formations by geophysical means. The Unnamed Unit is considered to be the lower part of the

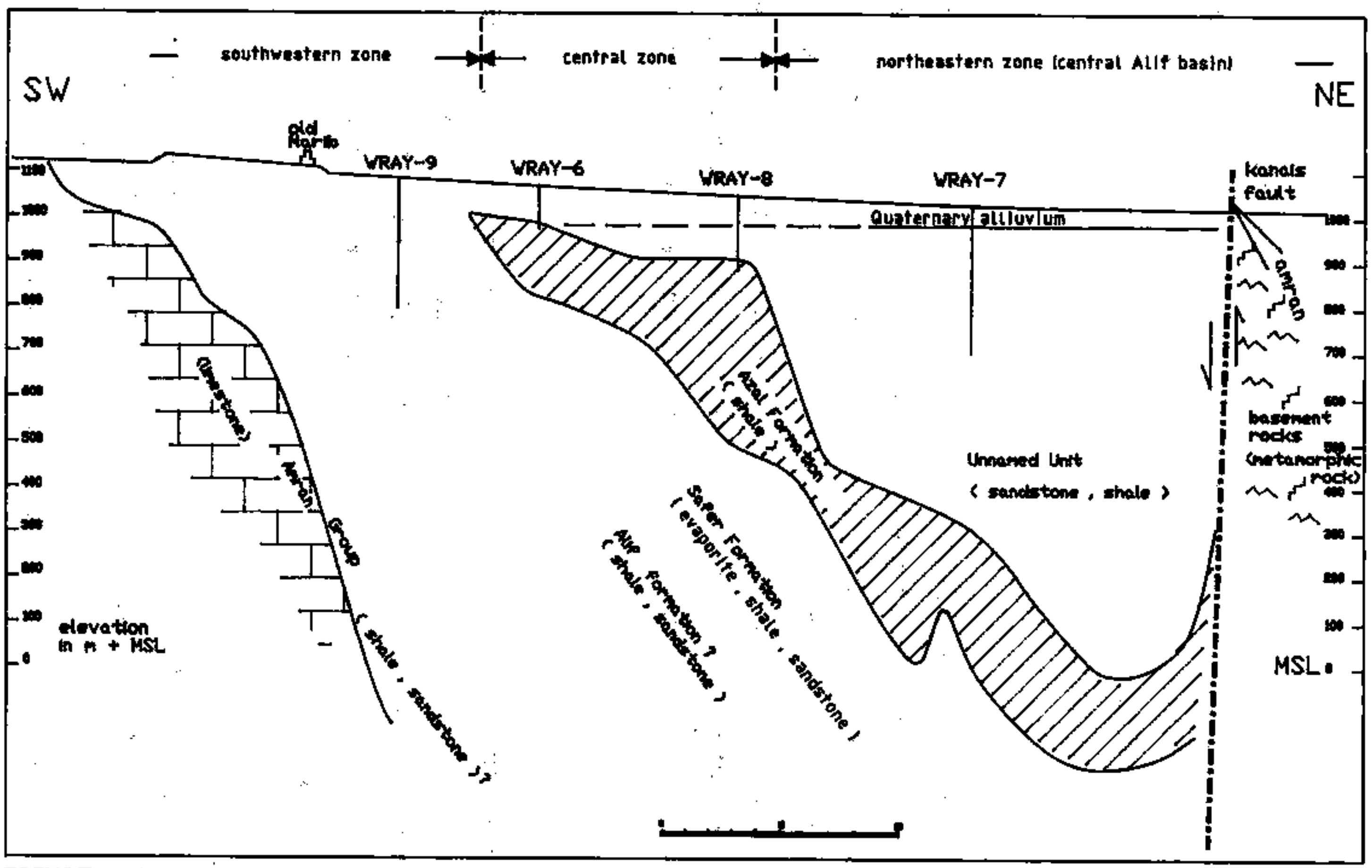


FIGURE 3.5

SIMPLIFIED GEOLOGICAL CROSS-SECTION THROUGH THE MARIB PROJECT AREA , location profile see figure 5.3

upper aquifer (see Figure 3.5).

Quaternary sediments

The Quaternary sediments consist of alluvial gravel, sands, silt and clays, aeolian sand dunes and basaltic cones and flows.

The alluvial sediments, present in and along the wide wadis, and the aeolian deposits outside the wadis cover the total area investigated. These sediments with high hydraulic conductivity form the upper part of the upper aquifer. This is at present the main source of fresh groundwater abstraction (see Figure 3.5).

The basaltic cones and flows are situated on the north - northwestern border of the project area. They are only significant in that they border the aquifer systems of the Marib area.

For more detailed information on the geology of the area concerned, see Geukens, 1966; Kool et al., 1990; Maycock, 1987 and Maycock, 1988.

3.3 Climate

General

A dry climate prevails in most of the Wadi Adhanah and Marib area. The climate varies from temperate on the Central Highlands to hot and arid on the Marib plain and the bordering foothills. Rainfall is moderate on the plains of the Central Highlands and the surrounding mountains and decreases eastwards from 400 mm/year in the west to less than 100 mm in the Marib area.

The main factors controlling climate are the topographical elevation and the three main meteorological mechanisms: the Red Sea Convergence Zone effect, the Southwestern Monsoon (Monsoonal Intertropical Convergence Zone effect) and the Subtropical Jet Stream from the Mediterranean.

During the period of observation, most of the rainfall in the catchment and Marib area fell in the spring, because of the south easterly airstream induced by the Red Sea Convergence Zone effect. The influence of the Southwestern Monsoon in summer decreases from the Central Highlands to the East. In the Marib area almost no rainfall occurs in summer. The westerly airstreams from the Mediterranean occasionally cause light rainfall in winter.

Meteorological data

Tables 3.2 and 3.3 present monthly meteorological data from the Marib and Dhamar stations. Marib (1100 m + MSL) represents the hot and dry climatic conditions of the Marib plain and the lower easterly parts of the catchment. The station near Dhamar (2310 m) represents the temperate climatic conditions of the intermontane plains of the Central Highlands. The period of observations are different, Marib represents 4 years (1985-1988) and Dhamar 8 years (1980-1987). Except for rainfall these periods are long enough to obtain 'long term' annual averages of the climatic parameters.

In Marib the temperature is high (annual average 26.4 °C) and relative humidity low (annual average 36%). The corresponding figures for Dhamar are 15.4 °C and 65%. Diurnal variation in temperature is highest on the Central Highlands, where the difference between the average maximum and minimum temperature is 21.6 °C. In Marib the difference is 16.3 °C. Highest humidities are measured during the spring rainy season.

Rainfall

The average rainfall distribution in the Wadi Adhanah catchment is given in Figure 3.6. The mean annual values for the different stations are derived from the available observation period of each station.
The general rainfall pattern demonstrates that rainfall decreases eastwards and northeastwards from the area around Dhamar (400 mm) in the southwestern corner of the catchment. On the Marib plain, close to the Rub Al Khali desert, the average annual rainfall was less than 100 mm.

TABLE 3.2

METEOROLOGICAL DATA MARIB (1985-1988)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg	Total
Temperature	Avg	19.1	21.9	25.8	26.8	30.2	31.5	33.1	32.9	30.1	25.4	21.3	18.4	26.4	
(deg C)	Avg Max	26.8	29.6	33.4	34.1	36.9	39.7	39.2	39.9	37.3	32.9	29.0	26.3	33.7	
	Avg Min	10.3	13.1	17.3	19.1	21.5	22.5	19.4	25.2	22.0	16.9	12.1	9.7	17.4	
Relative	Avg	46	43	39	45	28	24	31	33	30	32	35	43	36	
Humidity	Max	78	78	84	94	64	70	60	74	52	47	57	83	70	
(%)	Min	12	14	11	12	9	9	9	12	11	11	16	16	12	
Sunshine Hours	Avg	9.9	9.0	9.0	8.6	10.2	9.6	8.0	8.4	9.2	10.6	10.4	10.0	9.4	3431
Radiation (W/m2)	Avg	175	183	201	210	229	233	202	201	211	219	194	174	203	
Windspeed	Avg	2.4	2.8	3.3	2.8	3.2	3.7	3.9	4.4	3.8	3.0	2.5	2.9	3.2	
(m/s)	Max														
Wind dir.		NE	NE	SE/NE		NE	NE	N/NE	N	NE	NE2				
Rainfall (mm)		0.0	11.1	19.5	52.4	2.5	0.5	0.9	2.2	2.3	0.0	0.0	5.7		97.0
Atmospheric Pressure (mB)	Avg	894	892	890	892	885	887	887	872	890	894	895	896	889	

TABLE 3.3

METEOROLOGICAL DATA DHAMAR (1980-1987)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg	Total
Temperature (deg C)	Avg	11.9	13.9	15.8	16.6	18.4	19.5	19.3	19.4	17.9	13.6	12.3	12.3	15.9	
	Avg Max	24.3	25.3	25.6	25.9	27.8	29.4	29.4	29.7	28.7	25.1	25.0	24.2	26.7	
	Avg Min	-0.6	2.4	6.1	7.4	9.1	9.6	9.1	9.0	7.0	2.2	-0.3	0.3	5.1	
Relative Humidity (%)	Avg	62	63	74	75	71	61	63	73	61	55	59	67	65	
	Max	79	80	83	92	89	77	79	81	83	74	69	85	81	
	Min	32	35	42	32	38	37	22	27	19	10	25	24	29	
Sunshine Hours	Avg	8.7	8.0	8.0	8.0	8.6	7.8	6.9	6.8	7.9	9.5	9.2	9.0	8.2	2993
Radiation (W/m2)	Avg	154	213	177	226	229	248	224	214					210	
Windspeed (m/s)	Avg				1.1	1.5	1.4	1.6	1.4	1.3	1.2	0.9	1.0	1.3	
	Max														
Wind dir.															
Rainfall (mm)		2.9	21.4	40.4	73.5	45.3	11.2	35.6	61.4	8.7	7.6	6.3	10.6		324.8
Atmospheric Pressure (mB)	Avg														

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Windspeed* (m/s)	Avg	1.87	2.12	2.06	2.00	2.12	2.35	2.59	2.51	2.00	1.80	1.57	1.62	2.05

* windspeed measured in Rissbah (CHRDP)

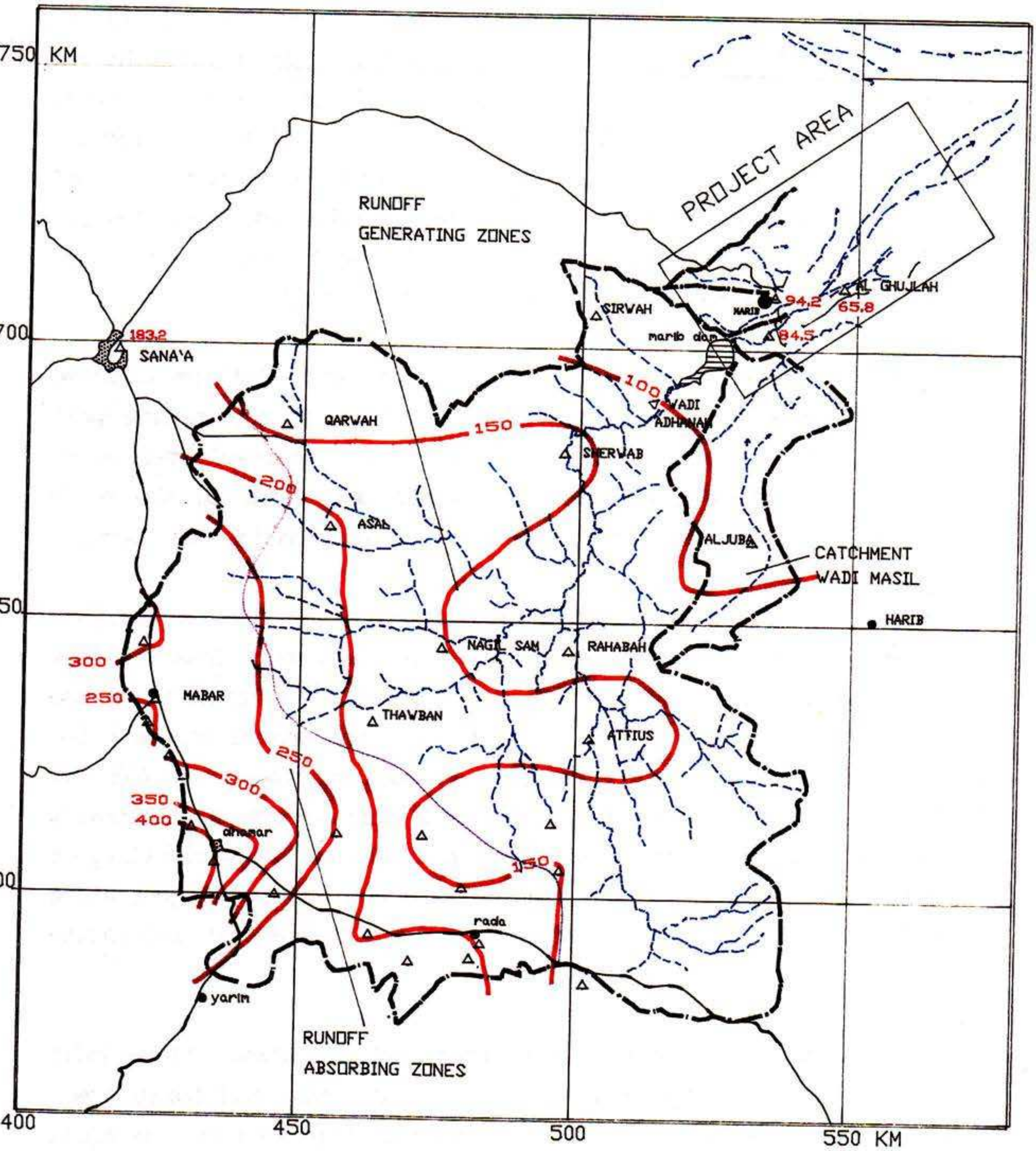


FIGURE 3.6
AVERAGE ANNUAL RAINFALL (IN MM), WADI ADHANAH CATCHMENT

The higher rainfall along the western boundary of the catchment is caused by the stronger influence of the summer monsoon.
The rainfall in the three years (1986-1988) that the WRAY project was carried out was probably not exceptional. The annual rainfall in the upper catchment has varied around the long-term average. The mean annual rainfall on the runoff-generating zone (see section 3.4) is 142 mm. During 1987 and 1988 it was 174 and 143 mm respectively. Higher than average rainfall was recorded during 1987 in the area between Rada and Attius. On the Marib plain the rainfall varies significantly over short distances. The mean annual rainfall is expected to be between 50 and 100 mm and it will decrease further eastwards towards the Rub Al Khali. It has to be emphasized that much longer records are needed to derive a more accurate mean annual rainfall.

A comparison of monthly rainfall data from several stations resulted in rather high correlations between the stations in the central part of the catchment, where the larger part of the precipitation is apparently caused by a similar large scale mechanism. On the Marib plain and on the intermontane plateau the correlation is much lower.

There are insufficient data to give a good idea of the year to year variation of the rainfall over the whole catchment. However, the stations with longer data records, located in the upper parts of the catchment (Central Highlands), indicate that the annual rainfall for particular stations generally varies between approximately 45% and 200% of the long-term mean annual rainfall. This variation illustrates the arid character of the area. It is expected that the variability of annual point rainfall of the stations inside the runoff generating zone of the catchment will be even higher because of increasing aridity in eastern direction (FAO, 1981).

During the observation period the rainfall distribution was markedly seasonal. In the centre and east of the catchment and Marib area, most of the total annual rainfall occurred from February to April (60-100%); only 0 tot 30% fell between July and September. In the western and southwestern areas on the Central Highlands rainfall was more evenly distributed over the two rainy seasons and some rainfall was recorded between the two seasons.

Most of the rain falls on only a few days a year. The highest daily rainfall ever measured in the catchment was 65.8 mm (29 March 1982 in Rada) and the highest daily rainfall registered during the investigation period in the runoff-generating zone was 39.0 mm (3 April 1987 in Rahabah).

Potential evapotranspiration

Potential evapotranspiration far exceeds the monthly and annual rainfall amounts observed. The reference crop evapotranspiration (evapotranspiration from an extensive 8-15 cm tall green grass cover of uniform height) calculated according to the modified Penman method (Doorenbos, FAO, 1977) varied from 3180 mm in Marib to 1922 mm in Rada and 1660 mm in Dhamar.

The evaporation from the Marib lake was derived from the open water evaporation according to the original Penman method by applying a reservoir coefficient of 0.8. The mean annual reservoir evaporation derived for the period 1986-1988 was 2093 mm.

3.4 Drainage pattern

The Wadi Adhanah and its tributary system mainly collects runoff from the part of the catchment that is located in the region of the Eastern Highlands and Midlands (Figure 3.1). During and immediately after the relatively short and heavy rainstorms runoff concentrates very quickly from the steep, barren and relatively impervious terrain. Perennial base flow is not present in the main wadi. The general runoff direction is eastward and runoff is conveyed through the tributary wadi system into the main Wadi Adhanah valley. Over a long distance the main wadi valley runs from south (near Rada) to north (near Sherwab), approximately paralleling to the eastern boundary of the catchment at a distance of about 20 km. The last part of the wadi course before it enters the Marib reservoir, is oriented northeast.

The catchment area of the Wadi Adhanah also includes intermontane plains of the Central Highlands. However, they are considered to be runoff-absorbing zones with an internal drainage system (see Figures 3.1 and 4.1). These areas only contribute to the runoff of the catchment after very heavy rains.

In addition to the Wadi Adhanah some minor catchments, the Wadi Masil, Wadi As Saila, Wadi Al Mil and Remaining areas drain into the Marib plain area (Figure 3.1). Surface water generated by the scarce rainfall on these catchments enters the Marib plain unhindered, where it partly infiltrates into the wadi beds and reaches the underlying aquifer and partly floods fields, sometimes considerably damaging the infrastructure.

The Wadi Adhanah conveys the catchment runoff into the lake behind the newly built Marib Dam. This dam was completed before the 1986 rainy season.
Before the construction of the dam, the floods of the Wadi Adhanah could pass unhindered into the Marib plain. After this point the wadi is called Wadi As Sudd; it continues northeastward and bifurcates after approximately 15 km into a southern and a northern branch, called Wadi Abida and Wadi Abrad respectively. The streambed of the Wadi Abrad can be followed northeastwards to its confluence with the Wadi Al Jawf. Before the dam was built only severe, torrential floods reached this point. Generally the flood discharge decreased downstream, because large amounts were diverted for spate irrigation and much infiltrated into the subsoil of the streambed itself.

Since the completion of the Marib Dam water is only released from the reservoir when the gate is opened. When the Marib Dam and Irrigation Scheme is operational water will be released from the reservoir into the Wadi As Sudd. Downstream two intakes have been constructed in the wadi bed to divert water into the main channels of the irrigation system. The first intake (diversion A) is located 10 km downstream of the new dam and the second (diversion B) is 4.5 km further downstream (Figure 4.2). Between the dam and the diversion structures the

groundwater reservoir will be recharged through infiltration and percolation through the wadi bed. At the intakes of diversion structures A and B water is diverted according to requirements into the main channels of the irrigation system. Excess water can be released through gates in the diversion structures into the existing wadi stream beds downstream.
The irrigation system has not yet been completed; only the secondary canals of the small southern branch (diversion A) have been completed. At that location irrigation experiments have been carried out since August 1989. The secondary canals of the large northern branch are under construction; it was scheduled for completion in November 1989. However, because of the uncooperative attitude of the local population it is difficult to predict the completion date.

3.5 Population and economic activity

3.5.1 Wadi Adhana Catchment

The higher intermontane basins on the western and southwestern fringe of the catchment (runoff-absorbing zones, 3300 km^2) are relatively densely populated with an estimated 50 - 100 inhabitants per km^2. The eastern mountainous part of the catchment (runoff-generating zones, 8200 km^2) is one of the sparsest populated areas in the Yemen Arab Republic, with 20 or less inhabitants per km^2 [Hoff, 1981]. In this part the population lives scattered in small villages, often composed of not more than 5 - 10 houses. Attius, Rahabah and Sirwah are the only villages of significant size (see Figure 3.1).

Agriculture is the main economic activity both in the higher western part and in the eastern mountainous areas.

There is considerable emigration to seek temporary work (10 - 20% of the male population) from the southern part of the catchment area (Rada, province Al Bayda) [Hoff, 1981].

3.5.2 Marib area

The population density in the Marib area (500 km^2) was estimated to be 26 persons per km^2 in 1976 (Dubach, 1978). According to information from the Population Studies and Research Centre (C.P.O.), Sana'a, the density was 49 persons per km^2 by 1986. The number of inhabitants continues to grow rapidly because of increasing agricultural development.

The main economic activities are agriculture and 'trade' of goods, from Saudi Arabia to the highlands of the Yemen Arab Republic.

Although the successful exploration and exploitation of oil and gas in the area is the most important activity in terms of macro economics, the local population is hardly involved in these activities.

4. SURFACE WATER

4.1 General characteristics

The catchment of the Wadi Adhanah is the principal source of surface water, its runoff-generating area covers 8200 km^2 (Figure 4.1). No perennial streamflow occurs, only intermittent flow which is mainly direct (or storm) runoff generated by the scarce heavy rainstorms that effect limited zones of the catchment areas only. During these rainstorms, excess rainfall runs off quickly over the steep, bare and relatively impermeable slopes of the mountainous catchment areas. This results in stormfloods in the main wadi channels, characterized by very fast rising water stages until a maximum is reached, followed by gradually falling water levels until streamflow ceases completely.

Since 1986 the intermittent streamflows of the Wadi Adhanah have been retained behind the new Marib Dam. The reservoir has a capacity of 396 million m^3 (retention volume). Outflow into the Wadi As Sudd downstream of the Dam is controlled by means of a radial gate construction at the end of a tunnel in the Dam. The maximum capacity of the gate is 35 m^3/s. Approximately 10 and 14.5 km downstream of the Dam intake constructions have been built in the wadi bed to divert the surface water into the main canals of the irrigation system (they were completed in 1987). The maximum design capacity of these canals is 25 m^3/s. The Marib Dam and Irrigation Project will be referred to as the Marib Scheme. Figure 4.2 shows the wadi channel network and the main canals of the irrigation network.

When the Marib Scheme is operational water can be released from the Marib lake and enter the old wadi bed (Wadi As Sudd) downstream of the dam. The initial plans for the Marib Scheme anticipate that half the amount of water released from the dam will infiltrate into the wadi beds and recharge the underlying aquifer; the other half will be diverted at diversions A and B into the main canals of the

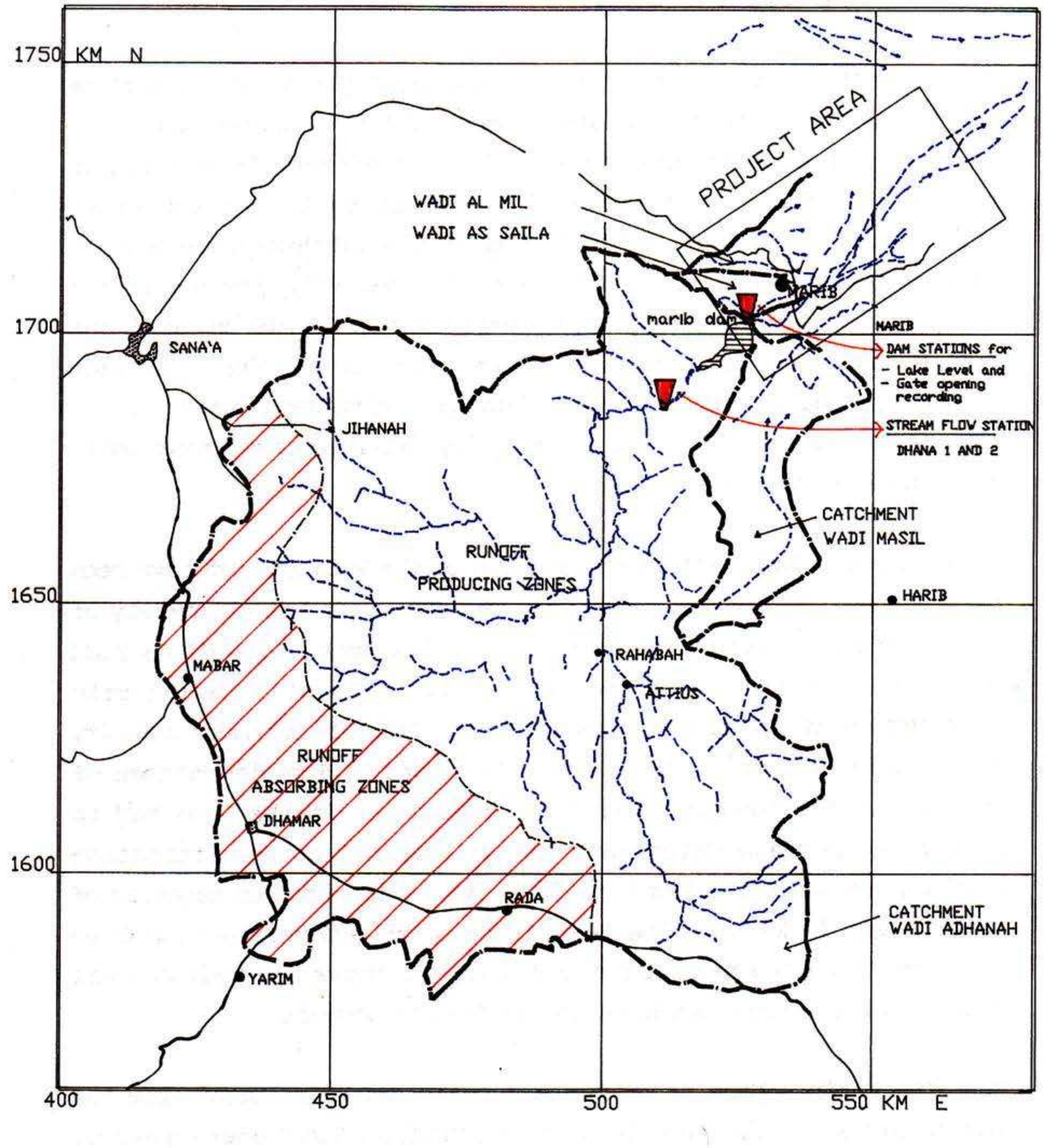


FIGURE 4.1.
LOCATION OF CATCHMENT AREAS AND OF STREAM FLOW AND MARIB DAM STATION

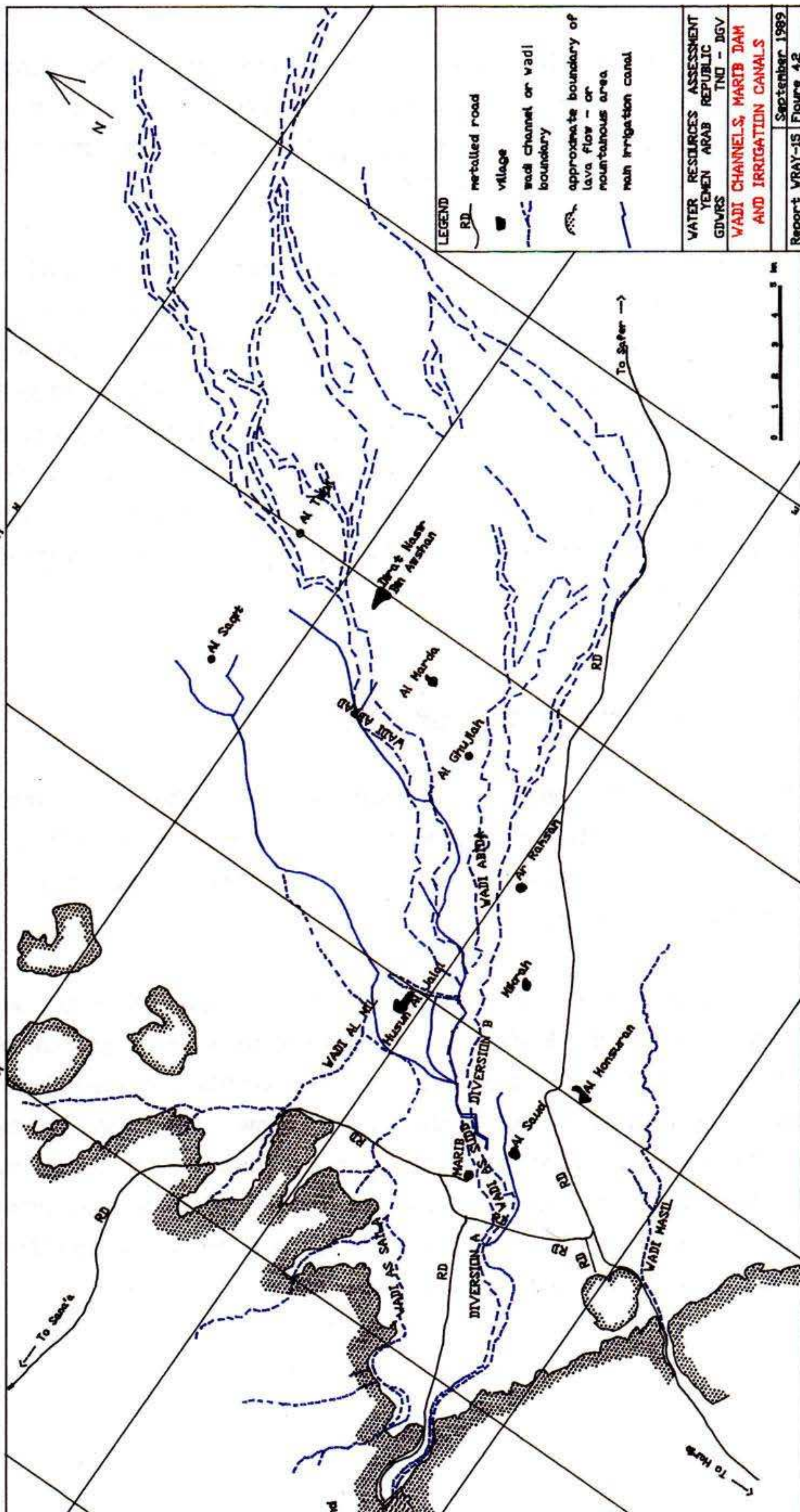

LEGEND
RD metalled road
village
wadi channel or wadi boundary
approximate boundary of lava flow - or mountainous area
main irrigation canal
WATER RESOURCES ASSESSMENT YEMEN ARAB REPUBLIC
GDWRS TNO - DGV
WADI CHANNELS, MARIB DAM AND IRRIGATION CANALS
September 1989
Report WRAY-15
Figure 4.2
N
1710 KM
1700 KM
1690 KM
1720 KM
1730 KM
520 KM
530 KM
540 KM
550 KM
560 KM
MARIB DAM and RESERVOIR
DIVERSION A
DIVERSION B
WADI AS SALA
WADI MASIL
WADI ABIDA
WADI AL MIL
MARIB
Al Marda
Al Ghujlah
RD

FIGURE 4.2

irrigation system. The secondary canals are still under construction and the construction of the tertiary channel network is foreseen for the years 1991 to 1995. It is expected that the tertiary system will gradually come into use from 1991 onwards.

Minor amounts of surface water are generated by rainfall on some smaller catchments located directly west of the Marib project area (the Wadi Masil, Wadi As Saila, Wadi Al Mil and remaining areas) and on the project area itself (total area involved about 1820 km^2, see Figure 4.1). Surface water generated in the minor catchments and in the project area itself enters the Marib plain unhindered where some of it infiltrates into the wadi beds and reaches the underlying aquifer and some inundates fields, sometimes (1988) damaging to the infrastructure.

4.2 Streamflow and Marib Reservoir

Streamflow records enable the area's surface water to be quantified. To measure the total surface water resources, streamflow must be observed at the boundaries between the "catchment areas" and the Marib Basin plain area.

It is estimated that 90% to 95% of the total surface water resources are supplied by the Wadi Adhanah. Data from stream gauging stations upstream of the dam and records of lake levels and quantity of flow released are used to determine the inflow. The rare floods of the remaining wadis together with surface runoff from local rainfall constitute a minor amount of the total surface water resources. These floods were not observed directly, the amounts involved were estimated from the rainfall figures.

4.2.1 Streamflow Wadi Adhanah (Water balance Marib Reservoir)

The Marib Dam has been built on the eastern boundary of the Wadi Adhanah catchment. To measure the streamflow of the Wadi Adhanah it is sufficient to determine the inflow from the wadi into the lake.

IF, Total inflow component is the sum of wadi flow, surface runoff from the lake surrounding area, rainfall on the lake and subsurface inflow. It can be quantified as the residual term of a water balance of the Marib lake (Figure 4.3 and Table 4.1):

$$\Delta S = IF - RF - E - L, \text{ where}$$

ΔS = Storage change reservoir
IF = Total inflow
RF = Released flow
E = Evaporation
L = Additional "losses"

ΔS, Storage changes of the reservoir are derived from the lake level records. These are recorded by an automatic recorder with solid state memory connected to a pressure transducer that has been installed by the WRAY project staff in the outlet gate of the Marib Dam. Daily average, minimum and maximum values and hourly observations have been stored since November 1988.

RF, Released outflow from the lake is derived from the continuous record of an automatic recorder connected to a potentiometer installed on the radial gate.

E, Evaporation from the lake is calculated from meteorological observations in Marib (CAMA station).

L, Additional Losses incorporate the sum of leakage, subsurface outflow and inaccuracies in the calculations of evaporation, released flow and storage changes.

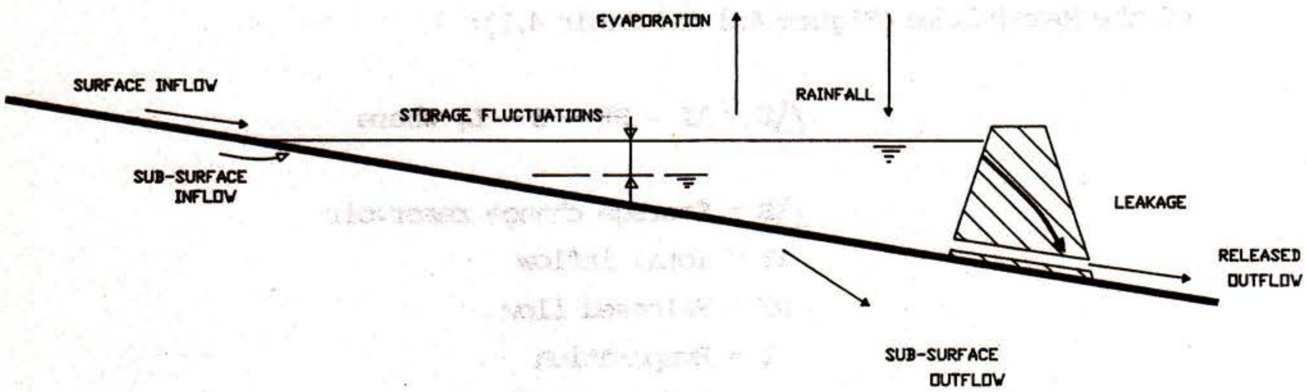


FIGURE 4.3
SCHEMATIZED WATER BALANCE MARIB RESERVOIR

TABLE 4.1

WATER BALANCE MARIB RESERVOIR
(1-4-1986 to 26-4-1989)

$\Delta S = IF - RF - E - L$

all values in million m³

	Released flow RF	Evaporation E	Inflow IF	"Losses" L	Storage change ΔS
1986*	1.8	17.2	89.5	8.6	61.9
1987	10.4	35.9	135.3	9.1	79.8
1988	110.3	33.9	87.2	7.1	-64.2
1989**	0.03	6.2	48.2	3.0	39.1
total	122.5	93.2	360.2	27.8	116.6
annual mean		# 34.9	## 104.0	# 8.1	

catchment area 8200 million m² (runoff-producing zone only)

* data from 1-4-1986 to 31-12-1986
** data until 26-4-1989
\# average of 1987 and 1988
\## average of 1986 to 1988

RESERVOIR STORAGE:
1-1-1986: 0.0 million m³
31-3-1986: 0.0
1-1-1987: 61.864
19-4-1987: 184.421 maximum storage reached during observation period (lake level 1214.09m, datum level about 71m + MSL)
1-1-1988: 141.706
26-4-1989: 116.629

The totals and yearly means of flow into the lake are presented in table 4.1. It is estimated that about 95 to 98% of total inflow is supplied by the streamflow of Wadi Adhanah. The yearly mean of total inflow derived from observations from three years (1986-1988) was 104 million m^3. However, if the data from 1989 until November are taken into account the yearly mean for the period 1986 - 1989 is estimated at about 90 million m^3. The discharges of the Wadi Adhanah during 1984 and 1985 have been very low, which would probably result in an even lower average discharge for the period 1984 -1989.
The average "long term" runoff estimated by Electrowatt amounts to 200 million m^3. However, this figure includes runoff from the runoff absorbing zones of the Central Highlands where the rainfall is highest. Subtraction of the runoff from these zones makes the Electrowatt figure to be 148 million m^3 per year, which is still considerably higher than the average runoff observed during the period 1986 -1989.

The year to year variation of streamflow is large, the highest inflow (135 million m^3) occurred in 1987, the lowest (87 million m^3) in 1988. However, the most recent information obtained from the lake and wadi stations which include the two rainfall seasons of 1989 suggests that 1989 was drier than the previous three years. Moreover, there are indications that 1984 and 1985 were also relatively very dry.

Generally, the major amount of streamflow occurs in the month of April; 66% of the total flow into the lake during the three-year observation period (1986-1988) occurred in April (see Figure 4.4).
The contribution of the summer rainy season is small; only 12% of the total inflow occurred in July, August and September. During these months the rainfall is concentrated more near the western boundary of the catchment, whereas during the spring rainy season the centre and east receive the major part of their annual rainfall. The proportion of the rainfall (=runoff coefficient) on the western region of the catchment that actually reaches the Marib lake is considerably lower than the runoff coefficient of the central and eastern parts of the catchment.

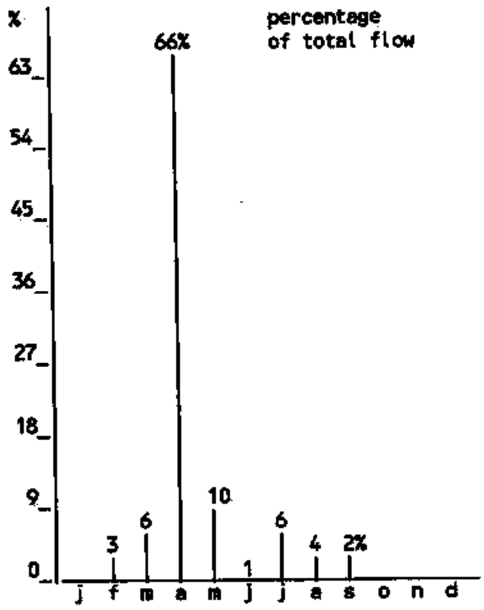


FIGURE 4.4

MONTHLY FLOW DISTRIBUTION WADI ADHANAH, period 1986-1988

The highest floods were registered in April 1987. The total monthly inflow was 86% of the annual flow. From 10 to 15 April (6 days) the lake inflow was 60 million m^3 or 45% of the annual flow. The maximum inflow during two days was recorded on 12 April when an average of 166 m^3/s was observed for 48 hours.

Relationship between rainfall and runoff

The part of a particular rainstorm that becomes runoff (=runoff coefficient) depends on the moisture conditions of the catchment at the onset of the storm (which is related to the antecedent precipitation) and on the storm characteristics like total rainfall amount and rainfall intensity. For example, concentration of certain amounts of rainfall in short periods will generate more (direct) runoff than in case the same amounts of rainfall are distributed over a much longer period.

In general higher rainfall during a certain period will generate relatively more runoff, indicating a higher runoff coefficient. This has been observed during the period 1987-1988; compared to the recorded rainfall and runoff amounts in 1988, the rainfall in the relatively wet year of 1987 was a factor 1.22 higher and the runoff a factor 1.55. The observed runoff-coefficients were respectively 9.5% and 7.4% for 1987 and 1988.

When shorter periods with high rainfall are considered much higher percentages of the rainfall became runoff, this is illustrated by the figures given in Table 4.2. In April 1987, 20% of the rainfall reached the Marib lake, wheras the comparable figure during a "lower" flood period in 1988 was "only" 13%. However, much longer records are needed to acquire a more accurate mean annual flow and a better understanding of the relationship between rainfall and runoff.

4.2.2 Streamgauging stations

Details of the Wadi Adhanah streamflow characteristics cannot be derived from lake level records. Therefore a stream gauging station site was selected for manual measurements of flows and cross sections

TABLE 4.2

RELATIONSHIP BETWEEN RAINFALL AND RUNOFF

	TOTAL RAINFALL million m^3	RESERVOIR INFLOW million m^3	RUNOFF COEFFICIENT
Annual			
1987	1424.9	135	0.095
1988	1169.8	87	0.074
Mean	1164.0	104	0.089
During Floods			
10/4/1987 - 15/4/1987	295.1	60.4	0.20
April 1987	574.8	115.9	0.20
21/4/1988 - 27/4/1988	206.8	26.0	0.13

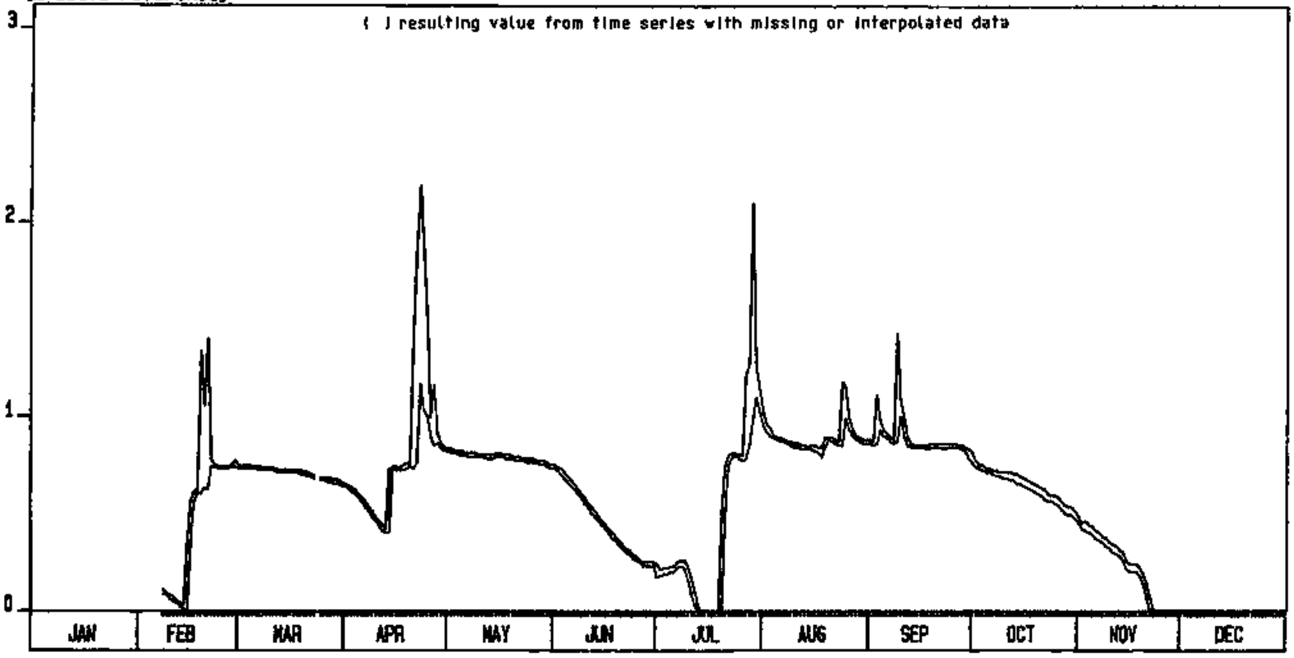
and to record stream stages.
The site is outside the maximum extent of the Marib lake, approximately 20 km upstream of the Marib Dam. The runoff-generating catchment is 7620 km^2 which is 93% of the catchment of the Marib reservoir (Figure 4.1). these differences in the areas of the catchment surface, the character of rainstorms that generally affect certain zones of the catchment and the storage capacity of the wadi above and below the wadi bed, mean that the total flow passing the streamflow gauging station will differ from the actual wadi flow into the Marib lake. Moreover it proved very difficult to derive the relation between stream stage and total streamflow even though 2 stations were present, enabling the slope-area method to be applied. Because the considerable width of the wadi (ca. 150m) and the high velocities, the relation between stage and discharge is very sensitive to slight changes in the wadi bed position, which might change considerably from one flood to another and even within one flood period. Consequently, the total flows derived from the stream stage records are rather inaccurate and therefore total flows should be derived from the water balances of the Marib lake.
However stream stage records are necessary for the study of other characteristics of flood hydrographs, relation between rainfall and streamflow, peak stream stages, stream velocities and sediment transport. Hydrographs of daily maximum and minimum stream stages in 1988 at stations Dhana 1 (right bank) and Dhana 2 (left bank, 327 m upstream from Dhana 1) are shown in Figure 4.5. At that time the natural stream channel for low flows was near the left bank. Flood hydrographs from station Dhana 2 are depicted in Figure 4.6; they are based on measurements taken at 15-minute intervals. This measurement frequency is initiated (preprogrammed) when water stages rise above a certain level.

Figure 4.5 demonstrates that the Wadi Adhanah streamflow regime is characterized by a sequence of several storm floods concentrated in the two rainy seasons, February to April and July to September. The flood periods (the rising and crest limb of the hydrograph) are followed by a recession period of several weeks until the streamflow

GENERAL DEPARTMENT OF WATER RESOURCES STUDIES

Daily Highest & LOWEST Streamstage

[m above reference] 1988

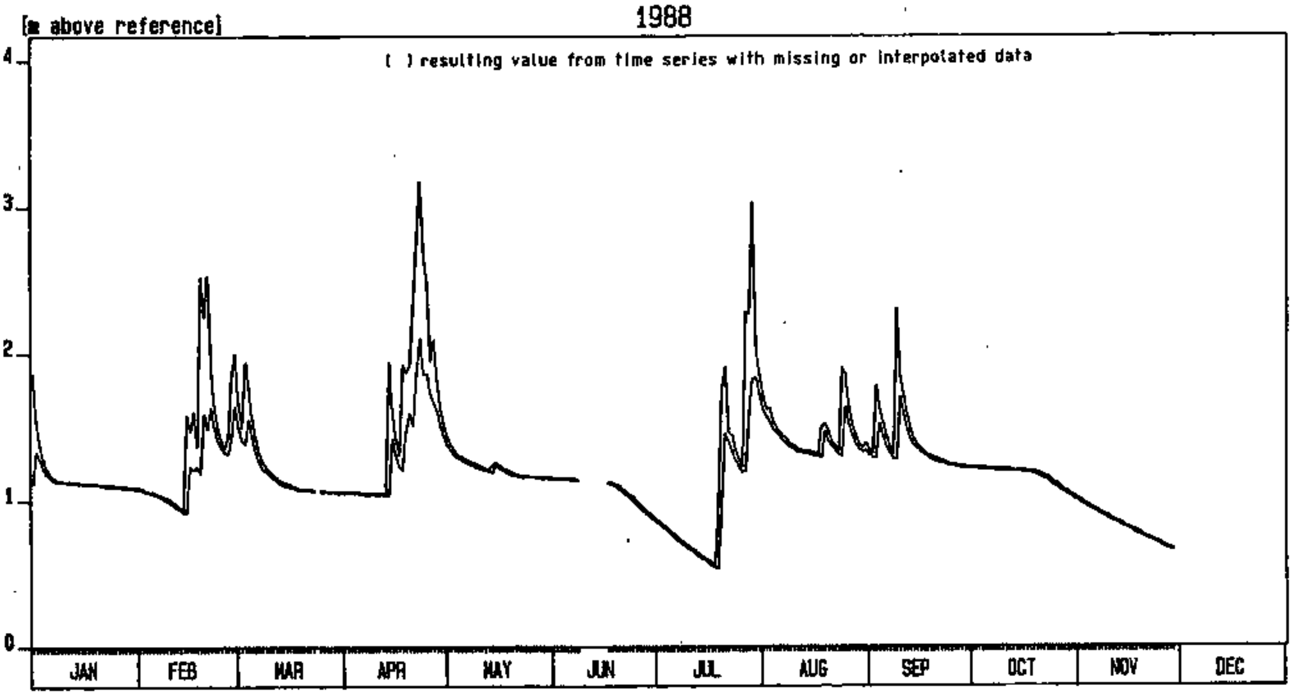


Station name :	DHANA1-A
Mapsheet :	1545 C1
Northings UTM:	1687950 mN
Eastings UTM:	512200 mE

GENERAL DEPARTMENT OF WATER RESOURCES STUDIES

Daily Highest & LOWEST Streamstage

[m above reference] 1988

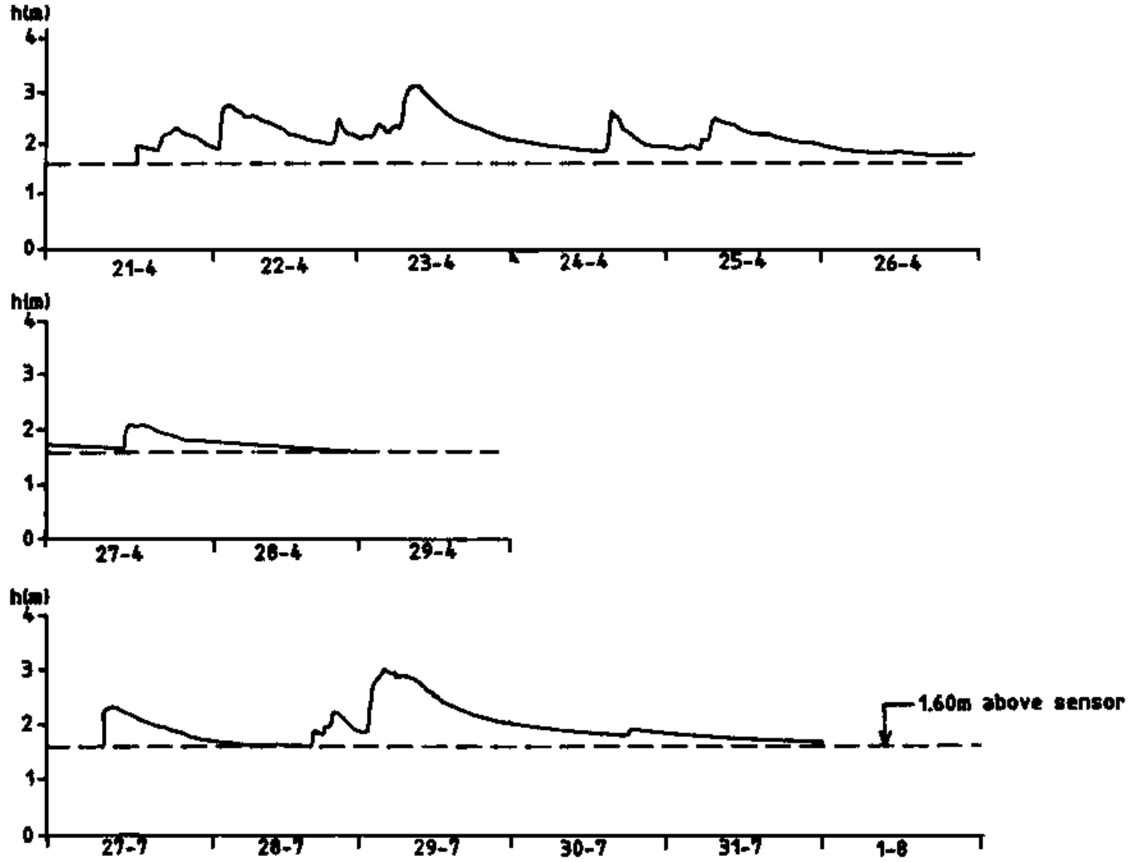


Station name :	DHANA2-A
Mapsheet :	1545 C1
Northings UTM:	1687950 mN
Eastings UTM:	512200 mE

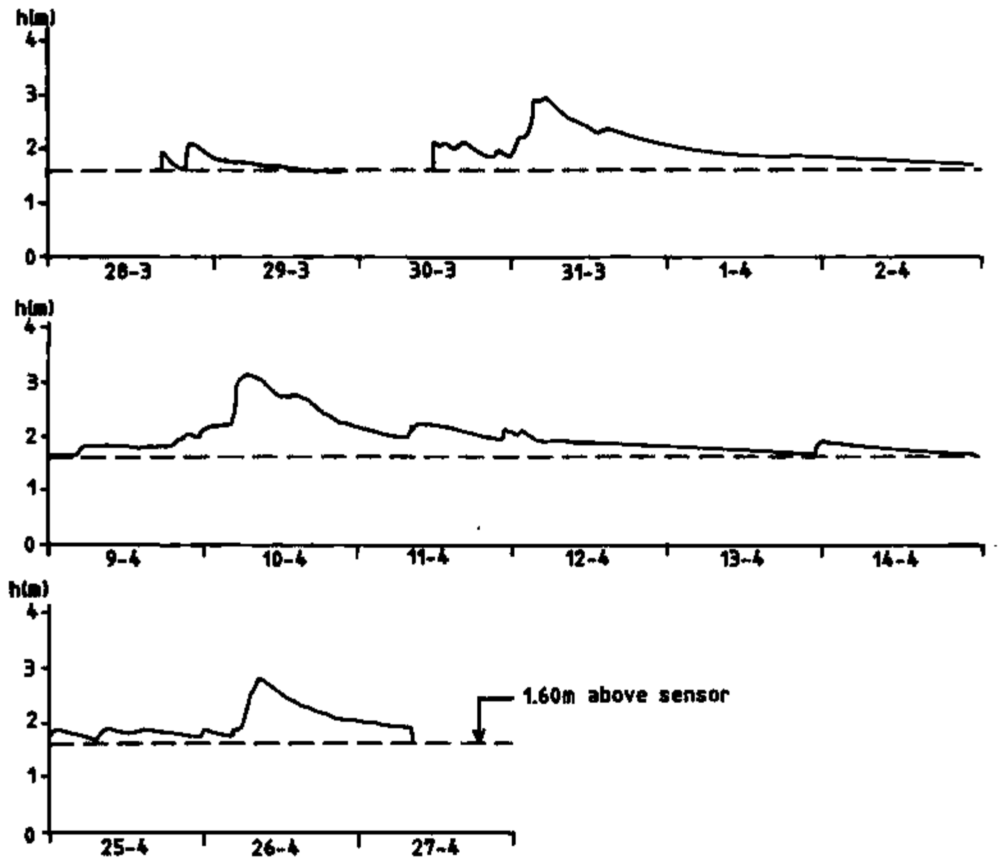
FIGURE 4.5

WADI HYDROGRAPHS 1988 FOR STATIONS DHANA 1 AND 2

- Hydrographs from daily maximum and minimum water levels
- water levels above sensor
- sensor Dhana 1 0,56m above reference
  Dhana 2 0,50m above reference



FLOOD HYDROGRAPHS 1988 FOR DHANA2-A (water levels above sensor/sensor 0.50m above reference) from observations at 15 min. interval for waterlevels > 1.60m above sensor



FLOOD HYDROGRAPHS 1989 FOR DHANA2-A (water levels above sensor/sensor 0.50m above reference) from observations at 15 min. interval for waterlevels > 1.60m above sensor

FIGURE 4.6
FLOOD HYDROGRAPHS 1988 AND 1989 FOR STATION DHANA 2

has completely dried up. The total period of streamflow appearance might be up to 100 days.

The hydrographs of 1988 demonstrate that the streamflow is relatively important in the summer rainy season this is contradictory to the general picture of major streamflow in the spring rainy season.
The flood hydrographs show that the highest stream stages are generally reached between 04.00 and 10.00 h. They lag about 11 to 13 hours behind the maximum rainfall rates of the flood-generating rainstorms in the higher parts of the catchments (Rahabah, Attius and Asal). During the passage of the flood the water level rises very quickly; rates of 53 cm in 15 min. and 90 cm in 45 min. have been recorded. After the flood peak has passed, the stream levels fall relatively slowly. After a rainy period with several floods it can take a month before the flow has ceased completely.

Table 4.3 shows some peak wadi discharges and stream levels, together with the derived mean velocities, average water depth and the average daily inflow to the lake. A maximum peak flow of 393 m^3/s was measured on 10 April 1989. However, when comparing the average two-day flow into the lake and assuming that the ratio of the meantwo-day lake inflow and the peak discharge were rather constant, the peak discharge on 12 April 1987 is estimated to be about 600 m^3/s. There are great differences between recorded maximum and average water depths along a cross section, because of the irregular shape of the wadi bed (see Figure 4.7). The total wadi bed is bankfull only during high water stages.
Mean velocities of 1.6 to 2.6 m/s at different peak stages have been observed, and maximum surface velocities above 4 m/s have been measured in the field.

The measurements of flow to date cannot yet be interpreted in terms of statistical frequency of occurrence. The magnitudes of floods were estimated for average return periods by Electrowatt (1978):

return period:	2	5	10	100 years
peak flow :	950	2600	3750	7250 m^3/s

TABLE 4.3

PEAK FLOW INFORMATION
STATION DHANA 2

	MAXIMUM STREAM LEVEL [m+ref]	MAXIMUM WATER DEPTH [m]	PEAK FLOW [m³/s]	AVERAGE VELOCITY [m/s]	AVERAGE DAILY LAKE INFLOW [m³/s]	AVERAGE TWO-DAILY LAKE INFLOW [m³/s]
12/4/1987			600*			166
23/4/1988	3.68	2.75	246	1.9	90	
29/7/1988	3.51		148	1.4	66	38
31/3/1989	3.50		308	2.3	110	63
10/4/1989	3.66	2.32	393	2.6	168	107

* derived from relation between peak flow and average two-daily flow into lake

TABLE 4.4

RUNOFF FROM OTHER AREAS
(beyond the Wadi Adhanah catchment)

	TOTAL RAINFALL million m³	RUNOFF COEFFICIENT (assumed)	RUNOFF million m³
Wadi Masil (900 km²)	78.0	0.04	3.10
Wadi As Saila (170 km²)	17.0	0.10	1.70
Wadi Al Mil (80 km²)	6.4	0.10	0.64
Remaining areas (70 km²)	4.2	0.10	0.42
local runoff Marib plain			2

the amounts mentioned in the table are mean annual values

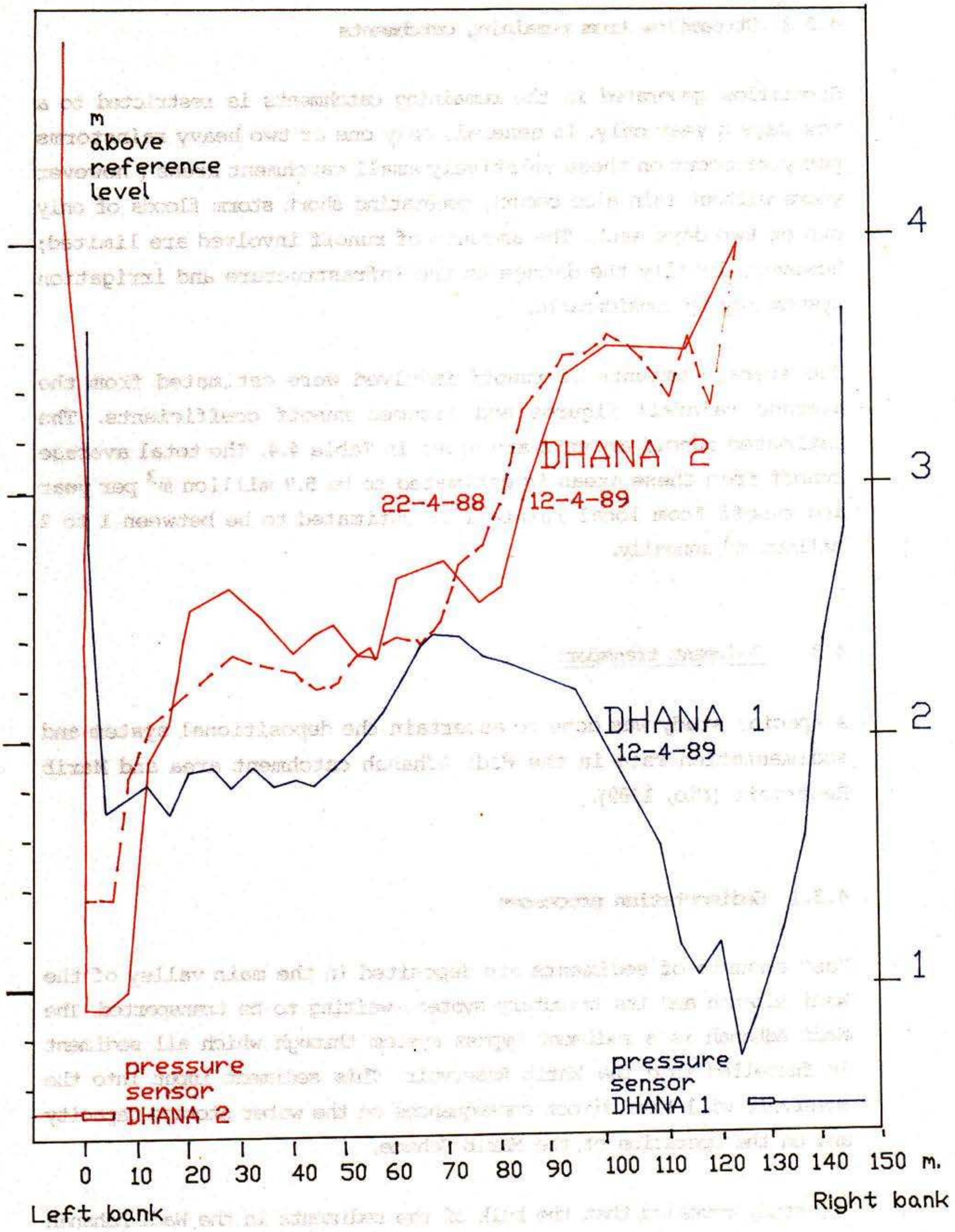


FIGURE 4.7

CROSS-SECTIONS AT STATIONS DHANA 1 AND 2
(distance Dhana 1 to Dhana 2 is 327 m)

4.2.3 Streamflow from remaining catchments

Streamflow generated in the remaining catchments is restricted to a few days a year only. In general, only one or two heavy rainstorms per year occur on these relatively small catchment areas (however years without rain also occur), generating short storm floods of only one or two days each. The amounts of runoff involved are limited; however, locally the damage to the infrastructure and irrigation system may be considerable.

The average amounts of runoff involved were estimated from the average rainfall figures and assumed runoff coefficients. The estimated runoff amounts are given in Table 4.4. The total average runoff from these areas is estimated to be 5.9 million m^3 per year and runoff from local rainfall is estimated to be between 1 to 2 million m^3 annually.

4.3 Sediment transport

A special study was done to ascertain the depositional system and sedimentation rate in the Wadi Adhanah catchment area and Marib Reservoir (Nio, 1989).

4.3.1 Sedimentation processes

Vast amounts of sediments are deposited in the main valley of the Wadi Adhanah and its tributary system, waiting to be transported. The Wadi Adhanah is a sediment bypass system through which all sediment is funnelled into the Marib Reservoir. This sediment input into the reservoir will have direct consequences on the water storage capacity and on the operation of the Marib Scheme.

The study revealed that the bulk of the sediments in the Wadi Adhanah is formed by the sand fraction, which largely originates from the

Tawilah Sandstone. The sand is funnelled into the main wadi through the Qarwah/Asal tributary system (QA in Figure 4.8). This system supplies most of the fine-grained sediment (fine sand to silt). The erosion in this region is more intensive, because of the relatively higher rainfall and the vulnerability of the poorly cemented porous Tawilah Sandstones. The Qarwah-Asal tributary system also supplies the very fine grained silt and reddish clay which are erosional products of the Amran carbonates (Figure 4.8).

The coarse-grained sedimentary material in the Wadi Adhanah, (boulders, pebbles and very coarse to medium sands) consists mainly of material derived from weathering of the Precambrian rocks. It is thought that the main source area is the southern area (the upstream parts of the wadi and the Attius tributary system (AS)), where transport is sustained by relative heavy rainfall. Further downstream the volcanic (basaltic) boulders and conglomerates are the dominant sedimentary material.

4.3.2 Sediment influx and storage reduction Marib Reservoir

Data obtained by echo sounding on the lake in Febr./March 1989 revealed that the total volume of sediment that had accumulated after the reservoir was first flooded in April 1986 is 4.5 million m^3 over an estimated survey area of 8.2 km^2 (Nio, 1989).
This means that the storage of the reservoir was reduced by 1.12% in its first three years of impounding and that the average sediment transport/supply into the reservoir is approximately 1.5 million m^3/year. Electrowatt estimated a higher average sedimentation transport of 2.5 million m^3/year (Electrowatt, 1978).

The observation period was characterized by floods that were mainly low except for April 1987 during which a moderate flood occurred. The average sediment load per m^3 was calculated to be 0.0145 m^3 (1.45%). Consequently, based on rainfall/runoff amounts for the period 1986-1988, the reduction in the storage capacity of the Marib Reservoir

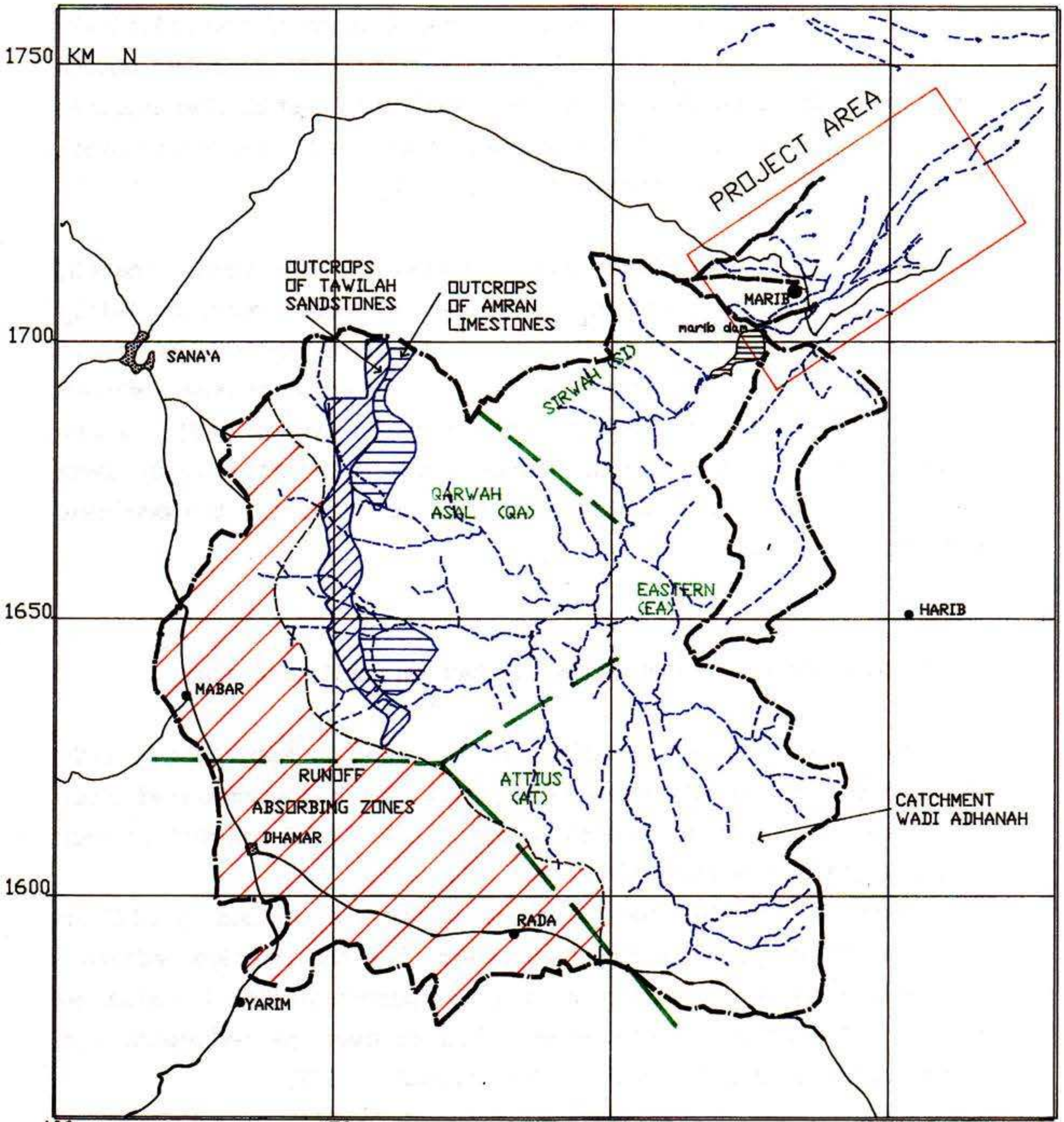


FIGURE 4.8

TRIBUTARY SYSTEM WADI ADHANAH CATCHMENT AREA would be only 15% after 40 years and not be an immediate cause of concern. However, for a more realistic prediction of the reduction in storage capacity, medium and high floods (for which sediment loads of 2% and 5% to 14% respectively are assumed) should be included. The occurrence of one high flood period could reduce the reservoir storage capacity by 6 to 17 million m^3, assuming sediment loads of 5 to 14%. Different storage reduction models, each with certain scenarios for low, medium and high flood sequences are presented in report WRAY-15.6 (Nio, 1989). These models predict a storage reduction between 15 to 35% within 30 years.

The fact that the major accumulation of sediments has occurred near the dam is cause for concern. Within 10 years the intake could be largely covered with sand hampering normal operation. It is not known whether sand will be flushed easily during normal discharge periods. This needs to be studied, because direct flushing (at high capacity) of the accumulated sediments is the most effective way to maintain the storage capacity and to prolong the life of the Marib Reservoir. However the question is whether this can be realized together with the designed extensive irrigation system.

Another way of temporarily reducing the input of sediments into the reservoir is to construct sediment traps within the 'low gradient' parts of Wadi Adhanah. This will increase the residence time of sands/silts in the Wadi Adhanah. The life of these dams is very restricted and more detailed sedimentological studies are necessary before this method can be applied.

4.4 Surface water use

The use of surface water in the catchment area has not been investigated in detail. The amounts of water involved are not known. However, in the sparsely populated main part of the catchment traditional spate irrigation is applied in and along the wadi valleys, especially in the wider parts and on smallintermontane plains. At certain suitable places pumps have been installed in the alluvial fill of the wadi valleys so that groundwater can be extracted after surface runoff has ceased.

The population density is higher along the marginal western rim of the catchment area because more water resources are available. As well as using direct surface runoff, some areas have a more continuous supply from springs.

The situation in the Marib plain area has changed drastically since the completion of the Marib Dam. Since the beginning of 1986, the use of surface water for spate irrigation has been restricted to the direct runoff from rainfall on the minor catchments and on the plain area itself. The amounts involved are small (see paragraph 4.2.3). During the past three years, water from the Marib Reservoir has been released only for the purpose of recharging the aquifer upstream of the diversion structures of the irrigation system. This situation will probably continue until the Marib Scheme starts operating, which is expected to be in 1991.

The initial Marib Scheme (Marib Dam and Irrigation Project) includes a gross command area of 6890 ha (Figure 6.4, page 101). It has been estimated that half of the amount of water released from the dam will infiltrate into the wadi beds and recharge the underlying aquifer; the other half will be diverted at diversions A and B into the main canals of the irrigation system. The Marib Scheme has been designed for an average recharge into the lake of 196 million m^3 per year (Electrowatt 1978). This amount considerably exceeds the annual flow observed during the last 5 to 6 years. This has to be taken into account for the development and management of the available water resources, which is discussed in Chapter 6.

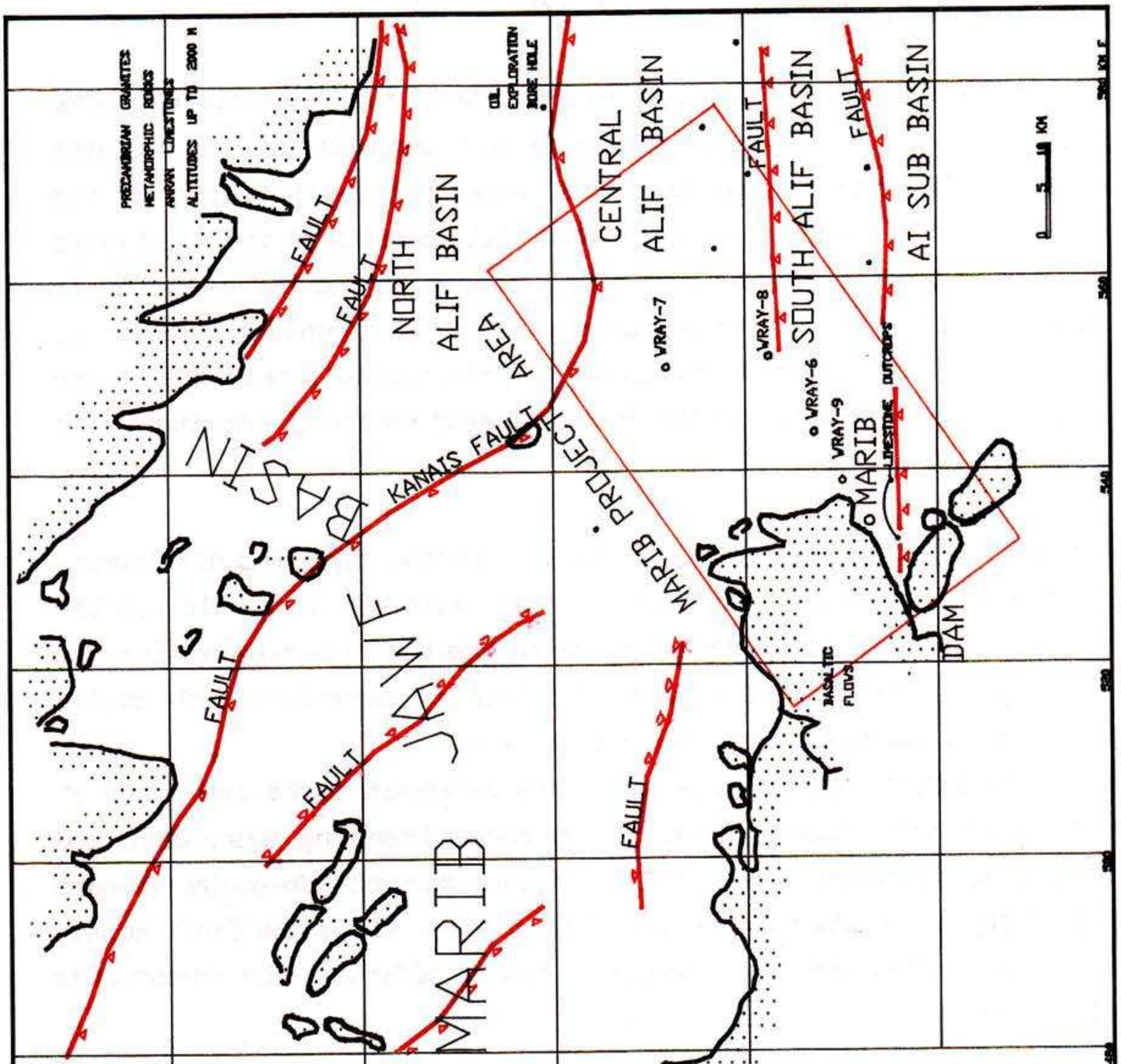


FIGURE 5.1

LOCATION MARIB PROJECT AREA IN THE MARIB JAWF BASIN,

WITH SOME GEOLOGICAL INFORMATION

It is believed that the presence of mobile fresh groundwater is virtually restricted to the sandy units of mainly the upper part of the basin fill. However the exact thickness of the fresh water bearing sandy layers could not be established, because the depths at which fresh groundwater occurs (probably down to more than 500m at some places), were beyond the exploration depth ranges of the investigation methods applied.

Groundwater is the main "perennial" source of water in the Marib-Jawf area. Wadi Al Kharid and Wadi Madhab, entering the Wadi Jawf Basin in the northwestern part are the only perennial streams. Important streamflow volumes which occur only during and directly after the storm rains in the surrounding mountains, are conveyed into the basin plain area by the braiding wadi systems. It is thought that the percolation of these storm floods through the wadi beds is the principal recharge source of the Marib-Jawf groundwater basin. And it is believed that recharge occurs mainly in the marginal zones of the basin, where the wadis enter the basin.

It may be assumed that the storm floods from the south-western flank of the Marib-Jawf Basin far exceed the storm floods from the very dry northeastern flank. The Wadi Adhanah catchment occupies approximately 40% of the runoff-producing zone on the southwestern flank of the Marib-Jawf Basin. Consequently, the construction of the Marib Dam, which captures the storm floods of the Wadi Adhanah in the Marib Dam reservoir, has deprived - at least temporarily - the whole Marib-Jawf groundwater basin of an important part of its recharge. The Marib-Jawf Basin is assumed to be connected with the Indian Ocean via Wadi Hadramawt in the east.

5.2 Marib aquifer system

The general aquifer system, as inferred mainly from the geophysical investigations (Kool et al., 1989) and from the WRAY exploratory boreholes, is shown in the schematic hydrogeological cross section

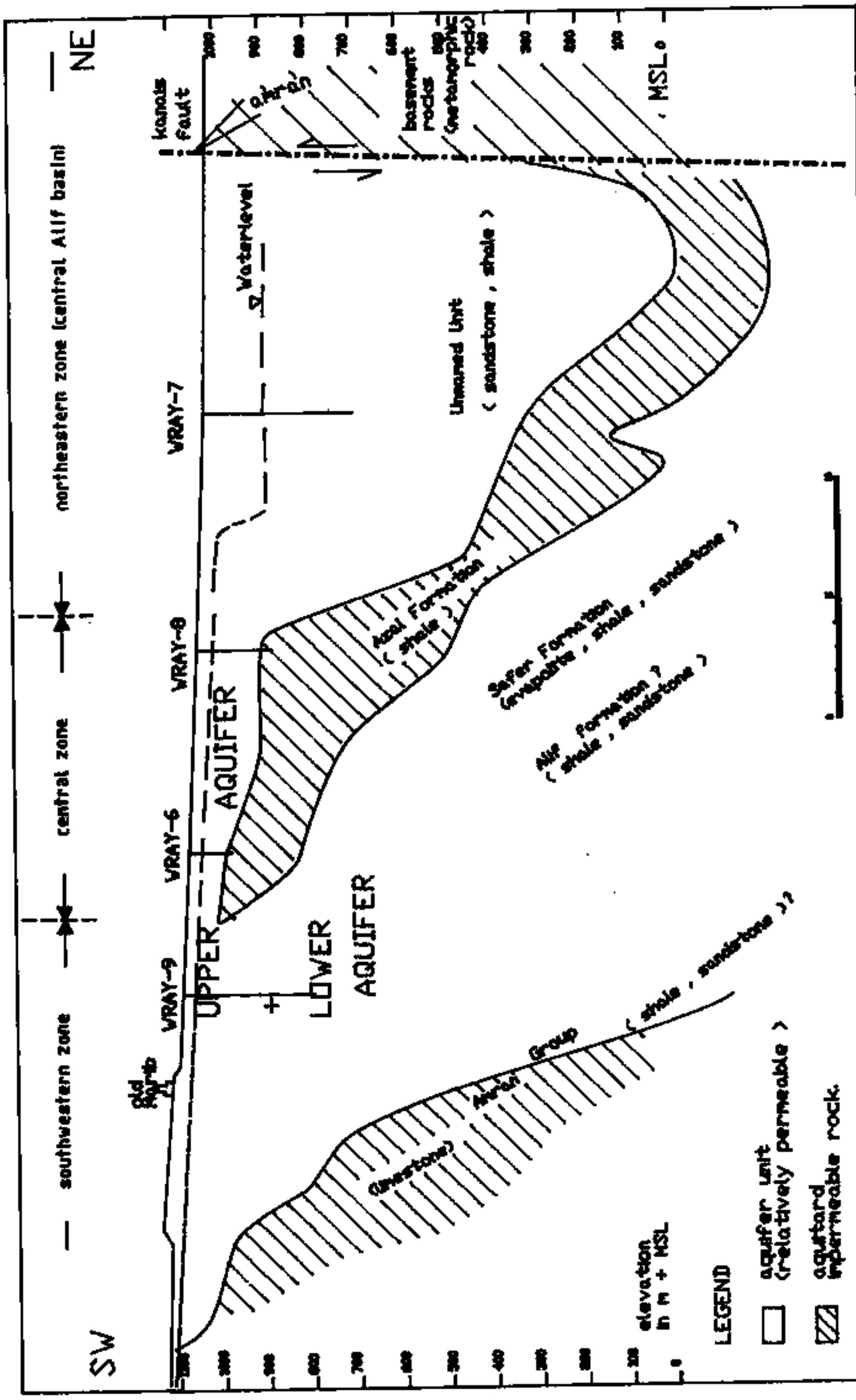


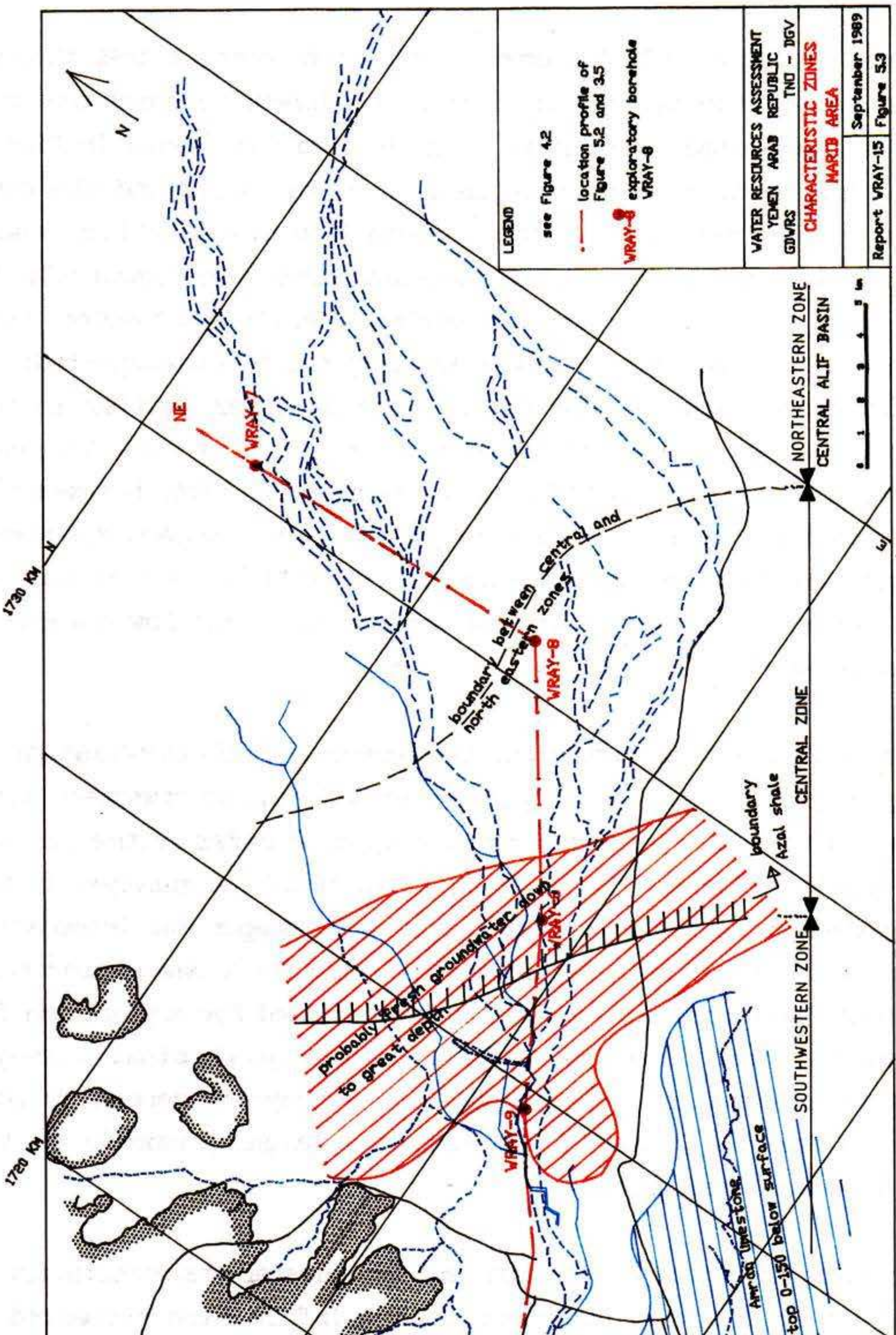
FIGURE 5.2

HYDROGEOLOGICAL CROSS-SECTION THROUGH THE MARIB AREA
location profile see figure 5.3

presented in Figure 5.2. The cross section runs more or less through the centre of the project area from southwest to northeast and includes the 4 WRAY exploratory borehole locations shown in Figure 5.3. On the basis of the presence of the Azal shale and the sub-basins, the project area has been divided into three distinct zones: the southwestern, central and northeastern zones (see Figure 5.3). An upper and a lower aquifer are distinguished. In the southwestern zone one aquifer system (upper + lower aquifer) can be distinguished; it is subdivided into a lower aquifer and an upper aquifer in the central zone of the Marib project area. In this zone the Azal Formation (shale) probably forms an impermeable layer between the upper and lower aquifer. The only possible interconnection between the upper and lower aquifer in this area would be through fracture or fault zones. It is not known how far the upper and lower aquifer system extends northeastwards.

The lithological composition and the groundwater characteristics of the upper part of the thick aquifer system in the southwestern zone, (whose northeast extension forms the upper aquifer in the central zone) are well known, thanks to the results of the surveys. In the northeastern zone the upper aquifer is much deeper and information about the aquifer has been obtained from only a few exploratory boreholes (WRAY borehole 7 and boreholes, drilled for exploration for hydrocarbon) and from the results of the geophysical surveys. However, information from geophysical surveys is generally less accurate for the deeper formations and largely depends on the reference data available.

Information about the composition and groundwater characteristics of the lower aquifer is rather scarce. The information presented is mainly based on the results of the interpretation of some seismic lines and on the information available from a few oil exploratory boreholes (Kool et al., 1989). Exploratory borehole WRAY-9 was drilled to explore the top of the lower aquifer in the southwestern part of the project area.



N
LEGEND
see Figure 4.2
location profile of Figure 5.2 and 3.5
WRAY-8 exploratory borehole WRAY-8
WATER RESOURCES ASSESSMENT YEMEN ARAB REPUBLIC
GDWRS TNO - DGV
CHARACTERISTIC ZONES MARIB AREA
September 1989
Report WRAY-15 Figure 5.3
NORTHEASTERN ZONE
CENTRAL ALIF BASIN
CENTRAL ZONE
SOUTHWESTERN ZONE
boundary between central and north eastern zones
boundary Azal shale
probably fresh groundwater down to great depth
Amran limestone top 0-150 below surface
NE
SW
WRAY-7
WRAY-8
WRAY-5
WRAY-9
1730 KM
1720 KM
1710 KM
1700 KM
1690 KM
520 KM
530 KM
540 KM
550 KM
560 KM

FIGURE 5.3

Upper aquifer

The upper aquifer (including the upper part of the aquifer system in the southwestern part) is formed by Quaternary alluvial sediments and semi-consolidated deposits of the Unnamed Unit which belongs to the Tawilah Group (Cretaceous). The total thickness of the alluvial sediments (unsaturated + saturated), which cover most of the project area, is estimated to be 50 to 70 m. The water -bearing thickness of the alluvial sediments depends on the position of the water table and varies from a few meters to a maximum of about 50 m in the southwestern and central zones. In the northeastern zone the alluvial deposits become unsaturated and the water table is situated in the semi-consolidated sandstone formation of the Unnamed Unit. It is assumed that the deposits of the Unnamed Unit are also present in the southwestern and central zones; however, the transition from the alluvial layers to the underlying formations of the Unnamed Unit could not be defined in the geophysical survey, hence the presence of the Unnamed Unit in this area could not be proven.

In the **southwestern and central zones** the top layers of the upper aquifer (thickness 10 to 30 m), which are positioned just below the water table, are formed by alluvial boulders, gravels and sands and are very permeable. They constitute the principal groundwater-transmitting layers from which most of the present groundwater abstraction takes place. Where they underlie the wadi beds they capture the recharge and convey most of it. In all three WRAY exploratory boreholes drilled in these zones the lower part of the upper aquifer is much more clayey than the upper part and permeability is very low.

In the **central zone** the base of the upper aquifer is formed by the Azal shale within a depth of 75 to about 200 m (Figure 5.2) below surface. Undoubtedly this shale layer constitutes an important barrier for the northeasterly flow of groundwater.

In the **northeastern zone** the top of the Azal shale formation dips to depths of more than 1000 m in the centre of the central Alif Basin.

It could form the ultimate base of the upper aquifer which consists of deposits of the Unnamed Unit only. However the 'actual' base is probably formed by the argillaceous lower sections of the Unnamed Unit. These sections may have been reached in borehole WRAY-7, where clay layers occur from 300 down to 330 m below surface. Because of the aquifer's considerable thickness in this area, its transmissivity is much higher in the northeastern zone than in the central zone.

Lower aquifer

As stated above, a lower aquifer (including the lower part of the aquifer system in the south-western zone) is thought to be present in the area (Figure 5.2). Because of the great depth at which the aquifer could occur, its thickness and extent could not be ascertained using the methods applied. Also it is not clear whether the very high permeability of the formations encountered in exploratory borehole WRAY-9 at a depth below 120 m should be attributed to the sandstone formations of Jurassic age, which are thought to constitute this lower aquifer.

The aquifer would be composed of the sandstone members of the Salif and Alif Formation (and maybe from the Amran Group). However, these sandstone layers alternate with shales and evaporites, which could result in a complex lower aquifer system with more saline groundwater.

The outcomes of the geophysical survey suggest that in the transition zone from the southwestern to the central zone of the Marib Basin, high electrical resistivities occur down to depths of 500m or more. This suggests the presence of fresh water in layers with high permeabilities (Figure 5.3). This layer complex dips northeastwards under the Azal shale. As stated above, neither the total depth nor the lateral extent of this layer complex insofar as it contains fresh groundwater could be established.

In the southwestern zone the lower aquifer plus the upper aquifer constitutes one aquifer system. The less permeable lower section of

the upper part will probably locally constitute an aquitard. In the southwestern zone recharge of the deeper part of the aquifer system will occur.
The base of the lower aquifer is formed by the limestones of the Amran Group, which outcrop in the southwest, forming the southwestern boundary of the whole Marib aquifer system. Some recharge from this 'boundary' may be possible through cracks, fissures, fractures or faults, particularly in the area around the Marib Dam, where the water pressures are high because of the water stored in the reservoir. Although the amounts involved could not be established, they are assumed to be very small compared with the 'normal recharge'.

In the southern part of the area, near the limestone outcrops, the thickness of the total aquifer system is considerably reduced because the limestone layers are near the surface. The area in which the top of the limestone sediments is encountered within a depth of 0 to 150 m is shown in Figure 5.3.

5.3 Groundwater levels and groundwater flow

Depth to groundwater was measured in 787 wells and is shown in Figure 5.4. The measurements vary widely ranging from 10.3 to 149.0 m However, depths of more than 60 m were only observed in the northeastern zone (in the Central Alif Basin) of the survey area, where depth to groundwater is about 140 m.

A discontinuity in the water table occurs near the boundary of the central and northeastern zones. Over relatively short distances (a few kilomets) the groundwater level falls by about 75m in the direction of the northeastern flow. Probably the groundwater has to flow through a zone of low transmissivity before it enters the principal sub-basin where the groundwater levels are determined by the hydraulic conditions of the groundwater-transmitting semi-consolidated sands of the Unnamed Unit.

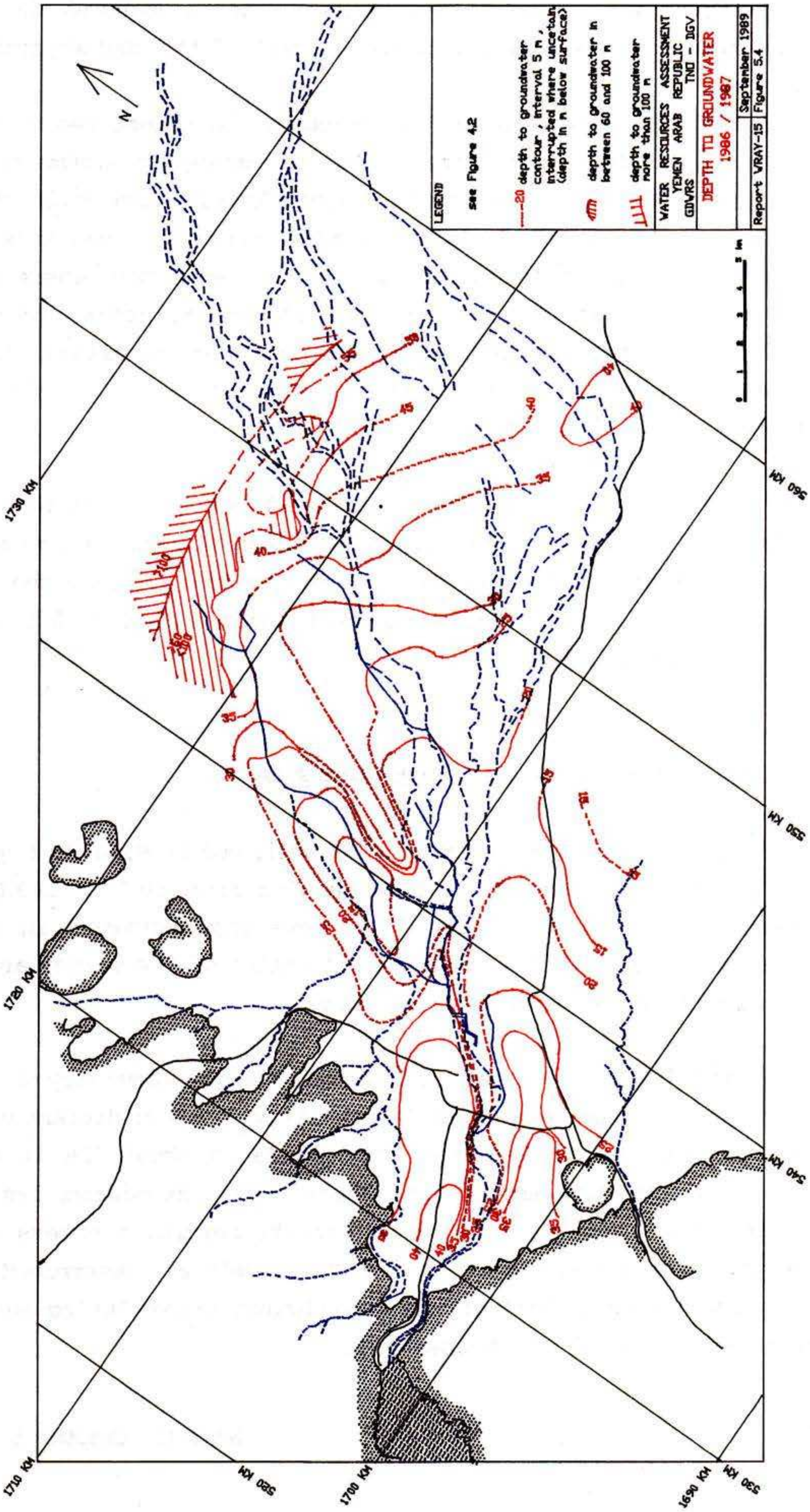

LEGEND
see Figure 4.2
20 depth to groundwater contour, interval 5 m, interrupted where uncertain (depth in m below surface)
depth to groundwater in between 60 and 100 m
depth to groundwater more than 100 m
WATER RESOURCES ASSESSMENT YEMEN ARAB REPUBLIC
GDWRS TNO - DGV
DEPTH TO GROUNDWATER
1986 / 1987
Report WRAY-15
September 1989
Figure 5.4
N
1730 KM
1720 KM
1710 KM
1700 KM
1690 KM
560 KM
550 KM
540 KM
530 KM
520 KM

FIGURE 5.4

Figure 5.5 shows the contour lines of the piezometric groundwater levels, measured in August 1987. The flowlines which can be drawn perpendicular to the contour lines more or less follow the courses of Wadi As Sudd and Wadi Abida, which were the main sources of recharge.

The hydraulic gradient (=difference in water level between 2 locations divided by the distance between them) is approximately 0.005 near where the wadi enters the basin in the southwest. The gradient flattens towards the northeast to a clear "low" gradient area in the southwestern zone (Figure 5.3), where deposits containing fresh water that have good hydraulic conductivity probably occur down to great depth. Further northeast the gradient increases because of the presence of the "barrier" formed by the Azal shale (Figures 5.2 and 5.3). It seems that all or most of the groundwater flow has to pass over this impermeable layer. At the boundary, the top of the Azal shale occurs at a depth of approximately 75m, considerably decreasing the thickness of the waterbearing formations. The depth to water is least (locally less than 15 m) within the area with low gradient and near the boundary of the Azal shale.

During the 18 months of the investigations, a general decline of water levels was observed throughout the entire area, because of continuing abstraction and almost no recharge. The annual decline varied from 2.4 m in the southwestern zone to 1 m in the central zone. However, the release of water from the Marib Dam Reservoir, which started at the end of 1987 and was continued in 1988, caused the water levels in the southwestern zone to rise considerably by up to 20 m near the recharge zones (wadi beds). All recharge took place in the southwestern zone, whereas in the central and eastern zones the groundwater levels continued to decline at more or less the same rate.

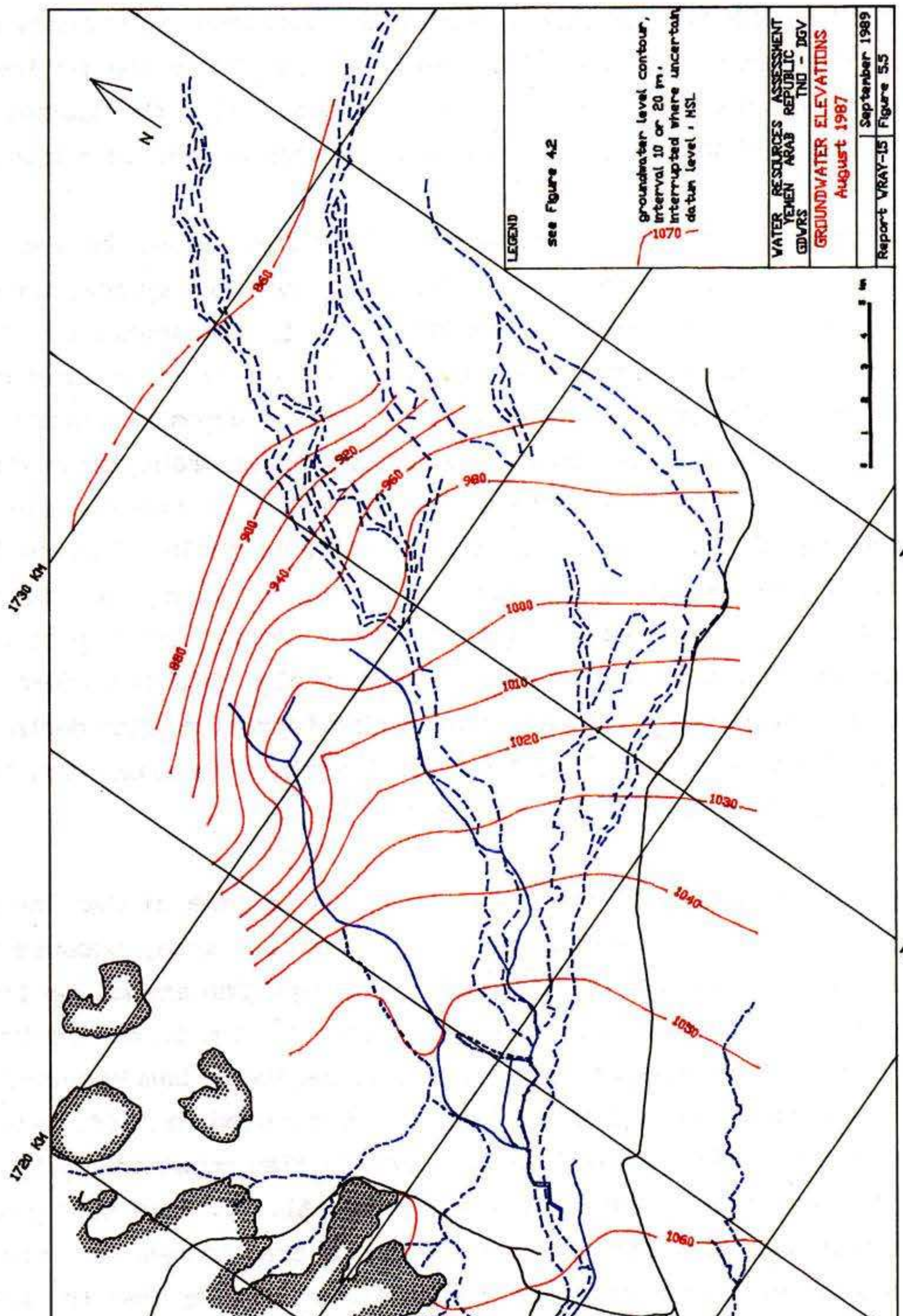

N
LEGEND
see Figure 4.2
groundwater level contour, interval 10 or 20 m; interrupted where uncertain; datum level : MSL
1070
WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
GDWRS TNO - DGV
GROUNDWATER ELEVATIONS
August 1987
Report WRAY-15
Figure 5.5
September 1989
860
880
900
920
940
960
980
1000
1010
1020
1030
1040
1050
1060
1070
1080
1730 KM
1720 KM
1710 KM
1700 KM
1690 KM
560 KM
550 KM
540 KM
580 KM
590 KM

FIGURE 5.5

5.4 Groundwater quality and groundwater temperature

Fresh groundwater occurs in the most of the Marib area studied. The salinity of groundwater was determined by measuring the electrical conductivity in private wells. The outcomes of the geophysical survey also indicated the salinity of groundwater. Figure 5.6 presents the electrical conductivity pattern based on measurements in existing wells and hence generally representing the conductivity of groundwater in the upper aquifer. However, some wells are deeper and probably represent the lower flow system.

The conductivity values measured (at 25^{o} C) range from 428 to 8640 microS/cm. Electrical conductivities higher than 2000 microS/cm indicate groundwater whose suitability for drinking and irrigation is severely limited. Water with electrical conductivities lower than 750 microS/cm is the most suitable for irrigating all kinds of crops.

Figure 5.6 shows a pattern of contours similar to that in Figure 5.7. The lower values are found in the recharge areas, hence in the wadi spread areas. The contour patterns of 1000 microS/cm and of 30^{o} C are more or less funnel-shaped, being narrow near the wadi entrance and widening in the direction of flow. The increasing values with distance from the wadi indicates a relation between longer residence time and higher salinization and higher temperatures.

However, some disturbances of this general pattern can be observed. High salinities occur, more or less coinciding with the shallow occurrence of limestone in the subsurface. This is observed in the southeastern margin of the area, along the road to Safer and Wadi Masil. In some places very fresh water and saline water occur only short distances apart. The highest salinities were observed in this area. Although it was expected that there would be a relation between depth of wells and electrical conductivity, no such relation could be established.

The occurrence of high salinities is probably associated with the composition of the underlying older formations, which could include evaporites (gypsum and salt).

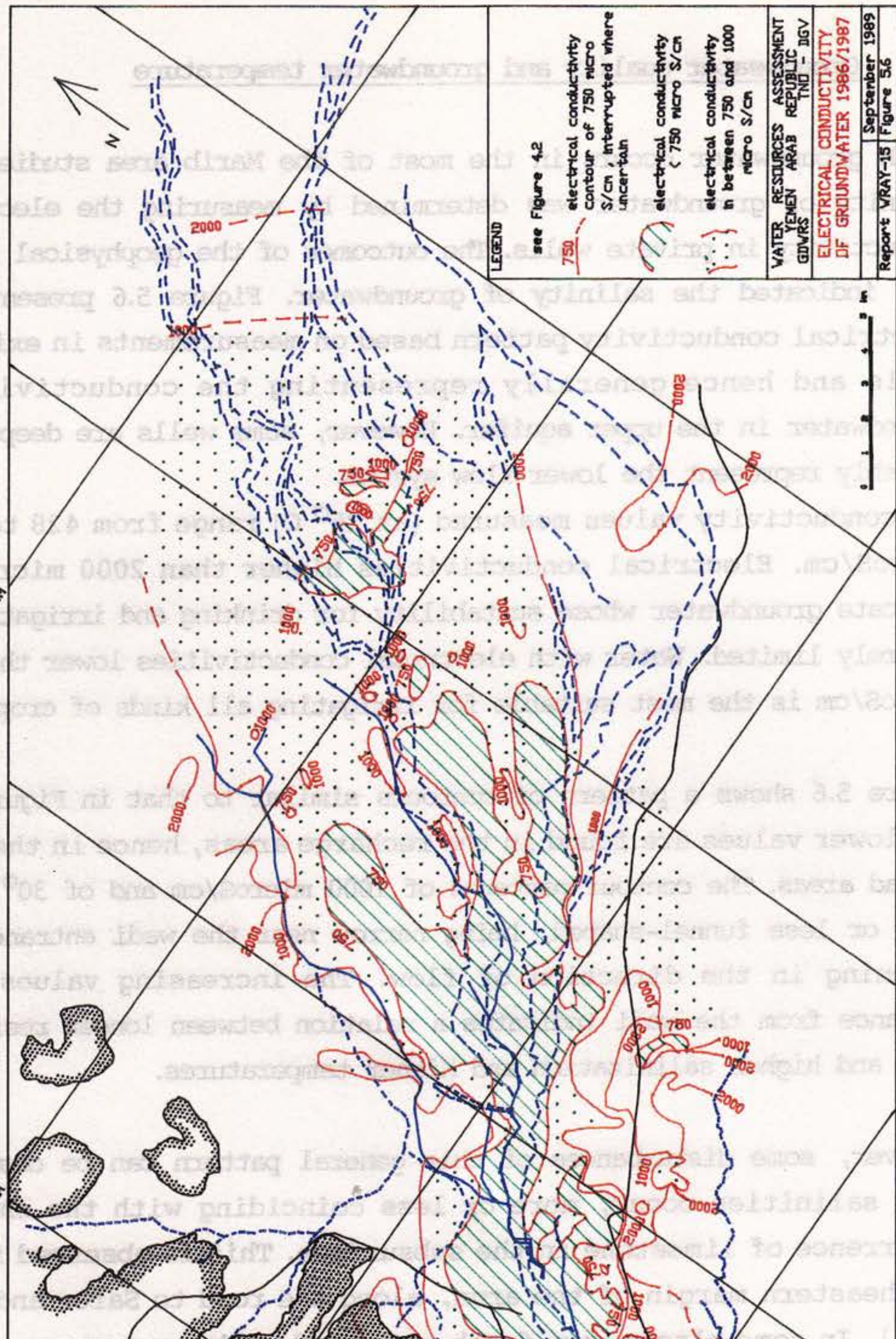
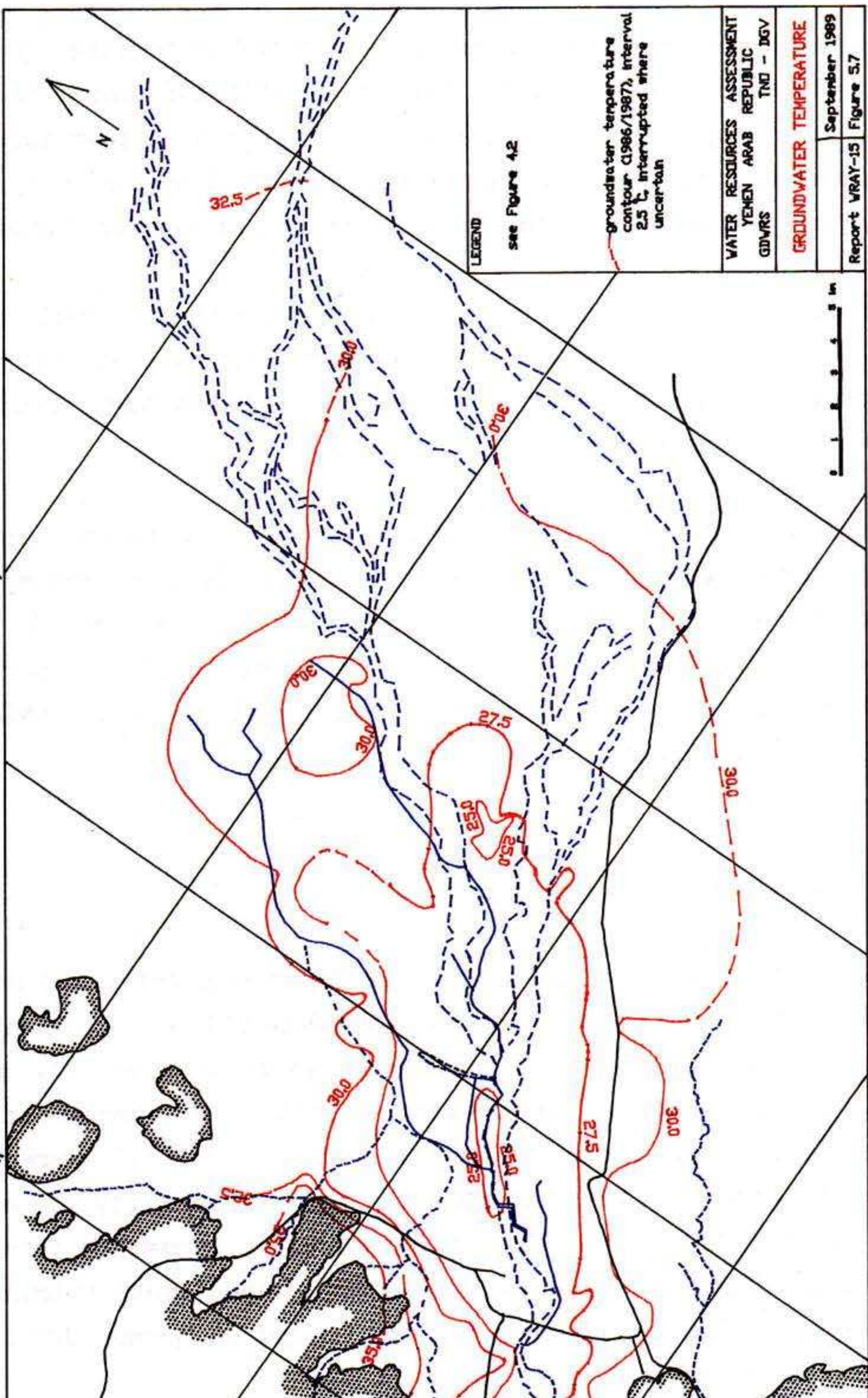

LEGEND
see Figure 4.2
750 electrical conductivity contour of 750 micro S/cm, interrupted where uncertain
electrical conductivity < 750 micro S/cm
electrical conductivity in between 750 and 1000 micro S/cm
WATER RESOURCES ASSESSMENT YEMEN ARAB REPUBLIC
GDWRS TNO - DGV
ELECTRICAL CONDUCTIVITY OF GROUNDWATER 1986/1987
Report WRAY-15
September 1989
Figure 5.6
N
1730 KM
1720 KM
1710 KM
1700 KM
1690 KM
560 KM
550 KM
540 KM
530 KM
520 KM

FIGURE 5.6



LEGEND
see Figure 4.2
groundwater temperature contour (1986/1987), interval 2.5 °C, interrupted where uncertain
WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
GDWRS TNO - DGV
GROUNDWATER TEMPERATURE
September 1989
Report WRAY-15
Figure 5.7
N
5 km
1730 KM
1720 KM
1710 KM
1700 KM
1690 KM
520 KM
530 KM
540 KM
550 KM
560 KM
32.5
30.0
27.5
25.0

FIGURE 5.7

The high salinities found in the area of new Marib probably have another cause. The water quality here is probably influenced by post volcanic activity. This is also indicated by the high temperatures, which sometimes exceed 35 ^{o}C. The narrow lobe of higher salinity 3 km west of old Marib, which coincides with higher temperatures, is noteworthy.
Salinities exceeding 2000 microS/cm were observed in some small areas in the northwestern and eastern margins of the survey area. A private well located in the northeast extremity of the Marib Basin abstracts water whose salinity exceeds 2000 microS/cm.

The results of the geophysical survey imply that at the margins of the study area the salinity increases surpassing 2000 microS/cm. The map derived from the geophysical survey is shown in Figure 5.8. This survey also revealed the presence of a layer of low electrical resistivity in the subsurface of the southwestern zone. This is probably attributable to clayey deposits.

5.5 Groundwater wells and abstraction

It is estimated that at the end of 1988 approximately 2360 wells (extrapolated from the well inventory of 1986-1987) were present in the Marib area. This means an enormous increase since the well inventory carried out by Electrowatt in 1977/1978, when about 500 wells were counted. During the last 3 years (1986-1988) more than 1000 wells were drilled (Figure 5.9). The availability of motor driven pumps, drilling rigs plus the government's increasing interest in the agricultural development of the Marib area, which culminated in the construction of the Marib Dam and Irrigation Scheme, led to an enormous boom in tubewell drilling.

Until the 1980s most wells were dug and only a few were drilled. Since 1980 most new wells have been drilled and the rate at which wells were dug has remained constant. An increasing number of dug wells have been deepened by drilling. In the 1980s the yields

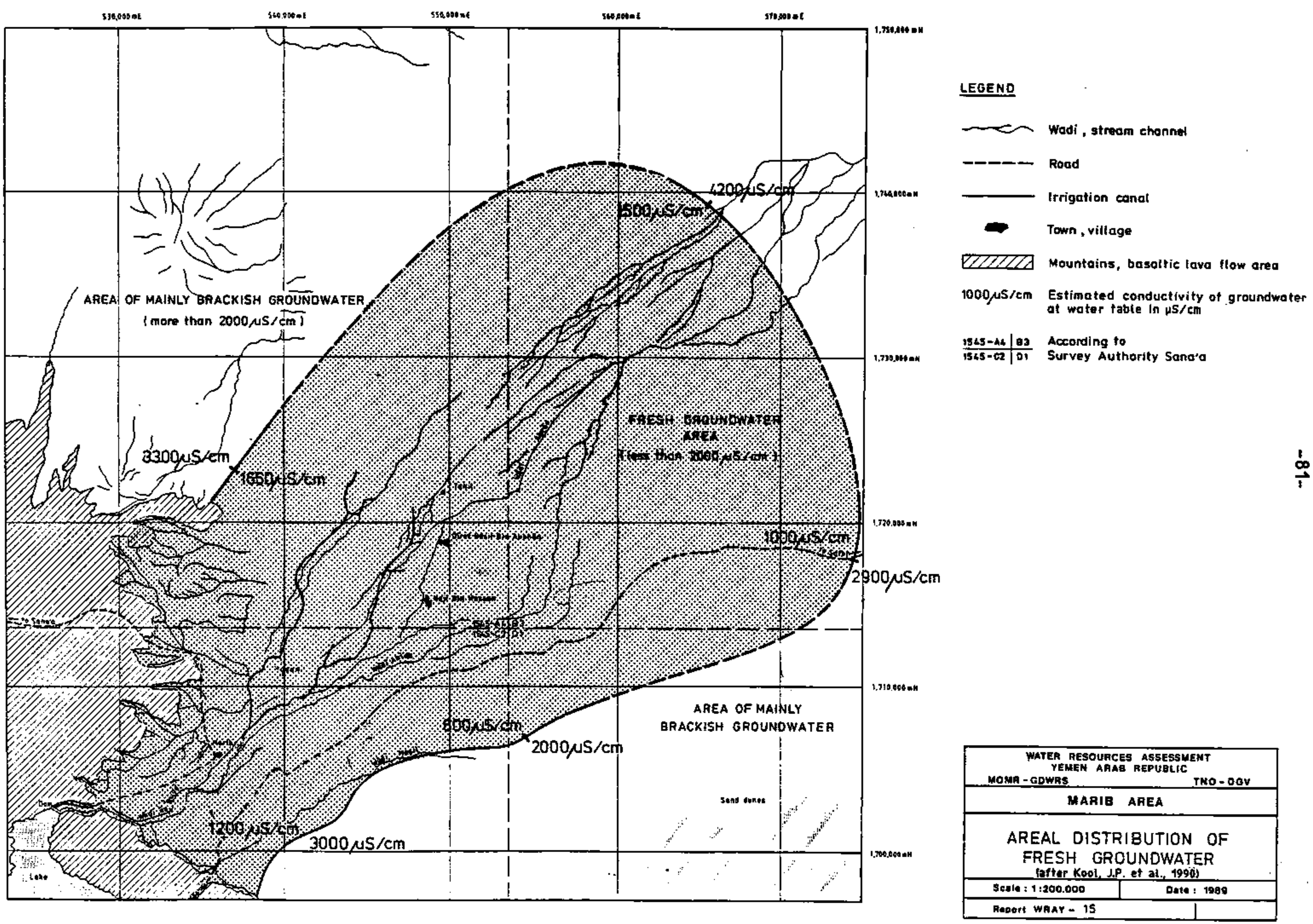

AREA OF MAINLY BRACKISH GROUNDWATER
(more than 2000 µS/cm)
FRESH GROUNDWATER AREA
(less than 2000 µS/cm)
AREA OF MAINLY BRACKISH GROUNDWATER
4200 µS/cm
1500 µS/cm
3300 µS/cm
1650 µS/cm
1000 µS/cm
2900 µS/cm
800 µS/cm
2000 µS/cm
1200 µS/cm
3000 µS/cm
Sand dunes
to Sana'a
Lake
LEGEND
Wadi , stream channel
Road
Irrigation canal
Town , village
Mountains, basaltic lava flow area
1000 µS/cm Estimated conductivity of groundwater at water table in µS/cm
1545-A4 B3 / 1545-C2 D1 According to Survey Authority Sana'a
WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
MOMR - GDWRS
TNO - DGV
MARIB AREA
AREAL DISTRIBUTION OF FRESH GROUNDWATER
(after Kool, J.P. et al., 1990)
Scale : 1:200.000
Date : 1989
Report WRAY - 15

FIGURE 5.8

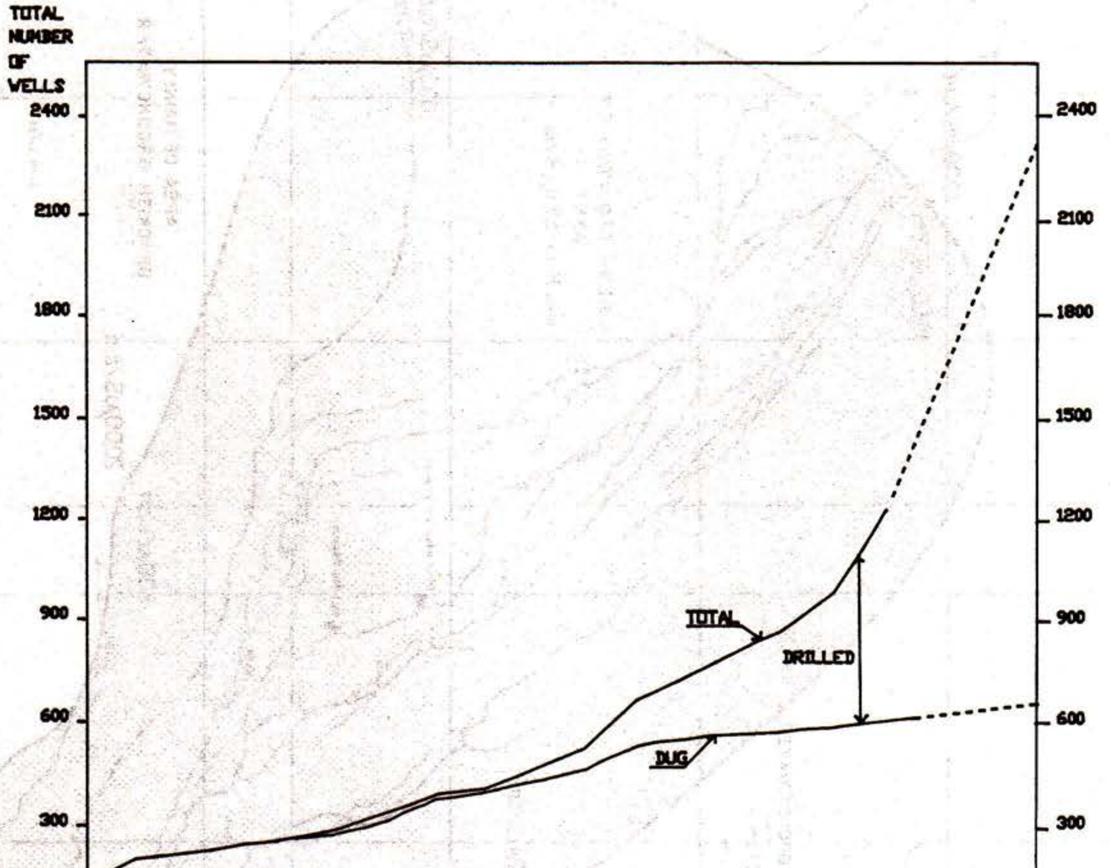


FIGURE 5.9
TOTAL NUMBER OF WELLS , 1970 - 1988

extracted from wells increased because pumps driven by diesel engine were installed. The average yield is estimated to be 16 l/sec.

It will be clear that total groundwater abstraction has increased enormously since about 1980. Electrowatt (1978) estimated annual abstraction to be 29 million m^3, delivered by about 400 wells yielding up to 10 l/sec. On the basis of the 1986/1987 well inventory the total abstraction in 1987 was estimated to be 136 million m^3. This means an increase of 470% in 9 years!

The distribution of the abstractions is shown in Figure 5.10. The average withdrawal is shown in mm. In 6 squares of 1 km^2 the abstraction exceeds 2000 mm (max. 2600 mm). The maximum abstraction rates are concentrated in the following areas: on the 1500- to 2500-year-old irrigation silts south and east of Marib, in or near the wadi spread areas, fingering out northeastwards where fine fertile fluvial sediments are found. In recent years the less fertile sandy grounds have also been brought into cultivation. If the distribution per km^2 is considered, the total abstraction appears to be distributed over 264 km^2, which results in an average abstraction rate of 520 mm. However, the actual cultivated area is much smaller, about 100 km^2, resulting in an average irrigation rate of 1360 mm per year.

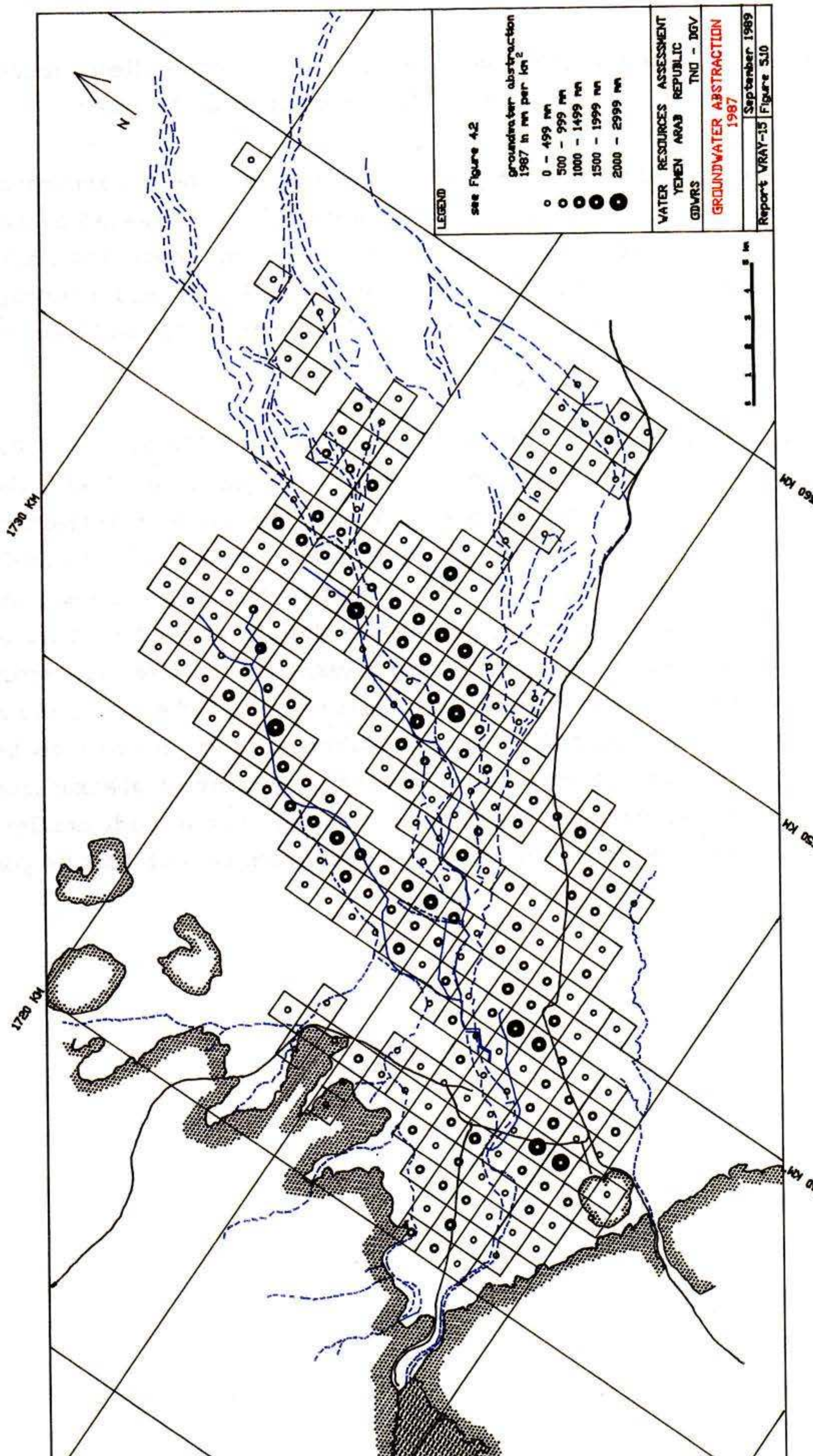

LEGEND
see Figure 4.2
groundwater abstraction 1987 in mm per km²
0 - 499 mm
500 - 999 mm
1000 - 1499 mm
1500 - 1999 mm
2000 - 2999 mm
WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
GDWRS
TNO - DGV
GROUNDWATER ABSTRACTION
1987
September 1989
Report WRAY-15
Figure 5.10
1730 KM
1720 KM
1710 KM
1700 KM
1690
560 KM
550 KM
540 KM
530 KM
520 KM

FIGURE 5.10

5.6 Groundwater recharge, storage and discharge

The general recharge, storage and discharge components relevant to the Marib groundwater reservoir are shown schematically in Figure 5.11. The approximate lateral boundaries of the system are given in Figure 5.12.

Recharge

The general recharge mechanism of the Marib-Jawf groundwater basin was described in paragraph 5.1. The Marib aquifer system is recharged in the following different ways:

a) by infiltration and subsequent percolation of streamflow through the wadi beds. This term is presented as RI in Figure 5.11.

Natural streamflow in the wadis occurs only for short periods, as storm runoff, during and immediately after rainstorms in the different catchments.

Since the completion of the Marib Dam, only a few minor wadis (with a total catchment of 1220 km^2) drain into the Marib plain. The total average annual runoff, including local runoff is estimated to be about 8 million m^3, see paragraph 4.2.3. Some of the storm runoff is diverted for spate irrigation and some recharges the groundwater. It is difficult to asses the groundwater recharge from this source; however rapid infiltration was observed in the field and it is assumed that about 50% or about 4 million m^3 recharges the groundwater reservoir annually.

The principal recharge source used to be the streamflow in the Wadi As Sudd and its eastern extensions, the Wadis Abrad and Abida.
Since the beginning of 1986 the storm floods , generated during the rainy season in the catchment of the Wadi Adhanah have been captured behind the Marib Dam. Hence the Marib Groundwater Basin has been deprived of its main natural source of recharge. Recharge now depends mainly on how much water is released through the gate of the dam.

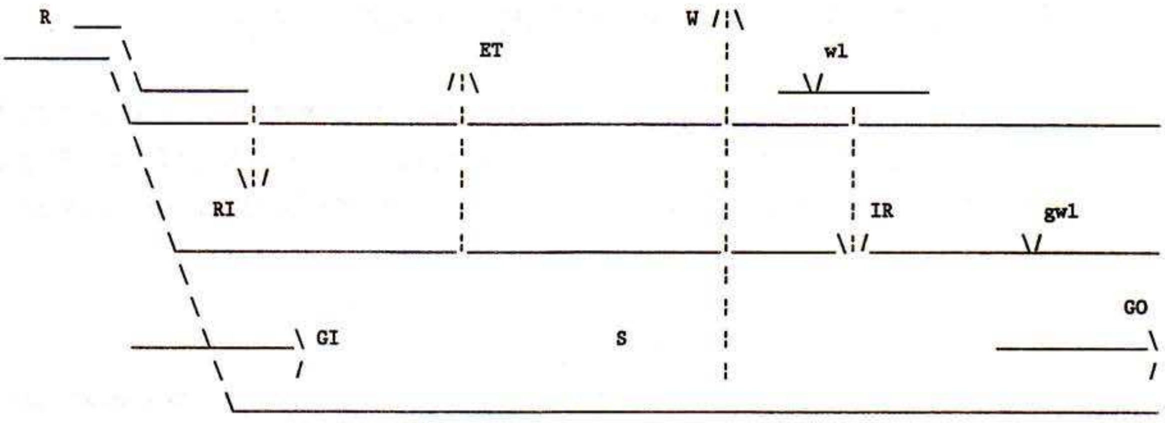


FIGURE 5.11

WATER BUDGET COMPONENTS OF THE SCHEMATIC MARIB GROUNDWATER BASIN

The groundwater balance equation is as follows:

$$RI + GI + IR = \Delta S + W + GO,$$ where

- R - surface runoff (flow released from reservoir)
- RI - surface runoff infiltration (and percolation) to groundwater
- GI - groundwater inflow.
- IR -irrigation return flow (to groundwater)
- ΔS - increase of groundwater storage.
- W - groundwater abstraction by wells.
- GO - groundwater outflow
- ET - evapotranspiration from groundwater.
- wl - water level
- gwl - groundwater level

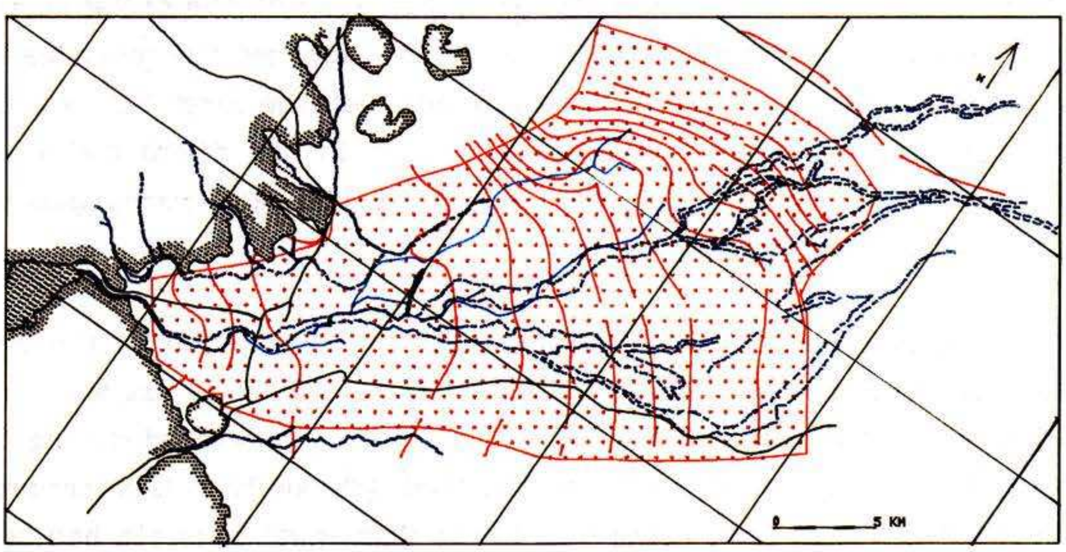


FIGURE 5.12

AREA CONSIDERED FOR GROUNDWATER BALANCE CALCULATIONS

Consequently, it depends on the operation of the dam and the reservoir. During the period of the present WRAY investigations the irrigation works were still under construction and the operation of the gate during this period was mainly intended to recharge the groundwater reservoir, to keep the remaining storage capacity of the reservoir high (water levels low) and to test the two diversion constructions in the Wadi As Sudd, respectively 10 km and 14.5 km downstream of the dam.

Because of the high infiltration capacity of the wadi beds upstream of the diversion structures, almost all the water released will infiltrate. It is estimated that the evaporation from the water surface between the dam and the diversion structures and the storage in the unsaturated zone below the wadi beds (groundwater levels rise close to the wadi bed) is only 3% of the released flow. Consequently, it is assumed that 97% of the total quantity of water released during the period 1986 to 1988 has recharged the groundwater reservoir. This means that the total recharge has included an amount of about 119 million m^3.

Before the dam was built flood water was transported over considerably longer distances and larger surfaces. Water remained standing on soils consisting of fine sediments, with low infiltration capacities. Consequently, losses resulting from evaporation and storage in the unsaturated zone must have been much higher. As well, floodwater was diverted for spate irrigation; according to Schoch (1978) an average area of 2000 ha would have produced one crop a year (estimation from the aerial photographs of 1973).

An indication of the amount of recharge from the wadi streamflow for the pre-1970 situation can be obtained by balancing the components of the groundwater budget. The budget has been assessed, assuming no change in storage, groundwater abstraction by wells is 1 million m^3 and assuming groundwater outflow to be equal to what it is at present. Then the total recharge of groundwater from surface runoff would be around 49 million m^3 if return flow from the spate irrigated area is assumed to be about 12 million m^3.

b) by infiltration and percolation of irrigation water (IR), through the bottom of the irrigation canals and ditches and through the irrigated soils. Locally where the soils are very sandy these irrigation losses could be considerable. The exact amount is very difficult to measure. A very rough estimate of the amount involved under the conditions met in 1987 is 30% of the total groundwater extraction plus spate irrigation, hence about 42 million m^3.

c) by infiltration and subsequent percolation of local rainfall It is assumed that these rainfalls can easily be stored in the unsaturated zone and then evaporate. Recharge could take place only where local rainfall is collected in wadis or depressions. This was considered in a) above.

d) by groundwater inflow, GI in Figure 5.11. This probably only occurs in the west through the wadi fill of Wadi As Sudd and through cracks and fissures of the rocky (limestone) boundaries. When the gate in the dam is closed the subsurface flow component will be equal to the leakage through the dam and subsurface flow under and around the dam site. The losses are related to the water level in the reservoir. According to Electrowatt (1978) the leakage is lower than expected; it is now assumed to be 30 l/sec (about 1 million m^3 per year). The total volume of subsurface inflow (including leakage) will probably be higher. Its magnitude is indicated by the volume defined as 'losses' (8.1 million m^3) in the water budget of the Marib Reservoir (paragraph 4.2.1). It is provisionally assumed that a volume of 3 million m^3 per year comprises the subsurface flow component into the Marib groundwater reservoir.

Adding up the different recharge components mentioned above, gives a total recharge of groundwater during the last three years (1986-1988) of approximately 266 million m^3.

Discharge

Natural groundwater outflow (GO in Figure 5.11) and artificial groundwater withdrawal by wells (W) are the principal outflow components. The following discharge components are involved:

a) **The groundwater withdrawal by wells** increased from about 29 million m^3 per year in 1978 to 136 million m^3 per year in 1987. The installation of tubewells is still continuing, consequently the groundwater withdrawal is a strongly increasing component.

b) **The natural groundwater outflow** can roughly be estimated with the help of the observed groundwater flow gradient and the measured transmissivities. The amount involved is approximately 60 million m^3 per year. Any change (decrease) in natural groundwater outflow will be very slow. The present amount is the response to impulses (recharge and discharge components) on the groundwater flow system in the preceding ten to hundred years.

c) **Direct evapotranspiration** (ET) from the groundwater storage only occurs when the water table is close enough to the ground surface. This is only the case in certain places in the wadi beds, during and after periods of high recharge and just downstream of the dam. Evaporation from the vegetation just downstream of the dam (0.6 km^2) is estimated to be 1.5 million m^3 per year; the other amounts are thought to be negligible.

The values mentioned above result in a total discharge of 592 million m^3 for the period 1986-1988. Because of the continuing rapid development of the Marib area coupled with the installation of new tube wells this figure is expected to rise, at least until the irrigation works become operational.

Storage

The reduction in groundwater storage during the observation period 1986-1988 equals recharge minus discharge, and is circa 326 million m^3, indicating a depletion of the reservoir. This depletion is confirmed by the declining groundwater levels observed.

It is estimated that, very roughly a total volume of 40 10^9 m^3 of fresh groundwater is stored in the Marib aquifer system. Taking into account the clayey and silt layers, probably around 10 10^9 m^3 can potentially be extracted by pumping, which means that only the most permeable parts of the total active fresh groundwater zones can be considered as zones with potential for groundwater extraction. The extractable volume is approximately 90 times the present (1987) annual depletion of groundwater. For this estimation an area of approximately 800 10^6 m^2 was considered, which is conservative compared with the fresh groundwater zone of about 1100 10^6 m^2 delineated by the results of the geophysical survey. Within the zone where fresh groundwater occurs down to great depths (paragraph 5.2), the lower boundary was taken to be 500m above m.s.l. (circa 550 to 600m below surface). Within the Central Alif Basin a 200 m thick waterbearing layer was assumed.

5.7 Groundwater in the Wadi Adhanah catchment area

The total catchment comprises 11500 km^2 and was too large to be investigated in detail within the limits of time, personnel and budget available. The survey concentrated on the hydrological regime of the catchment in relation to the water resources available in the priority zone, the Marib area. The potential groundwater zones in the catchment will be outlined briefly below.

The Wadi Adhanah catchment area comprises (going downstream) the following distinct zones:
- The intermontane Central Highland plains of Mabar, Dhamar and Rada. These plains with internal drainage systems are considered to be runoff-absorbing zones. It is estimated that they cover about 3300 km^2, leaving 8200 km^2 available for producing runoff (Figure 5.13). The following aquifer units are distinguished : alluvium, volcanic rocks and sandstones. In general the groundwater basins are

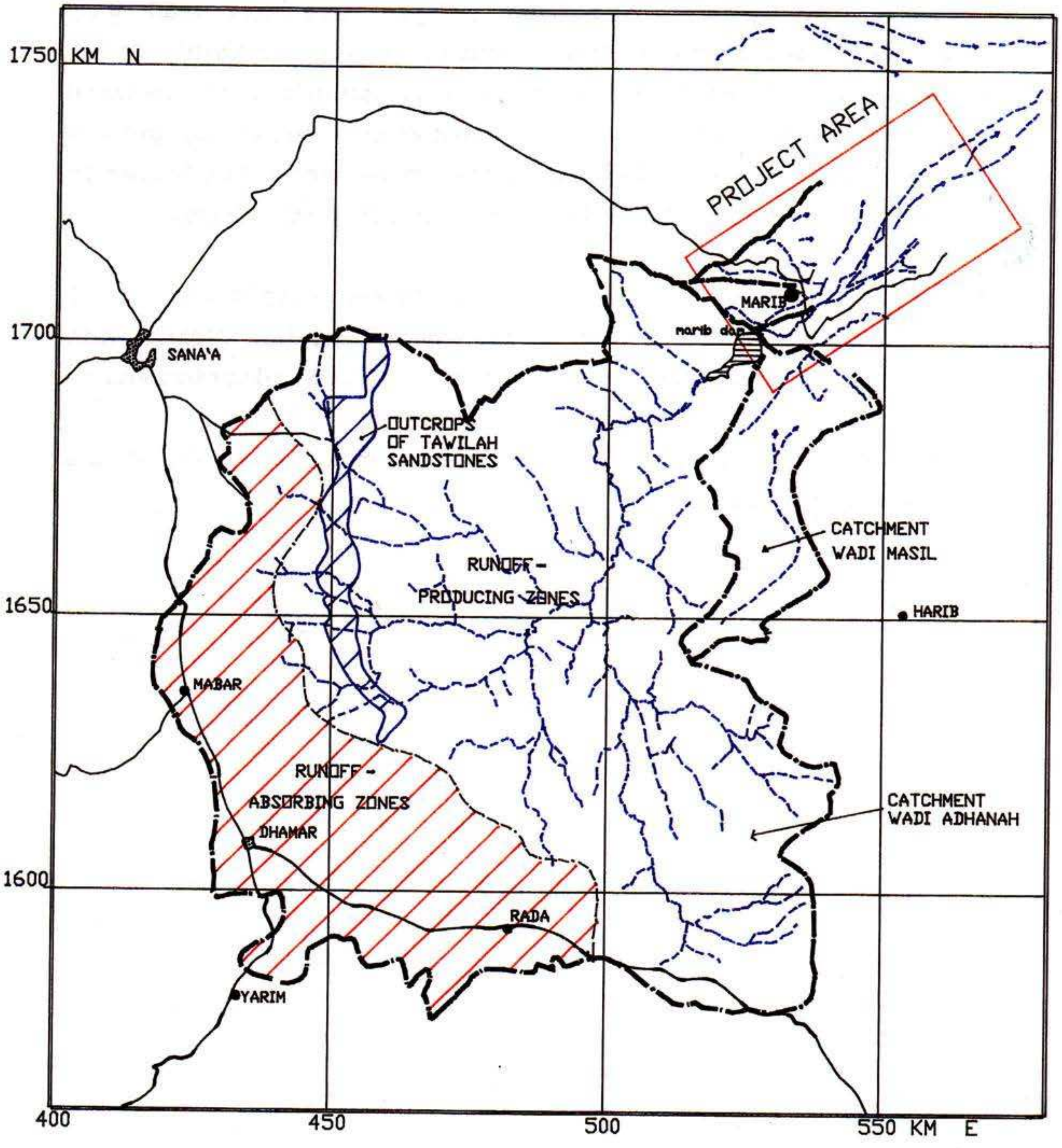


FIGURE 5.13

LOCATION OF THE RUNOFF-ABSORBING ZONE, RUNOFF-PRODUCING ZONE AND THE OUTCROPS OF TAWILAH SANDSTONES relatively heavily pumped to sustain a considerable population in practising irrigated agriculture. Varies studies have been and are carried out by other projects (some are still in progress).

- A large, sparsely inhabited northeast sloping area predominantly of metamorphic basement rocks. Groundwater occurrence is mainly local; in small alluvial basins and in valley fill deposits , in fractured and/or weathered zones and in the extensive wadi bed sands, gravels and boulders of the Wadi Adhanah further downstream. The latter is locally pumped to irrigate fields in or near the wadi valley.

In the runoff-producing area a belt of approximately 370 km^2 of Tawilah Sandstone outcrops east of the Central Highland plains. This aquifer unit is recharged by infiltration of precipitation and by storm floods through the wadi beds.

A detailed study needs to be made of this area, to establish the groundwater potential.

6. WATER RESOURCES DEVELOPMENT AND MANAGEMENT

6.1. General Remarks

The urgent need for a controlled development of the water resources in the Marib area is closely connected with the rapid economic and infrastructural development of the area. The rapid expansion of agriculture based on groundwater irrigation , the impact of the Marib Dam on the availability of water resources and the future implementation of the Marib Scheme are the main elements to be considered in a water resources development plan.

Even before work on the construction of the Marib Dam started, the area irrigated with groundwater was increasing rapidly because of the introduction of drilled wells and diesel-driven pumps. These developments freed farmers from having to choose areas to irrigate in accordance with the spates.

The completion of the Marib Dam in 1986 temporarely made irrigation almost completely dependent on groundwater. This led to a boom in drilling new wells. Some were privately financed, but farmers deprived of spate irrigation were also given grants to drill wells. The present situation of groundwater-dependent irrigation is expected to change gradually as the secondary canals of the Marib Dam and Irrigation Project, which are now under construction, are completed.

The operation and maintenance of the Marib Dam and Irrigation Distribution System (referred to as the Marib Scheme) will be the responsibility of the recently established Eastern Region Agricultural Development Authority (ERADA) of the Ministry of Agriculture and Fisheries. The operation of the Marib Dam and the main canals was handed over to ERADA back in December 1987.
Agricultural development and the implementation of the Marib Scheme are supported by the ERADP, the Eastern Region Agricultural Development Project, co-financed by the Yemen Arab Republic and IDA,

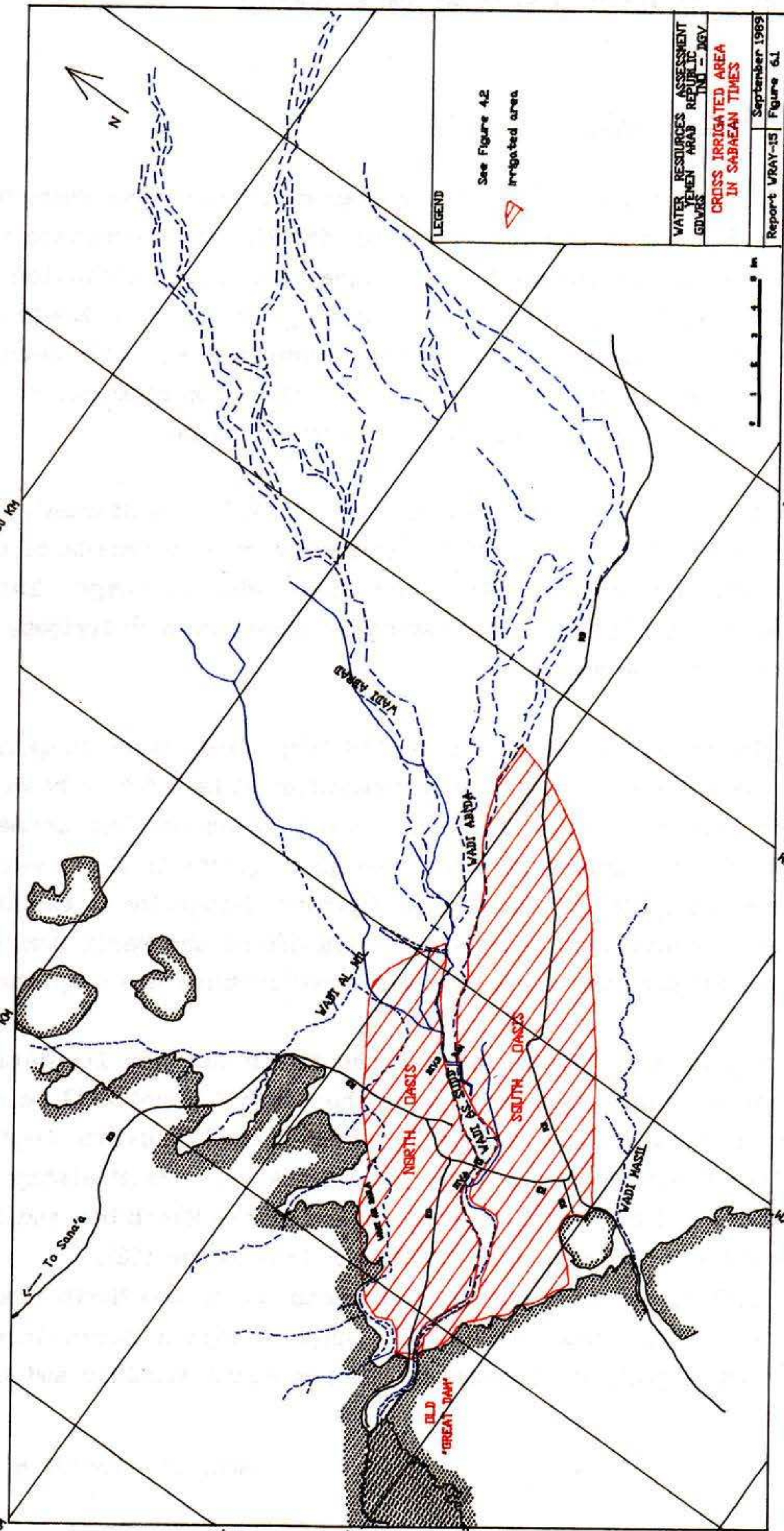

WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
GDWRS TNO - DGV
CROSS IRRIGATED AREA
IN SABAEAN TIMES
September 1989
Report WRAY-15
Figure 6.1
LEGEND
See Figure 4.2
Irrigated area
N
NORTH OASIS
SOUTH OASIS
WADI ABIDA
OLD "GREAT DAM"
To Sana'a
1710 KM
1720 KM
1730 KM
1700 KM
1690 KM
530 KM
540 KM
550 KM
560 KM
520 KM

FIGURE 6.1

the International Development Association under the guidance of the World Bank.

Implementing any water resources management plan in the Marib area is likely to be difficult, because of the special social circumstances. The relations between the different tribal communities in the area and between the tribes and governmental authorities are still subject to tensions and conflicts. Furthermore, the allocation of surface water resources was previously strictly ruled by Islamic law. New water resources development plans need to have strong local support before they can be implemented.

6.2. Surface water development

6.2.1 History

"The Great Dam" (Brunner, 1985)
The present situation, in which the streamflow of the Wadi Adhanah is controlled by a dam is not new. Three km downstream of the new dam, on the right and left banks, the remains of an old dam which was destroyed approximately 1350 years ago are found. This "Great Dam" was built in Sabaean times (approximately 500 B.C.). It lasted for more than a millenium and was rebuilt several times before finally collapsing at the beginning of the seventh century A.D.

The initial storage capacity was about 55 million m^3. Rapid silting up was probably avoided by handling the "sails" (floods) directly with limited retention, making use of big outlets on both sides of the dam. The Great Dam can probably better be considered as a diversion and spate braker rather than as a storage dam. Its main purpose was to raise the water to such a level that it could flow into distant fields. The gross irrigated area was around 9600 ha (Figure 6.1), moreover it is likely that spate irrigation was applied below the oasis.

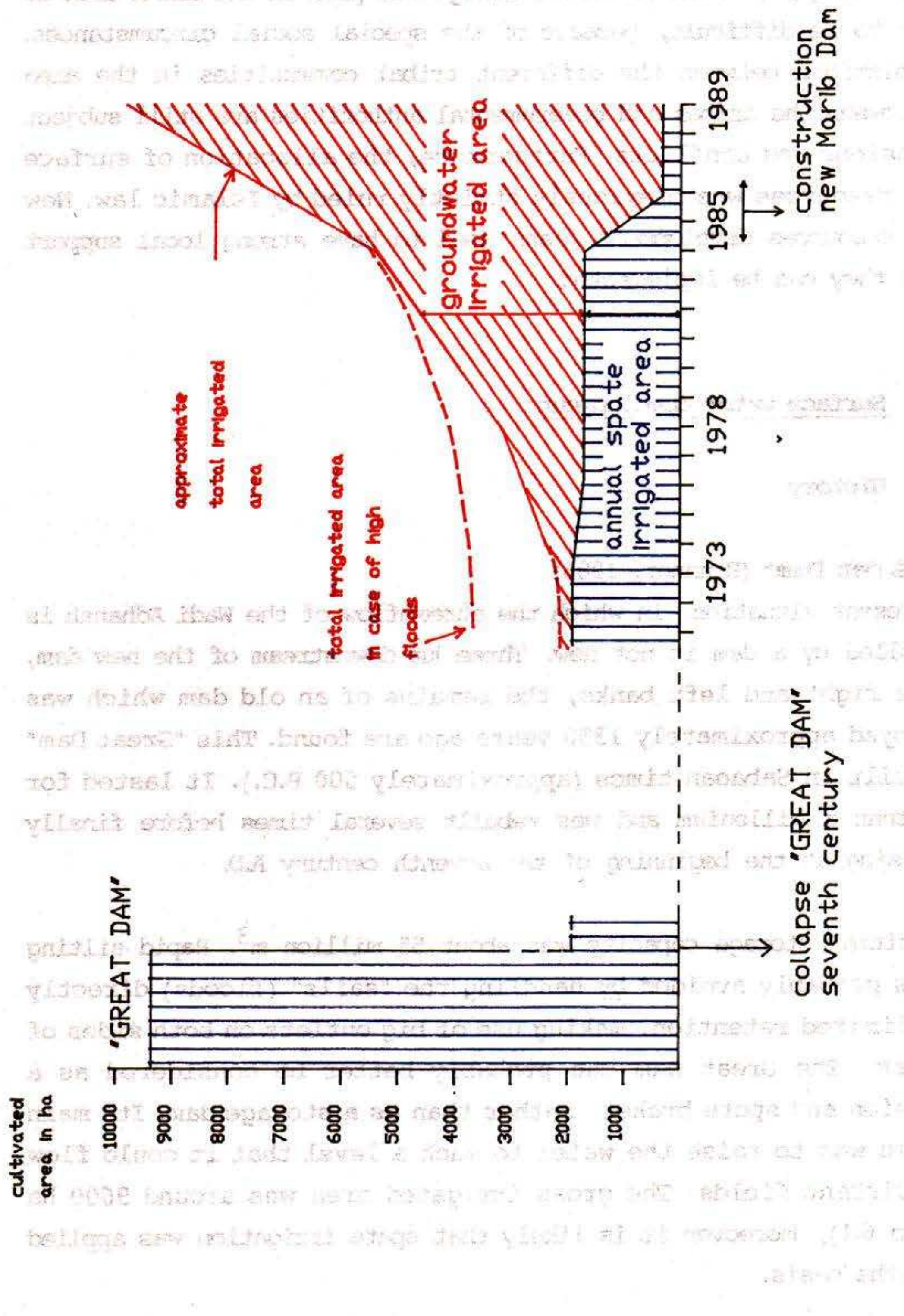


FIGURE 6.2
DEVELOPMENT OF GROUNDWATER AND SPATE IRRIGATED AREA

Before construction of the new Marib Dam

For hundreds of years after the collapse of the "Great Dam" until the 1970s spate irrigation was mainly applied downstream of the high areas of the ancient oasis.

From the aerial photographs taken in 1973 it was estimated that the overall spate irrigated area was 3900 ha, of which about 2000 ha produced one crop every year (Schoch, 1978). The WRAY project interpretation is shown in Figure 6.3. According to this interpretation the cultivated area was approximately 2500 ha.

In the 1970s groundwater pumps driven by diesel engines were introduced. This, together with the increasing use of cable tool drilling rigs in the 1980s in a rapid increase of groundwater irrigation (Figure 6.2). According to Electrowatt the total irrigated area in 1977/78 (3300 ha) did not differ much from the situation in 1973. However, it was estimated that half of the amount of water used for irrigation was abstracted from groundwater by means of wells; the remainder was obtained from spates (29 million m^3). It is assumed that until the construction of the Marib Dam the spate irrigated area remained approximately the same (Figure 6.2).

From 1986 until implementation of the Marib Scheme

(present situation)

All runoff from the Wadi Adhanah is retained by the newly constructed Marib Dam. The average annual inflow into the lake was about 104 million m^3 during the period 1986-1988. During the construction of the irrigation works water is released mainly to recharge the groundwater reservoir. From the beginning of 1986 until 1988 122.5 million m^3 had been released. Little surface runoff occurs, generated by the scarce rainfall on the remaining catchments and on the Marib plain itself. Locally it is captured and diverted for spate irrigation. The amounts involved are very small compared with the present groundwater development. Consequently, until the Marib Scheme is implemented, irrigation will depend almost fully on groundwater. The total cultivated area in February 1989 was circa 10000 ha (Figures 6.2 and 6.4).

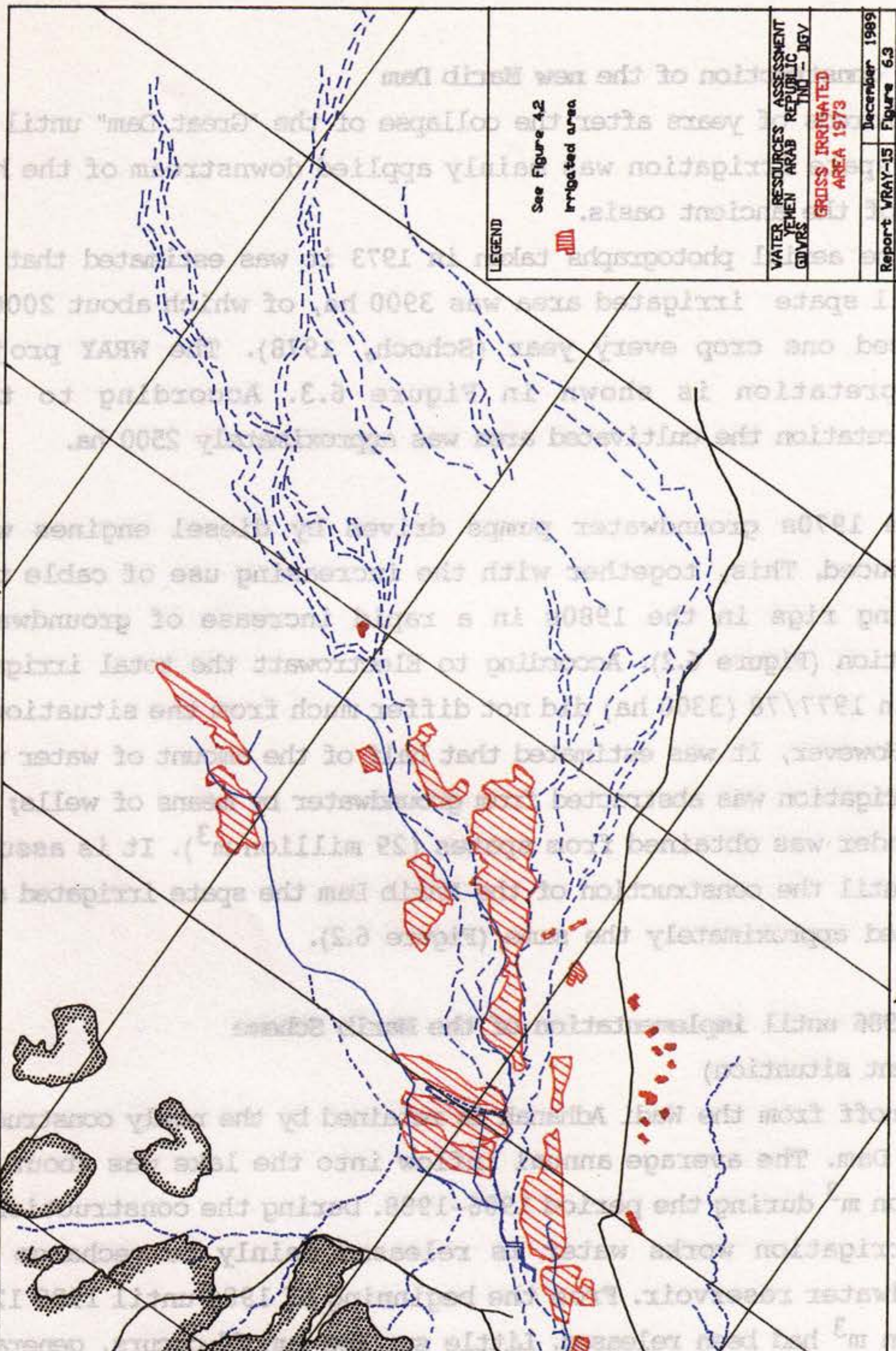

LEGEND
See Figure 4.2
Irrigated area
WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
GDVRS TNO - DGV
GROSS IRRIGATED AREA 1973
December 1989
Report WRAY-15
Figure 6.3

FIGURE 6.3

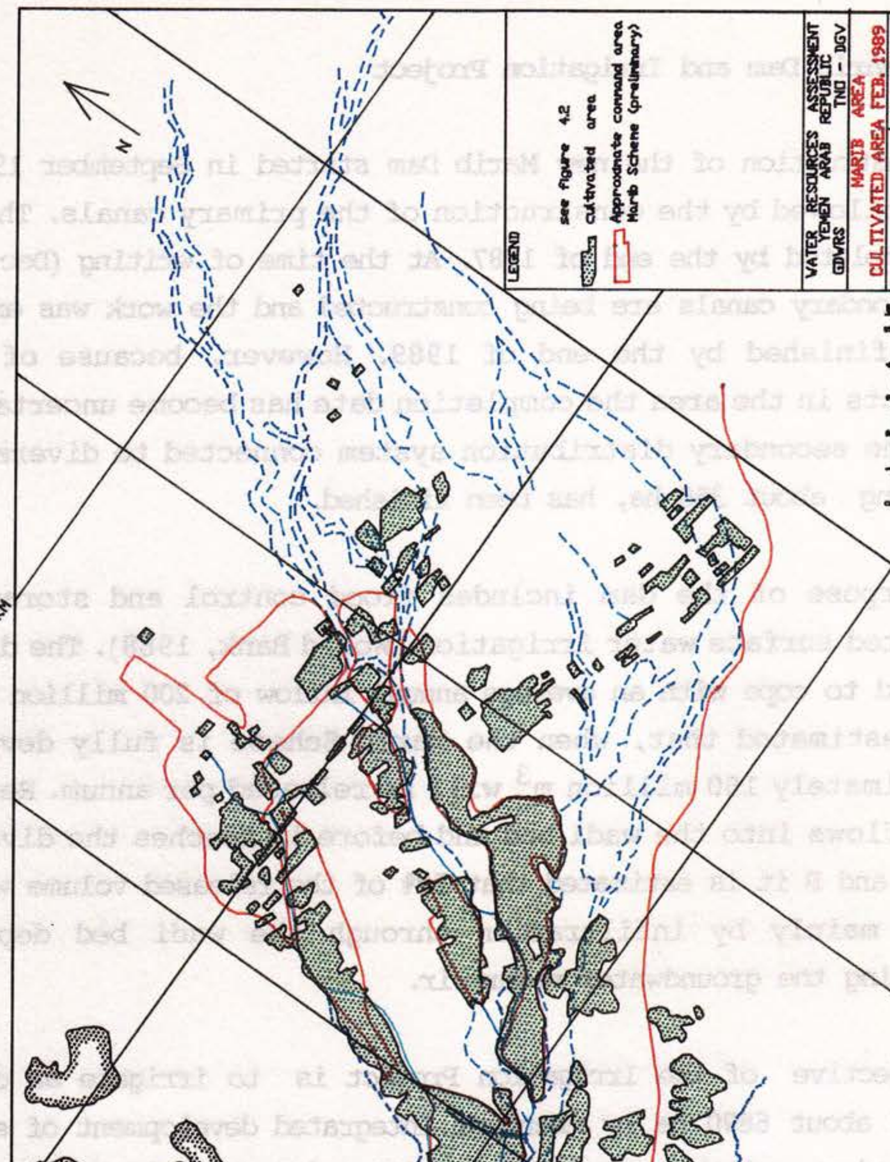

LEGEND
see figure 4.2
cultivated area
Approximate command area Marib Scheme (preliminary)
WATER RESOURCES ASSESSMENT
YEMEN ARAB REPUBLIC
GDWRS TNO - DGV
MARIB AREA
CULTIVATED AREA FEB.1989
June 1989
Report WRAY - 15
FIGURE 6.4
N
1730 KM
1720 KM
1710 KM
1700 KM
1690 KM
560 KM
550 KM
540 KM
530 KM
520 KM

FIGURE 6.4

6.2.2 Marib Dam and Irrigation Project

The construction of the new Marib Dam started in September 1984 and was followed by the construction of the primary canals. The work was completed by the end of 1987. At the time of writing (Dec. 1989) the secondary canals are being constructed and the work was expected to be finished by the end of 1989. However, because of local conflicts in the area the completion date has become uncertain and only the secondary distribution system connected to diversion A, supplying about 350 ha, has been finished.

The purpose of the dam includes flood control and storage for regulated surface water irrigation (World Bank, 1988). The dam was designed to cope with an average annual inflow of 200 million m^3 and it is estimated that, when the Marib Scheme is fully developed approximately 150 million m^3 will be released per annum. Released water flows into the wadi bed and before it reaches the diversion dams A and B it is estimated that 50% of the released volume will be "lost" mainly by infiltration through the wadi bed deposits, recharging the groundwater reservoir.

The objective of the Irrigation Project is to irrigate an overall area of about 6890 ha by means of integrated development of surface water and groundwater (World Bank, 1988 and Dogus information note). The command area of the Marib Scheme is shown in Figure 6.5. Groundwater development would benefit from the improved recharge resulting from perennial flows in the wadi bed and irrigation channels (Electrowatt 1978).
The total baseline surface water demand for the proposed cropping pattern is 164 million m^3, including the water demand of a small area outside the command area of the Marib Scheme (World Bank, 1988). After field efficiencies of irrigation are improved via the ERADP project, the total gross water requirements will be 122 million m^3; 70 million m^3 from surface water and 52 million m^3 from groundwater (including 15.5 million m^3 for irrigating the cultivated area outside the Marib Scheme command area).

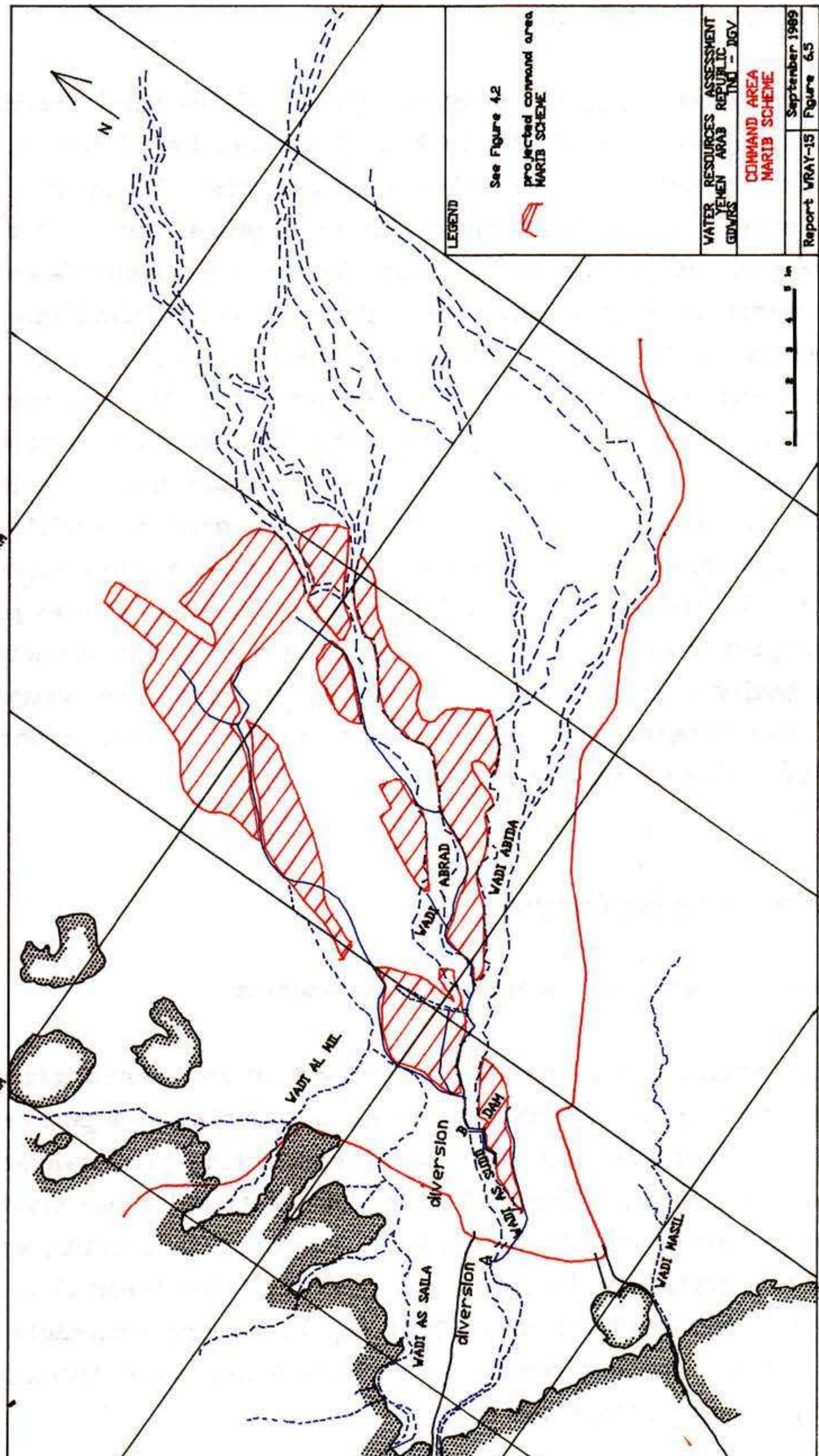

LEGEND
See Figure 4.2
projected command area MARIB SCHEME
WATER RESOURCES ASSESSMENT YEMEN ARAB REPUBLIC GDWRS TNO - DGV
COMMAND AREA MARIB SCHEME
September 1989
Report WRAY-15
Figure 6.5
WADI ABRAD
WADI ABIDA
WADI AL MIL
WADI AS SAILA
WADI AS SUDD
WADI MASIL
DAM
diversion
diversion
1730 KM
1720 KM
1710 KM
1700 KM
1690 KM
560 KM
550 KM
540 KM
530 KM
520 KM

FIGURE 6.5

6.2.3 Sediment Accumulation

The average reduction in the storage capacity of the Marib Reservoir observed during the period 1986-1988 (with several low floods and one medium flood) was only 1.5 million m^3 per year. Based on these figures, storage capacity reduction (15% in 40 years) would not be an immediate problem. However, tremendous amounts of sediments deposited in the valleys of Wadi Adhanah are waiting to be funnelled into the Marib Reservoir. One high flood (assumed sediment load 5% to 14%) could transport an enormous amount of sediment into the reservoir and considerably reduce the storage capacity. An attempt was made to simulate certain scenarios, using different frequencies of occurrence of medium and high floods. The resulting storage reductions within 30 years varied from 15% to 38%. However, the actual accumulation of sediments will also depend on how effectively flushing can take place at high capacity via the outlet. This is the most effective way of reducing sediment accumulation. Flushing is probably also needed to prevent the intake being covered with sediments (the greatest accumulation is near the intake).

6.3 Groundwater development

6.3.1 Areas suitable for groundwater abstraction

Areas with potential for groundwater abstraction are characterized by the presence of a groundwater reservoir consisting of a permeable rock matrix of sufficient thickness, containing groundwater of acceptable quality. In Figure 5.6 shows the electrical conductivities of the exploited part of the aquifer. The most favourable water quality is characterized by electrical conductivities lower than 1000 micro S/cm. Conductivities up to 2000 micro S/cm are acceptable for certain crops, whereas above 2000 micro S/cm, application for irrigation is very restricted.

Paragraph 5.2 described the aquifer system in the Marib plain area.

An "upper" and a "lower" aquifer are distinguished and their occurrence may be described by dividing the area into three zones: a southwestern, a central and a northeastern zone (see Figures 5.2 and 5.3). The same zonal subdivision was followed below when assessing groundwater abstraction potential.

Southwestern zone

In the southwestern zone one aquifer system ("upper + lower") has been distinguished. The permeable upper part (15 to 30 m) of the saturated zone is heavily exploited at present. The groundwater transmitting formations consist of coarse alluvial sediments overlying much less permeable clayey deposits. In general, wells with a depth between 50 and 75m are deep enough to exploit this zone of the aquifer. Laterally the exploitable upper zone of the aquifer is determined by the water quality (Figure 5.6). In the southern part the lateral extent of the suitable aquifer is about 6km, widening northeastwards.

The lower part ("lower" aquifer) of the aquifer system in the southwestern zone seems to become promising northeastwards. The top of this system has been explored by drilling (WRAY-9) and a very good permeable rock matrix has been encountered. The thickness of the aquifer could not be verified by drilling, but according to the geophysical survey the aquifer could be several hundreds of mets thick. It is not known whether the deepest part is sufficiently permeable for exploitation Indications about the lateral extent of the lower zone of the aquifer have been obtained from the geoelectrical survey and are shown in Figure 5.3. The wells for the exploitation of the lower zone of the aquifer should be at least 200m deep.

Central zone

In the central zone an "upper" and a "lower" aquifer are distinguished. They are the northeast extensions of the abovementioned upper and lower parts of the "single" aquifer system distinguished in the southwestern zone (Figure 5.2).

The "upper" aquifer is heavily exploited in the central zone too; the total saturated thickness increases northeastwards from about 50 to 200 m, as does the depth to the water table (from about 20 to 60 m). According to the findings of the WRAY exploratory drillings, only the upper 15 to 30 m of the saturated zone forms the most permeable part of the aquifer from which groundwater can be extracted. It is assumed that wells that are between 50 and 100 m deep are deep enough to exploit the most promising part of this aquifer.

The "lower" aquifer is assumed to be present under the Azal Formation (Figure 5.2). Very little is known of this aquifer; the interpretations of the geophysical investigations suggest that it will be in the southwestern part of the central zone promising at least. However, to reach this aquifer the hard Azal shale layer with an interpreted thickness of about 200 m will have to be penetrated and the total depth of wells will have to be up to 400 m.

Northeastern zone

In the northeastern zone, which is located in the Central Alif Basin, only the "upper" aquifer has groundwater abstraction potential. It consists of a thick sequence of semi-cemented sandstone layers of the Unnamed Unit (Figure 5.2). The total thickness of this unit is considerable, up to about 1000 m in the centre of the basin, however the lower sections of the Unnamed Unit are probably much more argillaceous and aquifer potential is doubtful.

Exploratory borehole WRAY-7 penetrated only the top of the formation, encountering a waterbearing layer approximately 160m thick, The lowest section drilled was very argillaceous between 300and 330m below surface. The present water table is encountered at 135 to 140m below surface. This means that boreholes down to a depth of at least 200m are necessary to extract groundwater.

The lateral extent and the gross volume of this reservoir might be considerable compared with the aquifers in the southwestern and central zones. The exact exploitable part is difficult to assess;

moreover, the water table is considerably lower than in the rest of the area, which makes extraction of groundwater much more expensive.

6.3.2 Function, extent and development of groundwater use

The total water demand is almost completely determined by the irrigation needs for agriculture and is at present almost fully fulfilled by abstraction of groundwater. Groundwater is also abstracted for domestic use; however, the quantities involved are negligible compared with the demand for irrigation water.

The gross irrigated area (derived from the aerial survey in Febr/March 1989) is approximately 10000 ha (see Figure 6.3). In 1973 the groundwater abstraction was still very low. Spate irrigation was the principal method applied to water the fields. In 1977/78 Electrowatt estimated the amount of groundwater abstraction at 29 million m^3/year. After the construction of the Marib Dam, the groundwater abstraction rate was estimated to be 136 million m^3/year in 1987, an average increase of 22 million m^3/year since 1985 (see also Figure 6.2).

6.3.3 Consequences of increasing groundwater development

Groundwater levels have generally declined since the construction of the Marib Dam. Without recharge from the Wadi Adhanah the average annual decline observed within the cultivated area was approximately 1.5 m. After water was released from the dam, the water levels near diversions A and B rose considerably, while beyond this area the levels are continuing to fall. The decline is not observed in the northeastern zone where extractions of groundwater are still limited.

The increasing agricultural development means that as long as the Marib Scheme is not implemented, the demand for groundwater will continue to rise and groundwater levels will continue to fall. Even after implementation of the Marib Scheme the groundwater levels will continue to decline (depletion of groundwater storage) under the present agricultural demand for water.

Continuing falling groundwater levels will result in the exhaustion of the intensively exploited highly permeable upper layers of the upper aquifer in the southwestern and central zones. Given the present water demand this may be expected to occur within 20 to 40 years.

The exhaustion of the abovementioned aquifer system will finally result in decreasing the flow of groundwater northeastwards into the northeastern zone.

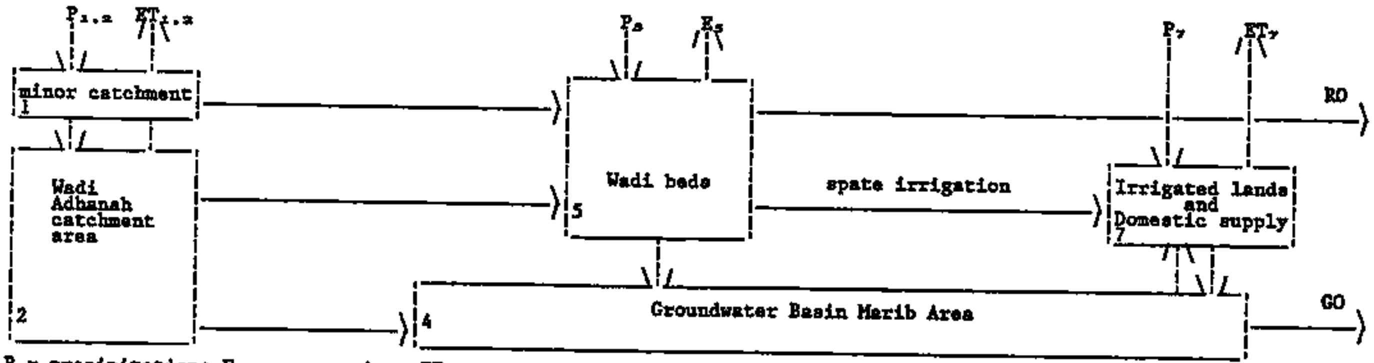
Near the boundaries of the fresh water zone, declining groundwater levels could result in lateral inflow of brackish water, which will hamper extraction for irrigation.

6.4 Integrated regional water resources management

6.4.1. Elements of the Marib water resources system and their interrelation

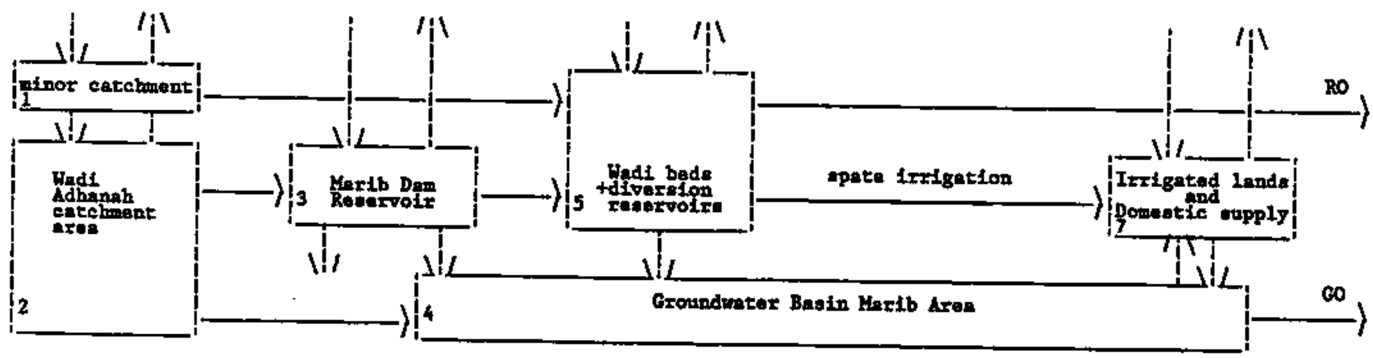
The water resources situation in the Marib area is fairly complex. The different subsystems and their interrelations are depicted in Figure 6.6. Three situations are given: the situation before the construction of the dam (A), the situation since the completion of the dam until the present (B), and the future situation after implementation of the Marib Scheme (C). The boundaries of the Marib area considered are given in Figure 5.12.

The figures indicate the main source of water (Wadi Adhanah catchment), and show the two major reservoirs (groundwater basin Marib Area and the Marib Dam Reservoir), the two major water conveyance conduits (aquifer and the canal system) and the two major

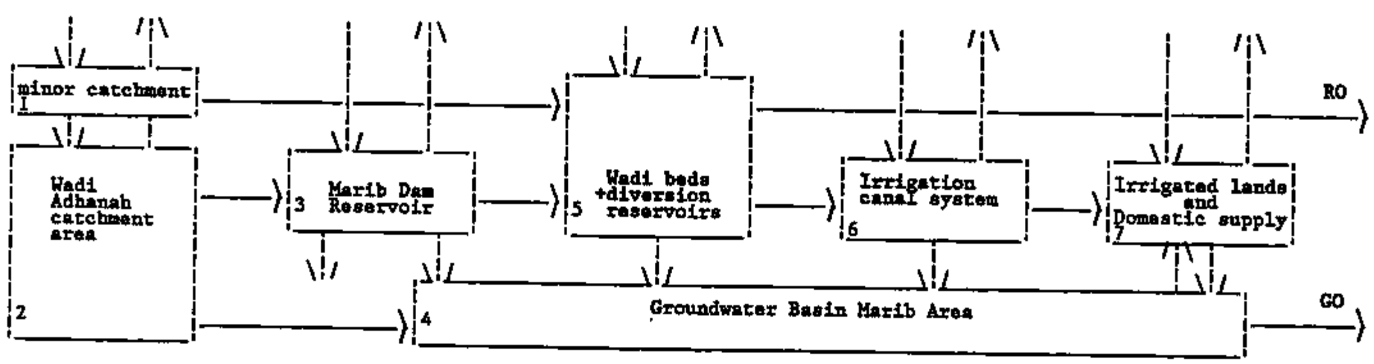


P = precipitation; E = evaporation; ET = evapotranspiration

A) Before the construction of the Marib Dam (before 1986)



B) Present situation, since completion of the Marib Dam (1986) until completion of the irrigation canals



C) During operation of the Marib Dam and Irrigation Scheme

FIGURE 6.6

GENERAL SYSTEMS APPROACH TO WATER RESOURCES MARIB AREA

demand sectors (irrigation and domestic use). The figures also show how these elements are interrelated, as far as inflows and outflows of water are concerned. It can be observed that 'losses' of water from one subsystem may constitute 'gains' for another subsystem. On the other hand, other losses may be interpreted as 'definitive' losses, e.g. all evapo(transpi)ration losses (E_i and ET_i), runoff outflow beyond the Marib area (RO) and the groundwater ouflow passing the boundaries of the Marib area (GO).

The three consecutive figures show the impact of the construction of the Marib Dam and irrigation canals on the water resources system. One reservoir (Marib reservoir) and one conveyance conduit (canal system) have been added. As result, more in- and outflow components are introduced. Especially important are the introduction of new losses (e.g. evaporation from the lake surface and the canal system) and the introduction of flow components, that can be manipulated. From the water conservation point of view it is important to know whether 'gains' of useable water are also obtained. This question will be tackled below, by examining certain water balances and by ascertaining the water resources available and the consequences of manipulating flow components between the systems. The different flow components are given for the three water resources situations mentioned above:

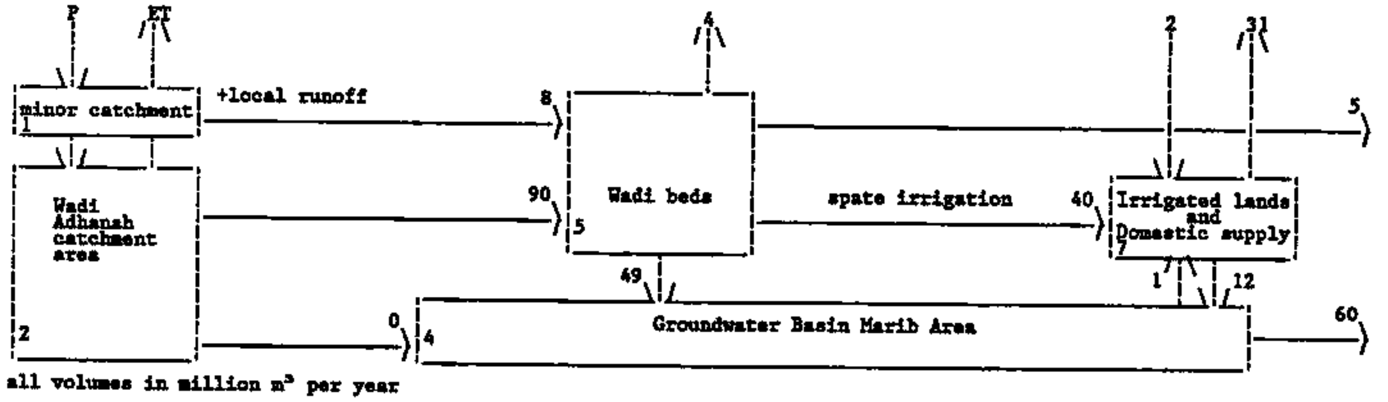
I: Average waterbalance pre-1970, the situation before the construction of the dam,

II: Water balance 1986-1988,the situation since the completion of the dam until the present,

III: Water balances after the implementation of the Marib Scheme, the future situation.

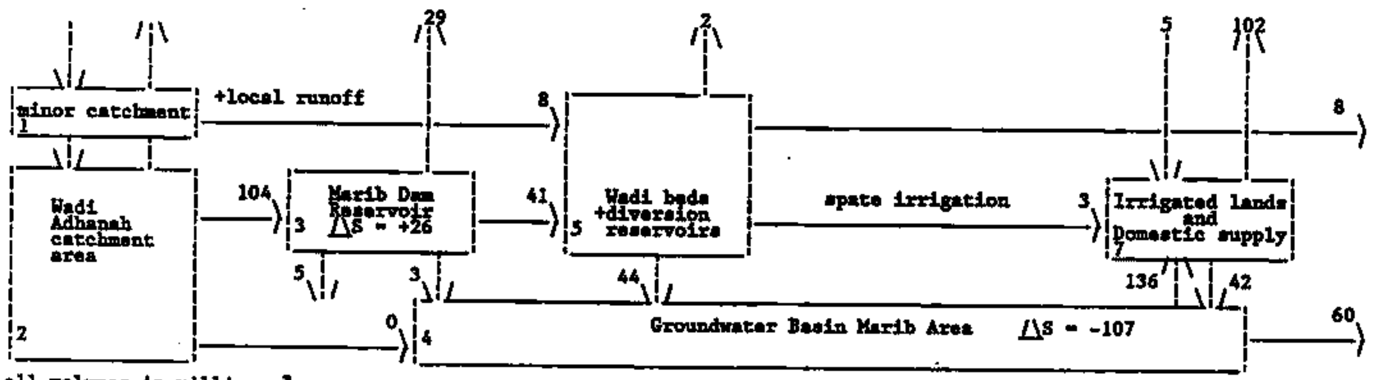
I: Average Water Balance pre-1970

Figure 6.7 (A) depicts the situation when mainly spate flows were diverted for irrigation and the groundwater abstraction from wells was very small. This situation existed for centuries, during which the groundwater flow was in a more or less steady state and the groundwater outflow component was constant. Because of the inert



all volumes in million m³ per year

A) PRE-1970 WATER BALANCE MARIB AREA



all volumes in million m³ per year

B) WATER BALANCES MARIB AREA, 1986-1988

FIGURE 6.7
WATER BALANCES MARIB AREA

groundwater flow system it is assumed that the present subsurface outflow still reflects the steady situation. The groundwater outflow component is estimated to be about 60 million m^3 per year.

The average annual discharges from the Wadi Adhanah catchment and the minor catchments are assumed to be equal to the average values estimated for the period 1986-1989, i.e. 90 million m^3 and 8 million m^3 respectivily. The latter also includes local runoff, hence precipitation on wadi beds can be omitted. The volume of spate flow diverted for irrigation is estimated from the cultivated area in 1973 and it is assumed that 30% of the spate water recharges the groundwater. Evaporation from wadi beds and precipitation are estimated, the other flow terms are balanced. This results in the volume lost by surface runoff , passing the area's boundaries being 5 million m^3.

II: Water Balance 1986-1988

The water resources assessment study included the observation or estimation of all components of the Marib water resources system since the completion of the Marib Dam. The annual averages of the three year observation period are given in Figure 6.7. (B). The subsurface outflow is still 60 million m^3 per year. Spate irrigation originates from storm runoff from the minor catchments and from local rainfall. Evaporation from wadi beds and precipitation on irrigated fields are estimates. The remaining components are measured or balanced. An important difference with the previous water balance are the losses introduced from the Marib Dam Reservoir subsystem, evaporation (29 million m^3) and "losses" (5 million m^3). The reduction of groundwater storage was approximately 107 million m^3/year during the observation period. The storage remaining in the Marib lake was 77.5 million m^3 on 31 December 1989.

A considerable volume of water was lost (evaporation and additional "losses") from the Marib Reservoir. As a result the available surface water resources were considerably reduced.

III: Water balances after the implementation of the Marib Scheme

When the Marib Scheme is implemented, various flow components between the subsystems shown in Figure 6.6 will have to be manipulated.
The following components can be controlled (to a certain extent) by human interference:

- -The flow rate of water released from the dam (related to the discharge of the Wadi Adhanah catchment) and therefore the evaporation from the lake,
- -the volume of water diverted into the irrigation system by operating the gates of the intake constructions of the canal system,
- -the recharge of the groundwater reservoir from the wadi beds by manipulating the infiltration rate through the wadi streambed,
- -the groundwater abstraction by means of pumping wells,
- -the recharge of groundwater from irrigated fields, by manipulating the field efficiency of the irrigation methods,
- -the demand for water in the irrigation sector,
- -the subsurface outflow component.

An important subsystem to be controlled is the demand in the irrigation sector. Under the present circumstances the gross demand for irrigation water (136 million m^3 in 1987) is already higher than the estimated average annual inflow (104 + 8 million m^3) into the system during the period 1986-1988.

A considerable 'loss' is the present subsurface outflow component (60 million m^3 annually). This component can be changed, however, the groundwater flow system is an inert system and the reaction of the system on impulses (change of recharge, of abstractions by wells and of the return flow from irrigated fields) is very slow.

Below, water balances for three water resources development options are given for the present demand (1988) for irrigation water. Three situations are compared, two extreme situations (storage dam versus flood control dam) and one intermediate situation (semi flood control/ semi storage dam).

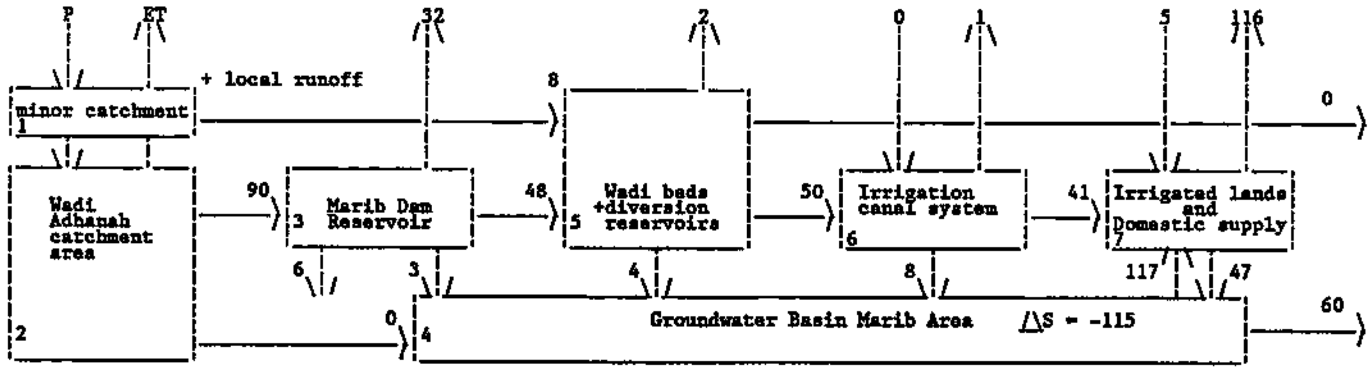
6.4.2. Three scenarios of future water resources development

In the first one, the Marib Dam is used as a storage dam and it is assumed that measures are taken to divert all released water into the irrigation canal system (it is assumed that a canal exist between the dam and the diversion constructions A and B). This situation is depicted in Figure 6.8, picture A.

In the second (academic ?) one, the Marib Dam is used as a flood control dam and all flow into the reservoir will be released as fast as possible. No water will be diverted into the irrigation canals. Use will be made of the diversion dams A and B to "control" the infiltration rate through the wadi streambed in such a way that besides some evaporation all released water will recharge the aquifer. Groundwater will be the only available source of water to irrigate the fields. This situation reflects more or less the situation during the observation period 1986-1988. (Figure 6.8 (B)).

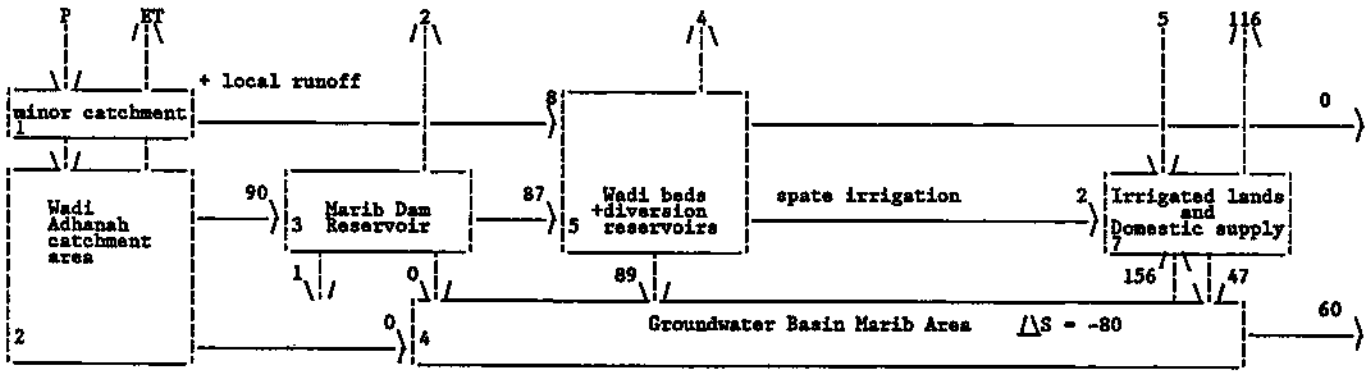
In the third scenario all water stored behind the dam will be released during and immediately after the rainy season. The Marib Dam and Irrigation Canals will be operated in such a way that the released water is diverted as much as possible into the irrigation canal system to meet crop requirements. The remaining amount will recharge the groundwater reservoir. The irrigation period (with surface water) will depend on availability of water stored behind the dam. Abstraction of groundwater will meet the remaining need for irrigation water. (Figure 6.8 (C)).

The presented water balance components in all three scenarios are reflecting the average situation. The average estimated annual discharge values for the period 1986-1989 were taken to be the annual discharges from the Wadi Adhanah catchment and the remaining catchments, i.e. 90 million m^3 and 8 million m^3 respectively.
These volumes do not necessarely reflect the long term mean annual flows. As stated before, a much longer observation period is needed to acquire a more accurate annual flow. However, for the operation of



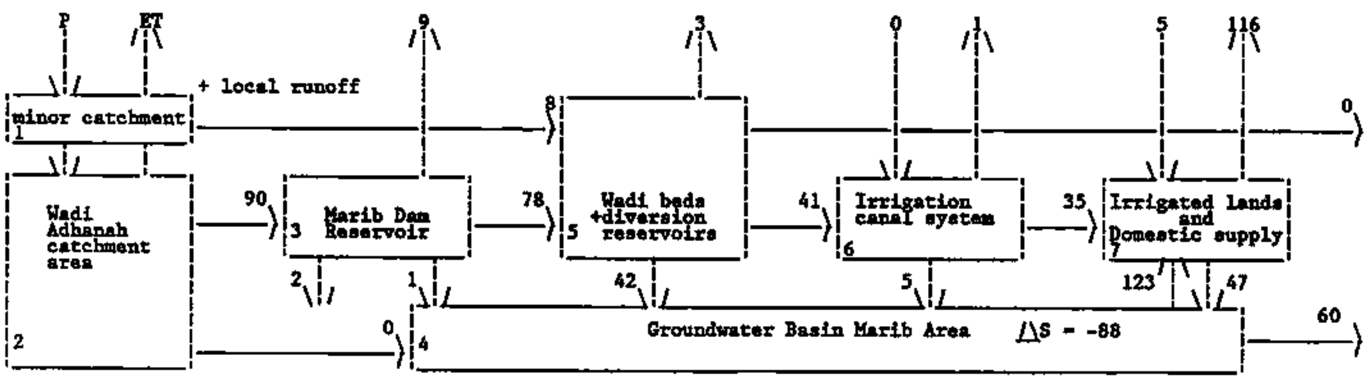
all volumes in million m³ per year

A) MARIB DAM USED AS STORAGE RESERVOIR



all volumes in million m³ per year

B) MARIB DAM USED AS FLOOD CONTROL DAM



all volumes in million m³ per year

C) MARIB DAM USED AS FLOOD CONTROL/STORAGE DAM

FIGURE 6.8

FUTURE WATER BALANCES MARIB AREA

the Marib Dam and Irrigation Canals it is certainly important to know how to handle these "actually" observed volumes of recharge.

SCENARIO A: MARIB DAM USED AS STORAGE RESERVOIR (Figure 6.8 (A))
Two years with an annual inflow of 60 million m^3 and one year with an inflow of 150 million m^3 are assumed. To be able to continue operation of the Marib Dam after two relatively dry years a certain minimum volume of water should be stored in the reservoir before operation of the dam starts. The minimum stored volume of water should be 80 million m^3 if the dam starts operating before the wet season and 150 million m^3 if it starts operating after the wet season. Then the average evaporation losses will be about 33 million per year. Other losses will be approximately 9 million m^3, consequently the average volume of water to be released will be 48 million m^3 per year if the annual average inflow into the lake is 90 million m^3.

The released volume of water (48 million m^3) is diverted immediately in a (new) canal to supply the existing irrigation distribution system. The conveyance efficiency (new canal 95%, primary canals 95%, secondary canals 90%) is assumed at 81%, leaving 39 million m^3 to supply the tertiary canals of the different irrigated lands. Including the 2 million m^3 from remaining catchments and from local runoff, gives a total of 41 million m^3. The evaporation from the canalsystem is estimated, the other components are balanced.

The annual reduction of groundwater storage will be 115 million m^3 as long as the groundwater outflow is equal to 60 million. The particularity of this scenario is that the total inflow into the system from the catchments is even less than the sum of "losses" (98 million m^3 and 102 million m^3 respectively).

In the abovementioned case water will be released all year round. If only summer crops are irrigated then the available water will be released in six months (from February until September), causing lower average lake levels and consequently lower evaporation losses (8 million m^3 less evaporation). The amount of evaporation is linear related to the lake surface. Mesures taken to reduce the lake surface will decrease the evaporation losses.

SCENARIO B: MARIB DAM AS FLOOD CONTROL DAM (Figure 6.8 (B))
Using the dam as flood control dam, water will be released after the rainy season, diminishing the evaporation and other losses from the lake. If the total average annual inflow will be released in a relatively short time (approximately 50 days) then the total losses from the lake are only 3 million m^3.
From the water conservation point of view (available water in the system) this option seems to be preferable. The depletion of groundwater storage for this option is about 80 million m^3 per year as long as groundwater outflow remains the same.

SCENARIO C: MARIB DAM AS FLOOD CONTROL/STORAGE DAM
This option allows for some flexibility without creating excessive evaporation losses. The irrigation period could be extended to 3, 4, 5 or even 6 months and longer, depending on water availability, and would be regulated by operation of the dam outlet and diversion intakes.
The volumes presented in Figure 8 (C), are based on a release period of 6 months (April through September) and on the assumption that half of the released volume of water is recharging the aquifer. With conveyance efficiencies for the primary and secondary canals of respectively 95% and 90%, an amount of 35 million m^3 is recharging the tertiary canals of the irrigated fields. After balancing all subsystems, the annual deficit of the groundwater reservoir amounts to about 88 million m^3.

It has to be realized that the presented figures reflect a presumed average situation based on certain assumptions and estimations. It is difficult to ascertain the margins of errors of the presented volumes. Only a qualitative approach of the accuracies of the different components of the water resources system can be given.
The "measured" flows as lake inflow, released flow and total lake

"losses" are rather accurate. Errors depend on the relation between lake levels, lake volumes and opening of the gate. Downstream of the dam the different components are much more based on assumptions and estimations. A very important volume is the extraction of groundwater by pumping, it is partly based on measurements and partly on assumptions. The results are thought to be reasonable, when compared with the total irrigated area and with the results of previous investigations. The return flow from irrigated fields is an assumption based on the locally very permeable soil. Accuracy of this component is very low. Another important component is the subsurface outflow. The given volume is based on extrapolation of some local measurements. Accuracy is low. Losses from wadi bed and irrigation canals are based on assumptions.

A final check is the calculated annual deficit of groundwater. This volume should be verified by the measurement of the actual changes of groundwater levels. Therefor a continued observation of the groundwater levels is necessary to monitor the consequences of the actual development of the water resources.

A summary of the principal components of the water resources system of the Marib area for the three scenarios presented above, is given in Table 6.1. A comparison of the scenarios allows to draw certain, more or less striking conclusions:

- The volume of water needed to meet the present (gross) demand (1988) for irrigation water is probably higher than the total average inflow of water into the water resources system of the Marib area.
- Consequently, in all three scenarios groundwater is being mined.
- Development of the water resources according scenario I creates a situation with total losses (including groundwater outflow) exceeding the total (surface) water inflow into the system. The rate of mining of groundwater is highest.
- Development of the water resources according a scenario that approximates the use of the dam as flood control dam seems to be preferable from the water conservation point of view.

TABLE 6.1

SUMMARY OF PRINCIPAL COMPONENTS OF THE WATER RESOURCES SYSTEMS MARIB AREA FOR THREE SCENARIOS

all values in million m³ per year

SCENARIO	TOTAL INFLOW	MARIB DAM RESERVOIR		WADI + CANAL SYSTEM	SURFACE WATER AVAILABLE FOR IRRIGATION [1]	GROUNDWATER	
		EVAPORATION	LOSSES	EVAPORATION		DEPLETION	OUTFLOW
I	98	33	6	3	41	115	60
II	98	2	1	4	2	80	60
III	98	9	2	4	35	88	60

[1] Amount available to recharge tertiary irrigation canals

6.4.3 Water Resources Management Issues in the Marib Area

To develop an adequate water management strategy for the Marib area, the first step, the assessment of the water resources of the area has been completed. The assessment allows to define briefly the following most important management issues:

- -Establishing an operation and maintenance plan for the Marib Dam and Irrigation system after completion of the irrigation distribution system.
- -Deciding whether controlled recharge of groundwater is desirable.

  The presence of the diversion constructions in the wadi downstream of the dam allows controlled recharge of groundwater in time and space. Recharge can be concentrated upstream or downstream of the diversions by manipulating the release rate from the dam, the water height above the wadi bed and the extent of the impounded area.
- -Controlling groundwater exploitation taking into account mining and the reduction of groundwater outflow.
- -Ascertaining the sustainable rate of water resources development in the region, including groundwater and surface water.
- -Deciding whether the emphasis should be on groundwater or surface water (conjunctive use?)
- -Anticipating water quality problems.
- -Ascertaining the scope and effect of increasing the water use efficiencies.

A rigorous analysis of these issues requires a detailed and highly interdisciplinary approach, including the socio-, economic- and environmental aspects. A discussion of this is beyond the scope of this report.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The investigations carried out by the WRAY project in the Wadi Adhanah and Marib area have substantially increased our knowledge of the area's water resources. The most significant new elements that have been added to the existing information in the area's water resources are listed below:

1) -For the first time rainfall data from the entire catchment of the Wadi Adhanah and from the Marib area have been collected, thereby enabling runoff data to be interpreted in the light of rainfall intensities and distribution.
2) -For the first time water stage and streamflow data on the Wadi Adhanah have been collected while simultaneously observing of areal rainfall; this has resulted in a better knowledge of the streamflow characteristics that must be understood for the proper operation of the Marib Dam and irrigation system.
3) -The evaporation losses from the Marib Reservoir can be high under certain operational strategies that strongly emphasize storage of surface water.

   If losses of water have to be minimized then high storage volumes in the lake have to be avoided.
4) -Storage reduction of the reservoir by sediment accumulation resulting from low floods is relatively unimportant.
5) -The surface water and groundwater systems in the Marib area are strongly interrelated; any emphasis on surface water use has direct (negative) consequences on the available groundwater resources.
6) -The general Marib aquifer and groundwater flow system have been delineated; an "upper" and a "lower" aquifer have been distinguished. The relatively shallow zone of the upper aquifer system in the southwestern and central parts of the Marib area is heavily exploited.

7) -The potential water demand currently exceeds the permanently available resources, which makes it essential to carefully consider alternative strategies and measures for optimal use of water.

8) -Evidence has been obtained of current groundwater mining, and it is expected that continuation of these practices will (in the relatively short term) have negative consequences such as:
-declining groundwater levels
-exhaustion of certain zones
-increasing costs of groundwater exploitation
-deterioration of groundwater quality in certain zones

9) -The impact of the new dam on the water management of the Marib area is considerable; many options for operation of the dam are possible. As yet, insufficient data are available to enable the best alternative to be determined.

10) -The probably impermeable Azal shale layer has been delimitted; the presence of this layer in the subsurface has important consequences for the groundwater flow system (relatively high groundwater levels and groundwater storage)

11) -The lateral extent of fresh groundwater and the occurrence of brackish groundwater has been delineated.

12) -Frequent monitoring of groundwater levels in a dense observation network of wells during periods of water release from the dam gave insight into the recharge characteristics of the groundwater reservoir and provided data for calibrating the numerical groundwater flow simulation model.

13) -The development of groundwater and surface water use has been assessed and alternative strategies for the operation of the Marib Scheme discussed.

14) -The elements of the Marib Water Resources System and their interrelations have been outlined, and an attempt has been made to quantify them.

Gaps and uncertainties still exist in our knowledge of the area's water resources. The operation of the hydrological monitoring network is continuing in order to observe and characterize the temporal variability of the hydrological phenomena.

7.2. Recommendations

1) -Active water resources management in the Marib area should be striven for and established soon, given the pace of developments in the area and possible problems in the near future.
2) -Water resources management should include integrated management of surface water and groundwater resources, because these are strongly interrelated.
3) -A regional water resources management plan should be drawn up.
4) -A pilot study on water resources management, based on the results of the assessment study, should precede the drawing up of this plan.
5) -For the development of a water resources management plan it is very important to consider the following aspects:
   - -the development of operational rules for the Marib Dam reservoir (probably not too much storage should be created in view of the high losses and the possibility of groundwater storage)
   - -the possibilities of reducing groundwater flow (and losses by groundwater "outflow")
   - -the possibilities of influencing the recharge of groundwater in time and space
   - -the desirability of groundwater abstraction control in quantity, time and space
   - -the life-time of the Marib Reservoir in view of sediment accumulation
   - -the safety of the dam (this is closely connected with the operational rules for the dam)
   - -the feasibility of different strategies and measures in view of the socio-economic circumstances in the area (tribal communities, governmental capacities, economic trends)
6) -The water management plan should be part of governmental policies regarding the economic development of the Marib area.
7) -Hydrological monitoring and periodic measurements of sediment accumulation have to be continued in view of:
   - -reducing uncertainties by collecting long time series of

data

-determining the effect and efficiency of water management

8) -The relevant national and local authorities (ERADA, Technical Secretariat of the High Water Council) and the local population have to be strongly involved in order to establish commitments in connection with the strategies developed and the decisions made.

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APPENDIX 1

LIST OF PERSONS INVOLVED IN THE WADI ADHANAH - MARIB INVESTIGATIONS

APPENDIX 1: List of persons involved in the Wadi Adhanah-Marib investigations

1.1 GDWRS team of WRAY II and III (1985 - 1989)

Ahmed Wahib	Co-manager/General Director till February '89
Mahmood Al Udaini	Co-manager/General Director from February '89
Mohamed Danikh	Hydrologist/Director surface water department
Ali Saad Atrous	Hydrogeologist/Director groundwater department
Ali Al-Thary	Geophysicist/Director geophysics department
Gazi Thabet	Hydrologist
Abdul Aziz Ahmed	Hydrologist
Abdulla Saeff	Hydrologist
Noori Gamal	Hydrogeologist
Abdul Khalek Albarakani	Hydrogeologist
Amin Mahjub	Hydrogeologist
Ali Kassim	Hydrogeologist
Ahmed Ali Ashami	Hydrogeologist
Abdullatif Hassan	Geophysicist
Mohamed Asbahi	Geophysicist
Khalid Al Shehari	Geophysicist
Abdul Haveth	Geophysicist
Yahya Al Kibsi	Geophysicist
Abdul Rahman Abdulah	Drilling supervisor
Nabil Abdul Kader	Database
Abdul Kader Ali	Database (employed by WRAY)
Faysal Hazza	Database
Basma Al Qubati	Database
Mohamed Ali Abdu	Database (employed by WRAY)
Ahmed Fara	Geologist
Saad Saleh	Hydrological Technician/accountant
Mohamed Nassiri	Hydrological Technician
Fuad Al Kabir	Hydrological Technician
Abdul Aziz Hussein	Hydrological Technician
Ahmed Abdu Saef	Hydrogeological Technician
Abdul Karim Al Natari	Hydrogeological Technician
Wadea Rashid	Hydrogeological Technician
Mohamed Al-Fakeh	Geophysical Technician
Kennedy Kassim	Geophysical Technician
Aidrous Ahmed	Geophysical Technician
Abrahim Ali Saef	Technician
Abdu Al-Arramy	Technician
Taher Ali Musleh	Mechanic
Ahmed Addahbaly	Assistant Technician
Fatuma Ahmed Al-Seyary	Typist
Ahmed Al-Hoashaby	Driver/Technician
Abdul Hakim	Driver
Saleh Al-Koal	Driver/Technician
Saeed Abdul-Waly	Driver
Ali Ushaish	Driver
Abdul Bari	Driver

Hail Abdullah	Cook
Abdu Ali	Cook
Abdu Abbas	Cleaner
Ahmed Al-Arramy	Watchman
Mohamed Sharaf	Administrator
Mukbil Ali Abdu	Accountant (1986 - 1987)

1.2 Dutch team of WRAY II and III (1985 - 1989)

Residents:

F.C. Dufour	co-manager	from 01/09/85 - 31/12/89
K.V. Heynert	hydrologist	from 01/09/88 - 31/12/89
J.P. Kool	geophysicist	from 01/03/86 - 01/06/89
W.M.J. Luxemburg	data base	from 01/05/87 - 31/12/89
P.S. Nota	data base	from 01/09/85 - 30/04/88
H. Uil	senior hydrogeologist	from 01/10/85 - 31/12/89
G. Verbeek	geohydrologist	from 01/09/88 - 31/12/89

Non-resident:

J.A.M. van der Gun	project supervisor	from 01/09/85 - 31/12/89

Non-residents (short missions):

C.J. Bos	electronic engineer
W. van Dalfsen	senior geophysicist
G.F.J. Jeurissen	supervisor
J.B.M. Langbein	draughtsman
D.G. van de Leygraaf	geophysical operator
P.J.M. Mulder	hydrogeologist
S.D. Nio	sedimentologist
W.M.A. Otte	geophysicist
J.W. Reckman	instrumentation engineer
M.C. Schravesande	accountant
J.F.M. Stradal	drilling supervisor
C.B.M. te Stroet	modelling expert
L. Vasak	hydrogeologist

Non-residents (supporting from the Netherlands)

J.B.J. Beekman	purchase of equipment
K.W. Bouwman	accountant
J.J. van Duyn	secretary
J.A.M. Duijnisveld	secretary
J.C. van Heusden	purchase of equipment
P. van Straalen	accountant

WRAY 15 Appendix 1

APPENDIX 2

LIST OF WRAY REPORTS ON THE WADI ADHANA - MARIB INVESTIGATIONS

APPENDIX 2: List of WRAY reports on the Wadi Adhana - Marib investigations

2.1 Interim reports

WRAY-8.1 Abdul Aziz Ahmed, H. Uil, S. Vasak, 1988
Well Inventory Results

WRAY-8.2 Mohamed Danekh, Noori Gamal, H. Uil, 1988
Hydrological Networks

WRAY-8.3 Kool, J.P., 1987
Geophysical Investigation

2.2 Final reports

WRAY-15 Uil, H and F.C. Dufour, 1990
Main Report

WRAY-15.1 Kool, J.P., Ali Ahmed Athari, Abdullatif Hassan Saeed, Khaled Mohammed Al Shehari, 1990
Geophysical Investigation

WRAY-15.2 Uil, H., Noori Gamal, S. Vasak, 1990
Well Inventory Results

WRAY-15.3 Heynert, K.V. and H. Uil, 1990
Hydrological Networks

WRAY-15.4 Verbeek G., 1990
Aquifer Tests

WRAY-15.5 Noori Gamal and Ali Saad Atrous, 1990
Exploratory Drilling Program

WRAY-15.6 Nio, S.D., 1990
Sediment Transport and Accumulation

WRAY-15.7 Verbeek G. and C. te Stroet, 1990
Numerical Modelling of the Groundwater-Flow System

APPENDIX 3

LIST OF SATELLITE IMAGES OF THE WADI ADHANA - MARIB AREA USED BY THE WRAY PROJECT

APPENDIX 3: List of Satellite images of the Wadi Adhana - Marib area used by the WRAY project

Landsat Nasa Erts; scale 1:1 000 000 (paper print)
scale 1: 500 000 (paper print)

Grid reference	Date	Type
E 2274 - 06364	23/10/1975	Panchrom/Multispect.
E 2274 - 06371	23/10/1975	Panchrom/Multispect.
E 2257 - 06424	06/10/1975	Panchrom/Multispect.
E 2257 - 06430	06/10/1975	Panchrom/Multispect.

SPOT Image, Toulouse, France; scale 1:100 000 (paper print)
scale 1:400 000 (film)

Grid reference	Date	Type	Proc. level
KJ 148 - 319	26/12/1986	Panchrom.	1B
KJ 149 - 319	26/12/1986	Panchrom.	1B
KJ 147 - 319	27/04/1986	Multispectr.	1B
KJ 147 - 320	06/01/1987	Multispectr.	1B
KJ 147 - 321	05/12/1986	Multispectr.	1B
KJ 148 - 319	27/05/1986	Multispectr.	1B
KJ 148 - 319	02/04/1988	Multispectr.	1B
KJ 148 - 320	06/01/1987	Multispectr.	1B
KJ 148 - 321	05/12/1986	Multispectr.	1B
KJ 149 - 319	30/03/1987	Multispectr.	1B