THE HASHEMITE KINGDOM OF JORDAN
MINISTRY OF PLANNING
IN ASSOCIATION WITH
WATER AUTHORITY OF JORDAN

WATER RESOURCES STUDY OF THE JAFR BASIN

FINAL REPORT

MAIN REPORT

MARCH 1990

JAPAN INTERNATIONAL COOPERATION AGENCY

WATER RESOURCES STUDY OF THE JAFR BASIN FINAL REPORT MAIN REPORT MARCH 1990

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PREFACE

In response to a request from the Government of the Hashemite Kingdom of Jordan, the Japanese Government decided to conduct a study on the Water Resources of the Jafr Basin and entrusted the study to the Japan International Cooperation Agency (JICA).

JICA sent to Jordan a survey team headed by Mr. Takao Ichimiya, the Nippon Koei Co.,LTD from July,1988 to January,1990.

The team held discussion with concerned officials of the Government of Jordan, and conducted field surveys. After the team returned to Japan, further studies were made and the present report was prepared.

I hope that this report will contribute to the promotion of the project and to the enhancement of friendly relations between our two countries.

I wish to express my sincere appreciation to the officials concerned of the Government of Jordan for their close cooperation extended to the team.

March,1990

Kensuke Yanagiya

Kensuke Yanagiya
President
Japan International Cooperation Agency

March,1990

Mr. Kensuke Yanagiya
President
Japan International Cooperation Agency
Tokyo, Japan

LETTER OF TRANSMITTAL

Dear Sir,

We have the pleasure of submitting to you a Final Report of "Water Resources Study of the Jafr Basin" which is prepared for the consideration by the Government of Jordan in implementing the water resources development in the nation's socio-economic development objective.

This report consists of three volumes. The Summary Report contains the summary of the study result. The Main Report comprises the result of the water resources potential study in the upper Hasa and Jafr basins. The computer simulation study indicates that it is worth to develop the water resources in two aquifers such as "Amman - Wadi sir" and "Lower Ajlun". Supporting report contains the analysis and discussions in the sector of surface hydrology and groundwater to support the main report.

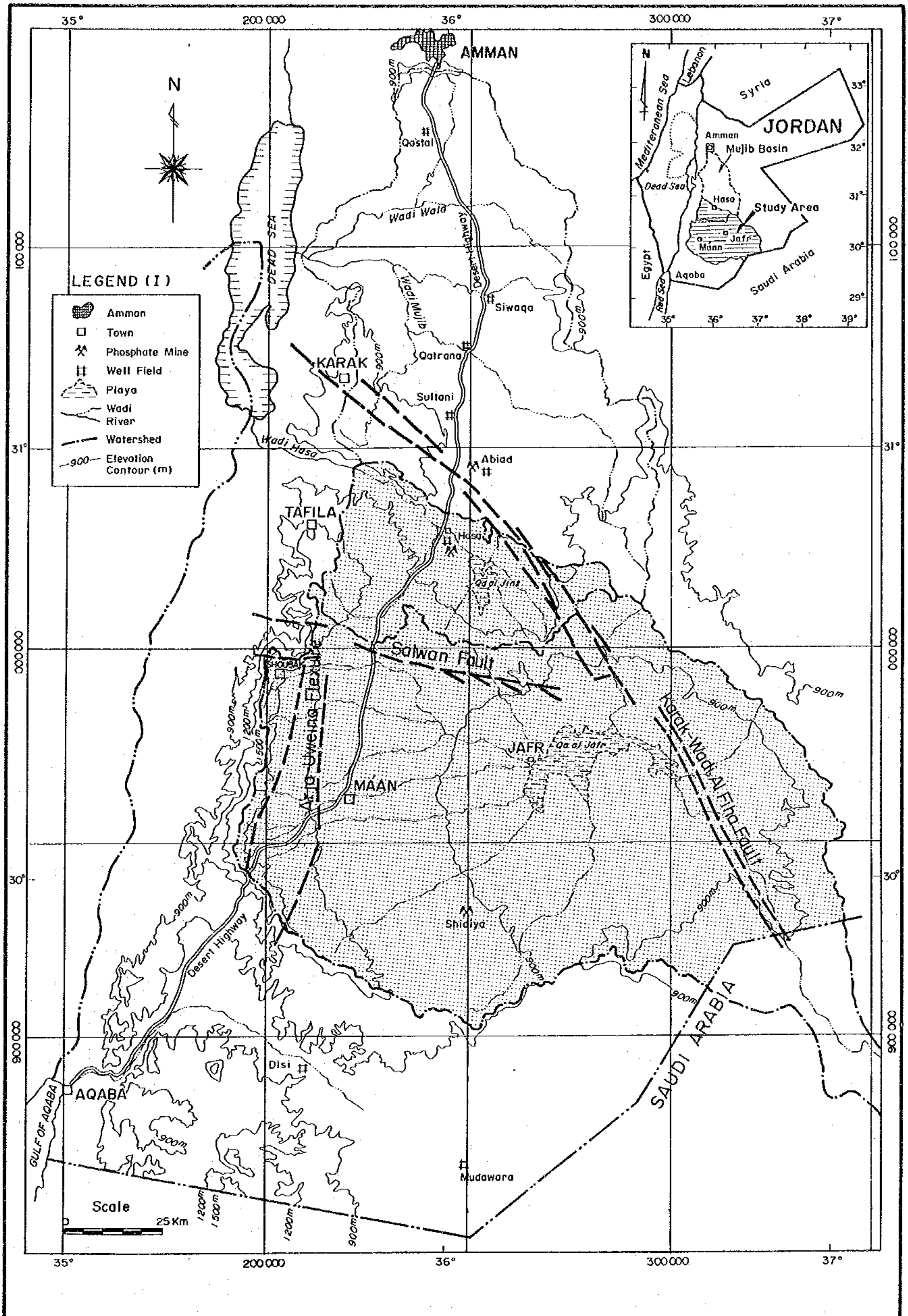
All members of the Study Team wish to express grateful acknowledgment to the personnel of the Advisory Committee of JICA, Ministry of Foreign Affairs, Embassy of Japan as well as officials and individuals of Jordan for their assistance extended to the Study Team.

In conclusion, the Study Team sincerely hopes that the study results would contribute to the socio-economic development and the well-being in general and to the future water resources development in the country.

Yours Sincerely,

T. Ichimiya

Takao Ichimiya
Team Leader
Water Resources Study
of the Jafr Basin



Location Map

THE HASHEMITE KINGDOM OF JORDAN

Water Resources Study of the Jafr Basin

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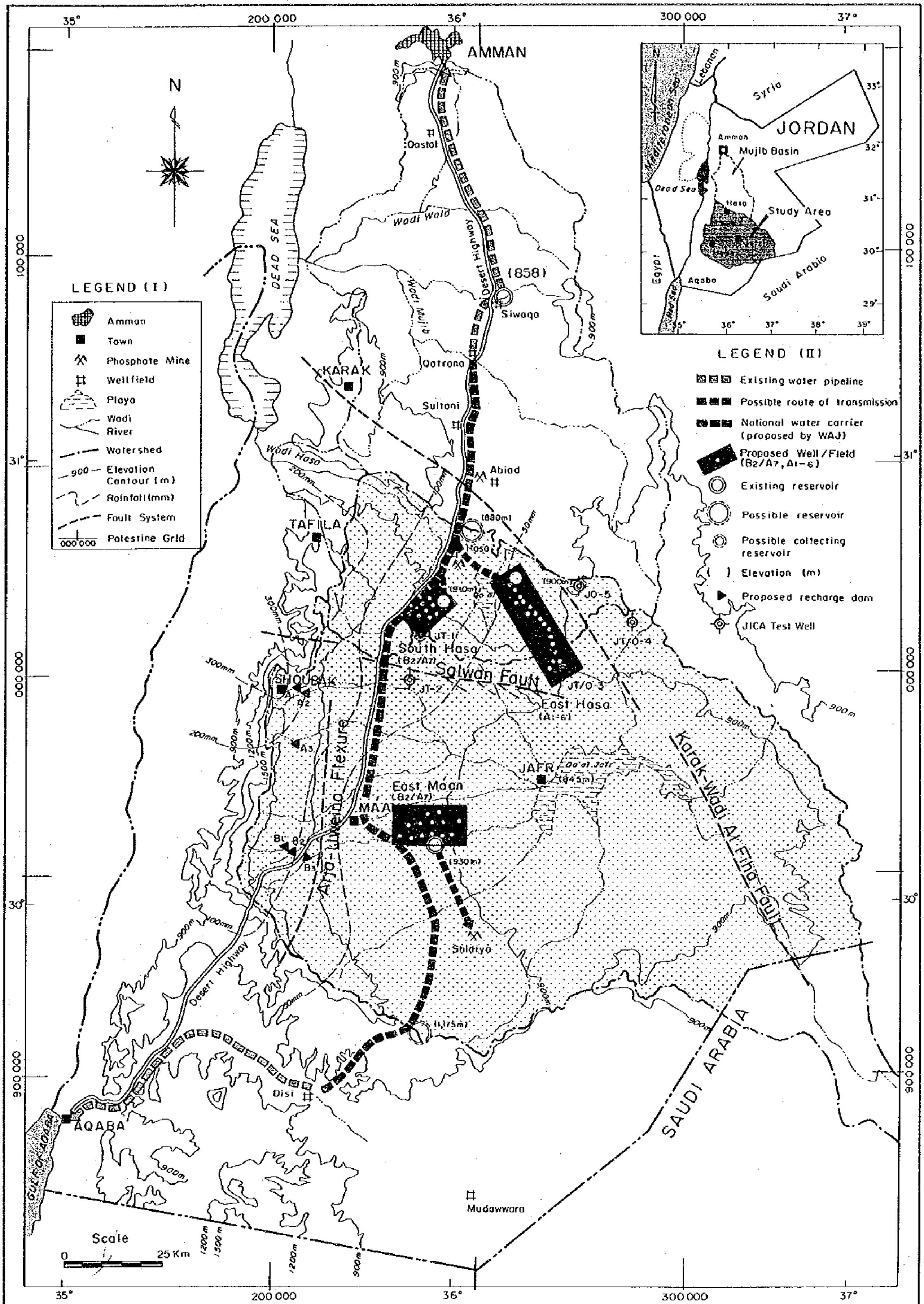

Development Alternative

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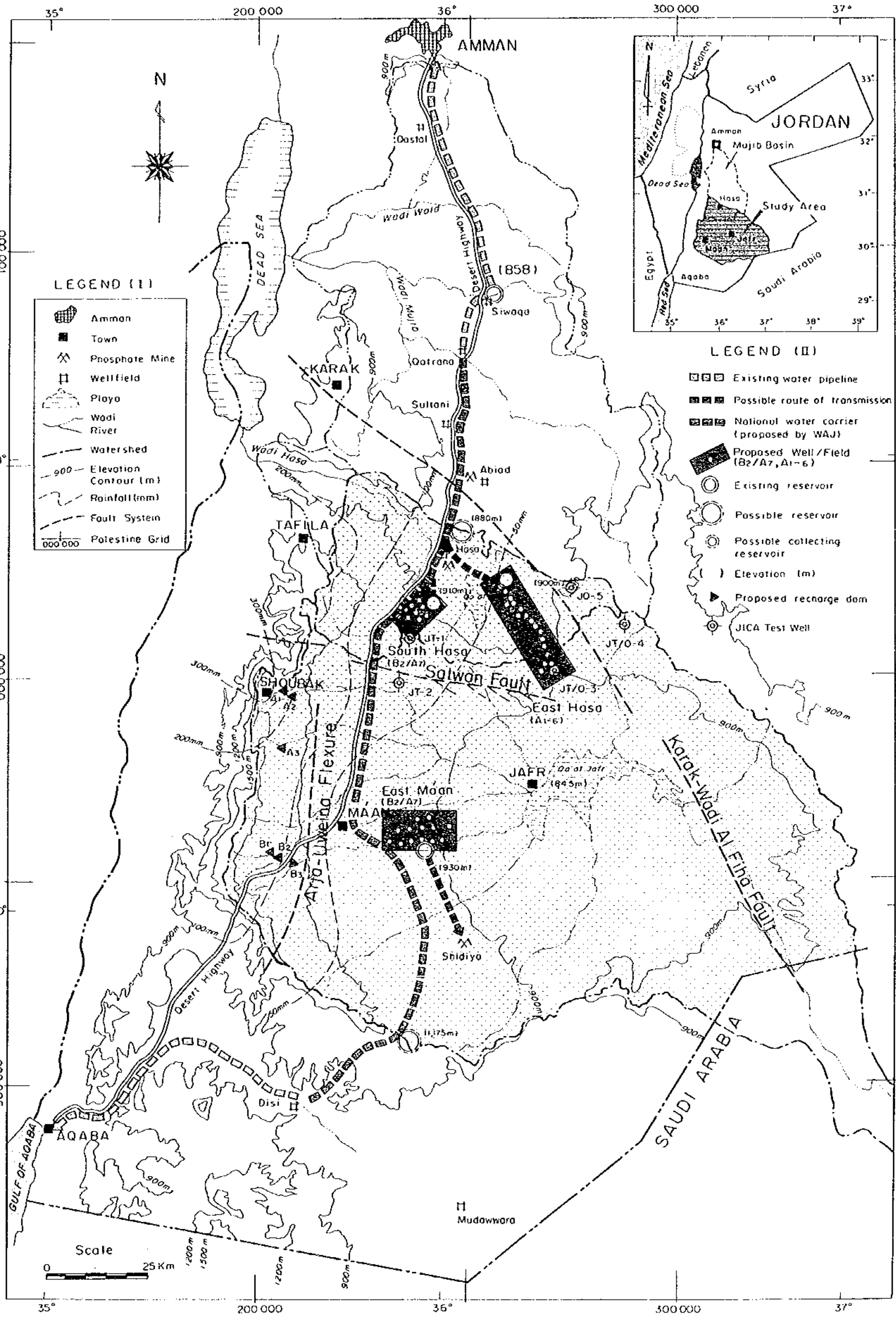

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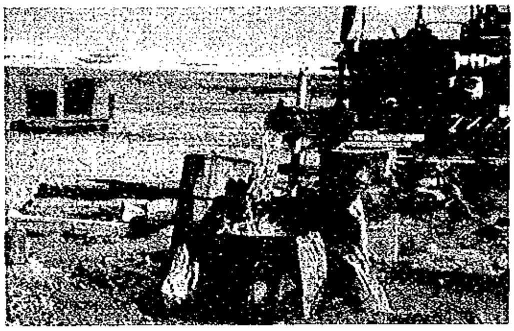
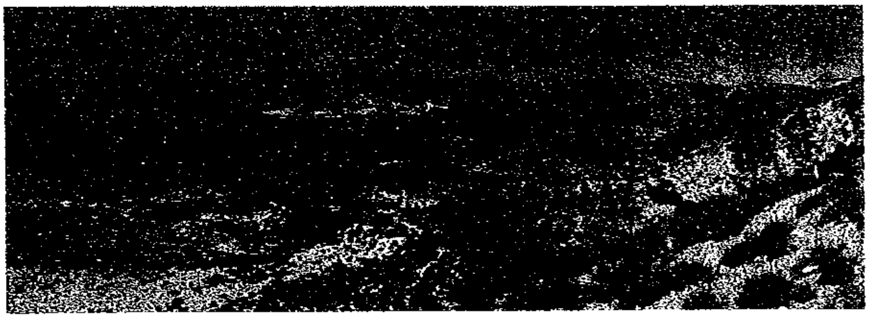


Pumping test at test well JT-3; Excellent quality of pimped water from deep aquifer of Lower Ajlun (A1-6), with T.D.S. of 330 mg/l.(December,1988)

Upper Hasa basin; Southwards view from Hasa town. (July,1988)

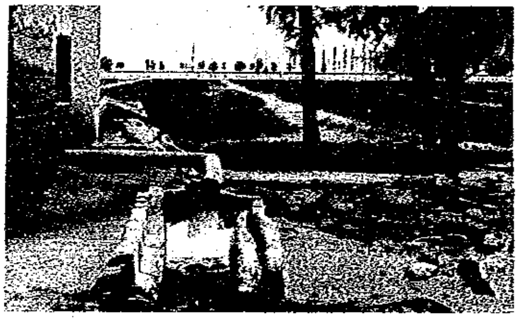
Outcrop of Amman (B2) formation in the Western Highlands; Alternating silicified limestone and chert, with frequent joints, cracks and fissures. (December,1988)



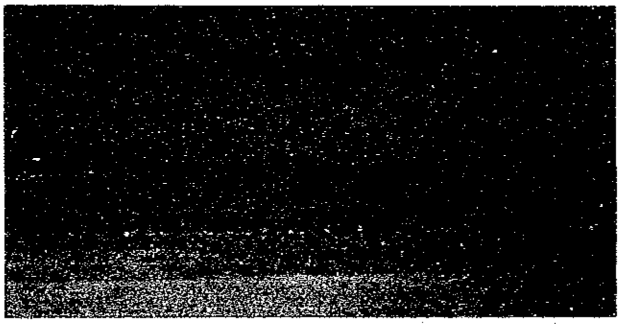
A-2 groundwater recharge damsite; Northwestern part of the Western Highlands in the Jafr basin, where pervious Amman (B2) formation outcrops in and around the damsite. (July,1989)

Wadi Jurdhan at middle reaches; Eastwards and/or downstream view from Desert Highway bridge. (July,1988)

Groundwater recharge area of the Western Highlands, which is covered with snow in December,25,1988. (December,1988)



Groundwater irrigation at Al Jafr; Abstracting from shallow water table aquifer of Rijam (B4), of which water salinity was increased by excessive irrigation return flow and/or deep percolation. (June,1989)



Qa' Al Jafr, end of the wadi course at the center of the playa, ; 10 km northeastwards from Al Jafr town. (October,1988)

SUMMARY

A. Background

1. The Hashemite Kingdom of Jordan is making steady progress in the economic development of the country, but is handicapped by the limited availability of water. Great efforts have been made in the water resources development sector with the allocation of JD 250 million in the 1981-1985 five-year plan or about one sixth of the national budget. Such efforts will be continued also in the future.

2. The Government of the Hashemite Kingdom of Jordan (hereinafter referred to as "the Government of Jordan") decided to make a study of the water resources of the Jafr basin and the upper Hasa basin, which are adjacent with each other, and requested the Government of Japan to provide the required technical assistance. In response to this request the Government of Japan through the Japan International Cooperation Agency (hereinafter referred to as "JICA") the sole official agency for the implementation of the technical cooperation programs of the Government of Japan commenced the Study in close cooperation with the Government of Jordan through Water Authority of Jordan (hereinafter referred to as WAJ) as the executive agency of the Study. In a short period of time, JICA organized a Preliminary Study Team and dispatched it to Jordan in February 1988. The Scope of Work for the Water Resources Study of the Jafr Basin (hereinafter referred to as "the Study") was agreed upon on 25 February,1988. JICA further organized a team for the Study (the Study Team) and dispatched it to Jordan on 6 July 1988.

B. Present Situation

3. <u>Geography</u> : The Jafr basin is located in the southern part of the central Jordan plain and lies to the east of the western highlands. The basin has an area of 13,500 km^2, most of which may be classified as an arid desert. The basin displays a classic centripetal drainage pattern

with all wadis draining from the encircling highlands to the central El Jafr Playa, the largest concave surface in Jordan. The catchment lies at an elevation of between 850 m in the El Jafr Playa and 1,750 m in the Western Highlands. The Upper Hasa basin is situated adjacent to the northern Jafr Basin by watershed. The catchment area is about 2,200 km^2, and lies at an elevation of between 400 m at the basin outlet near Tannour and 1,250 m in the eastern highlands. The wadis in the southern-western highlands are characteristically narrow and moderately incised, while the wadis are gentle in the eastern part of the basin where the elevation is about 900 m. All the wadis in the upstream reaches drain flashing floods to the central playa named Qa El Jinz.

4. Geology: The geologic groups comprise "Disi", "Khreim", "Kurnub", "Ajlun" and "Belqa", which are of sedimentary origin, ranging in age from Cambrian to Cenozoic. The lower part of the sedimentary sequence consists mainly of sandstones of the Paleozoic and the lower Mesozoic, while the upper part comprises alternating limestone, sandstone, chert, marl and shale of the upper Mesozoic and Cenozoic. The Ajlun group is composed of two formations of "lower Ajlun (A1-6)" and "Wadi Sir (A7), while the Belqa group comprises three formations of "Ruseifa-Amman (B1/2)", "Muwaqqar (B3)" and "Rijam (B4)". These thick sequences are bisected by the fault structures such as "Karak - Wadi Al Fiha", "Salwan" and "Arja-Uweina flexure", which are not continuous system but consists of a series of the discrete faults.

5. Climate: Annual minimum temperature is recorded in January, ranging from 3.9°C at Hasa to -2.6°C at Udruh on average, and annual maximum temperature is recorded in July or August, ranging from 35.5°C at Jafr to 27.4°C at Shoubak on average. Annual total evaporation measured by a class-A pan ranges from 1,800 mm at Shaubak to 4,200 mm at Jafr.

6. Rainfall : The hydrological year is divided into two distinct seasons, namely, the rainy season from October to May and the dry season from June to September. In the rainy season, more than 95% of precipitation is observed, including snow. The annual rainfall decreases from 300 mm in the western highland to less than 50 mm in the eastern

part. Long-term average annual rainfall of the Upper Hasa basin and the Jafr basin is 92 mm and 51 mm, respectively. In these, precipitation is limited to a small area. Taking for example the historical flood recorded at the Wadi Jurdhan on March 11, 1966, the rainfall gauging station at Ma'an had a record rainfall of 50 mm for 15 minutes while the rainfall gauging station at Udruh and Basta in western watershed areas recorded rainfall of 10 mm in 24 hours. These three rainfall stations are only about 20 km apart.

7. Runoff: Runoff usually takes place for a few days during floods. There is no perennial stream flow. A typical local floods was that of March 11,1966 flood which had a peak discharge of 120 m^3/sec at Wadi Jurdhan, north of Ma'an. This flood is nearly equivalent to the 10-year probable flood in terms of peak discharge and had a duration of about 10 hours. There also seem to be different runoff patterns in the study area. In the rainy western, in watershed areas which are covered by less pervious material, runoff seems to appear at wadis immediately after rain. This is in stark contrast to the central and eastern part of the study area which are covered by relatively thick layer of silty material. In these areas where the moisture retention capacity of soils is considered greater, it is understood that wadis are likely to have no stream flow if rainfall is less than 8 mm per day. The long-term average annual runoff is estimated at 13.8 MCM for the Upper Hasa basin with a runoff coefficient of 6.8 %, and 22.9 MCM for the Jafr basin with runoff coefficient of 3.3 %.

8. Hydrogeology: Aquifers have been recognized in argillaceous, arenaceous and/or carbonate rocks of the Cambrian to Paleogene age such as "Disi" (D), "Kurnub" (K), "lower Ajlun" (A1-6), "Amman - Wadi Sir" (B2/A7) and "Rijam" (B4). In the course of the present Study, attention was focused on the aquifers in the Ajlun and the Belqa such as A1-6, B2/A7 and B4. The regional groundwater flows in the aquifers of both B2/A7 and A1-6 are confined by three major faulting structures such as "Karak - Wadi Al Fiha" fault, "Salwan" fault and "Arja - Uweina" flexure. The main sustained aquifer is the B2/A7, which is intersected by two major faulting structures, the east-west "Salwan" fault and

north-south "Arja-Uweina" flexure. While the regional groundwater flow in the A1-6 is confined to the area between the north of the "Salwan" fault and the west of the "Karak - Wadi Al Fiha" fault. The shallow unconfined aquifer of B4 is found in the central part of the Jafr basin, which receives a limited amount of groundwater recharge through the outcrops in the wadi course during the occasional floods.

9. Water Quality: The quality of groundwater in the B2/A7 is excellent to good with water salinity (T.D.S.) in the range of 300 to 700 mg/l, which meets drinking water standards, and is suitable for most uses. While the T.D.S. increases to more than 1,000 to 3,000 mg/l in the south-eastern part of the Jafr basin. The quality of groundwater in the A1-6 aquifer is excellent with T.D.S. at 330 mg/l in the area of the north of the "Salwan" fault. A part of the B4 aquifer such as limited area in the western part of the Jafr town is contaminated by excessive irrigation returns, of which T.D.S increased from 350 to 3,500 mg/l.

10. Present Water Use: The present use of water resources in the Study area is dependent on the groundwater resources in the B2/A7 aquifer. A very small amount of 1.1 MCM/y, however, is being pumped from the shallow unconfined aquifer of the B4 to irrigate some pilot farms. Abstractions are preliminary estimated by WAJ at 18.4 MCM/y in total, which includes the biggest consumer of the Hasa phosphate mine of 7.4 MCM/y, and Shoubak irrigation of 3.3 MCM/y. No surface water is used, whereas 0.75 MCM/y of spring water is being used for the local villages and farms in the Western Highlands.

C. Study Tasks

11. Work Stage: The Study has comprised four stages of the investigations as follow:

12. The 1st stage investigation: The 1st stage was used for preparing the Inception Report in August 1988. Investigations and analysis to follow were carried out during the period from July 1988 through March 1989 as shown below;

- Data collection of topographical maps (1/50,000), aerial photos (1/50,000) and Landsat imagery (1/750,000), geological maps (1/50,000 1/1,000,000), hydrogeological maps, land use map, population, meteorology, soil moisture, stream flow, suspended solids in the flash flood, well inventory, well drillings, pumping test and water quality test.
- Geological and hydrogeological mappings
- Geophysical prospecting by VLF (Very Low Frequency)
- Test well drillings 7 in number with a total depth of 2,940 m.
- Groundwater monitoring
- Hydrogeological analysis
- Topographic mapping for recharge dams
- Runoff analysis by using tank model method
- Flood frequency analysis
- Sedimentation analysis
- Seminar on surface hydrology; data base
- Submitting Progress Report (March 1989)

13. <u>The 2nd stage investigation</u>: The 2nd stage was initiated by discussing the Progress Report. An hydrogeological analysis was carried out to construct the groundwater simulation models of both B2/A7 and A1-6. The computer program of UNISSF, which was designed for the FEM (Finite Element Method) simulation model, was transferred to WAJ's VAX-8200 computer system. Investigations and analysis to follow were performed during the period from May 1989 through September 1989 as shown below;

- Transfer of the computer simulation program of UNISSF to WAJ computer VAX-8200
- Hydrogeological analysis
- Groundwater modeling
- The first seminar on the groundwater model simulation
- Steady state calibration of the groundwater simulation models (B2/A7, A1-6)
- Non-steady calibration of the groundwater simulation model (B2/A7)

- Simulations for alternative groundwater development plans
- Salt-water balance simulation by using tank model
- Submitting Interim Report (October 1989).

14. The 3rd stage investigation: The 3rd stage was initiated by discussing the Interim Report. Alternatives of the water resources development plans, groundwater monitoring and groundwater modeling were studied during the period from October 1989 to January 1990, including the following;

- The second seminar on the groundwater model simulation
- Installation of computer plotter CALCOMP-1043
- Conceptional design of the water source facility and preliminary cost estimate thereof for the selected alternatives
- Water demand and model predictions
- Alternative development plan
- Groundwater monitoring plan
- Submitting Draft Final Report (January 1990)

15. The 4th stage investigation: A Draft Final Report was explained to and discussed with the Government. The 3rd computer simulation seminar was held to transfer the technology of operating the simulation models. A final report is herewith prepared, incorporating the Government's comments.

D. Water Resources Development Plan

16. Storage Dam : A prefeasibility study of storage dams in western wadis of the study area were conducted by WAJ, which was finalized in October 1988. This study aimed at identifying the best construction sites of dams with purposes of water supply for irrigation use and livestock husbandry, water supply to local people and a phosphate mine in Shidiya etc..

17. Recharge Dam : In the beginning, total eight recharge dams were planned to recharge B2/A7 aquifers by infiltration along wadis in the

Western Highlands. Among them, two dams of group-C, which are located in the southern part of the Western Highlands, were canceled owing to unsaturated and/or poor inflow characteristics. For this study, recharge dams which are located on the upstream part of wadis from the storage dams proposed by WAJ, were intended to divert the spilt water into these storage dams. From 23 years hydrological records, catchment area, annual average runoff, gross storage capacity,effective storage capacity and dam height of each recharge dams are estimated as follows:

Dam No.	Catchment Area (km)	Average Annual Inflow (MCM)/1	Maximum Annual Inflow (MCM)/2	Gross Storage Capacity (MCM)/3	Effective Storage Capacity (MCM)	Dam Height (m)	Priority /4
A1	34.3	1.5	5.6	3.7	3.2	19	C
A2	32.2	1.9	9.1	6.0	5.3	18	A
A3	31.1	2.0	12.0	8.5	7.8	39	B
B1	55.7	0.8	3.6	2.4	2.1	20	A
B2	135.9	1.6	8.9	4.2	3.7	19	C
B3	71.7	0.9	4.8	2.0	1.7	10	A
	Total	(8.7)					

Remarks; /1 ; Average of 23 years between 1963/64 and 1985/86

/2 ; Maximum in 23 years between 1963/64 and 1985/86

/3 ; Gross storage capacity is equal to effective storage capacity plus dead storage due to 50-year sedimentation

/4 ; Priority ranking is based on the environmental aspect (compensation) and dam cost; A: No restricting factor, B: Cost effectiveness will be checked for high dam, C: Problem in compensation

18. Groundwater Development in the lower Ajlun (A1-6) Aquifer: The highly confined groundwater in the lower Ajlun (A1-6) remains untapped. The aquifer will be promising in the area to the north of the Salwan fault. The quality of groundwater is good, as water salinity in T.D.S. less than 350 mg/l. The "East Hasa" wellfield, which is located 40 km

to the southeast of Hasa town on the Desert Highway, is proposed for examination of the aquifer potential in the simulation model. From the model simulation study, the potential yield is preliminarily estimated at 5 to 10 MCM/y.

19. Groundwater Development in the Amman - Wadi Sir (B2/A7) Aquifer: Groundwater in the B2/A7 aquifer is being exploited in the areas of the Western Highlands and Hasa mine. In the area to the east of the Desert Highway, the aquifer is confined and untapped. From the model simulation study two potential wellfields, tentatively named "East Ma'an" and "South Hasa", are proposed for coordination with the increase in water demands in the regions and/or the entire Kingdom of Jordan. The "East Ma'an" wellfield, which is located about 20 km to the north of the Shidiya mine, is estimated to produce 5 to 10 MCM/y with installation of 10 to 20 production wells with a depth of 250 m each. The "South Hasa" wellfield, which is situated 10 km to the south of Hasa town, is also estimated to produce 5 to 10 MCM/y by installing production wells 10 to 20 in number with a depth of 350 m each. These two experimental wellfields are located about 1 to 15 km distant from the possible route of WAJ's national water carrier (Disi - Mudawwara - Amman route).

20. Groundwater Development in the Rijam (B4) Aquifer: At Al Jafr town in the central Jafr basin, irrigation has been practiced since 1965 by pumping groundwater from a shallow unconfined aquifer in the Rijam (B4) formation since 1965. Since around 1971, salinity of the Rijam (B4) aquifer has increased and its yield has become unsuitable for irrigation use. The sustained yield of the Rijam (B4) aquifer is evaluated to be less than 2 MCM per annum, due to the limited groundwater recharge through the wadi beds during the occasional floods. It is assumed that the salinity accumulation of the Rijam (B4) aquifer is caused by leaching water which transports (i) salt accumulated at the root zone by irrigation water together with (ii) salt contained in leaching water itself, while the salinity-accumulated aquifer is continually diluted by adjacent salinity-less aquifer. As long as present conditions continues, the salinity accumulation of the irrigation area is

anticipated to decline to T.D.S. of about 1,000 ppm in year 2000, which is considered acceptable for irrigation use. No extensive exploitation will be recommended without any counter-measures to protect the salt accumulation in both surfacial soils and the underlying aquifer of the B4. Groundwater use for irrigation is not promising without counter-measures for desalination of groundwater and/or replacing the irrigation method from the existing gravity flow to the drip method.

21. <u>Conjunctive Development Plan</u>: The average annual runoff at the proposed recharge dam sites is estimated at 8.7 MCM/y in total, consisting of 5.4 MCM/y of group-A and 3.3 MCM/y of group-B. The recharge dams are located in the outcrop area of the B2/A7 which are highly pervious with fissures, open cracks and caves. Volume of infiltration through the reservoir is estimated to be equal to the average annual inflow minus annual evaporation from the reservoir surface. The group-A dams, of which infiltration capacity is estimated at 5.2 MCM/y, will be a significant source of the groundwater recharge in the northwestern part of the Western Highlands where intensive agricultural development is being practiced. The group-B dams, of which infiltration capacity is estimated at 3.2 MCM/y, are located in the southwestern part of the Western Highlands where water is taken both for irrigation and for water supply to Ma'an city from the wells dug into the B2/A7 aquifer. These recharge dams may act as a significant source of increasing the potential of groundwater in the B2/A7. The recharge dam development scheme will be incorporated in the future groundwater development in the Western Highlands.

E. Conclusions and Recommendations

22. <u>Conclusions</u>: As the result of the Master plan level study, the distribution, location and potential of the water resources which consists of the groundwater and surface water in the upper Hasa and Jafr watershed have been clarified. Of the potential clarified, the sustained yield of groundwater in the B2/A7 aquifer is worthy of future development. From the steady-state model simulation study, the deep aquifer of the lower Ajlun (A1-6) is preliminarily evaluated to be

promising. The salt accumulation problems in the Rijam (B4) aquifer are critical and require the counter-measures. The groundwater recharge dams are worthy of future development in the Western Highlands.

23. Recommendations:

Amman - Wadi Sir (B2/A7) Aquifer

- Of the schemes formulated under the present study, the most promising ones are for development of groundwater in the B2/A7 aquifer. After confirming the water use plan of these watersheds, it is recommended that test well drillings be made on the respective wellfields namely "South Hasa" and "East Ma'an" whenever such schemes become needed.

- To re-confirm the quantity and quality of the groundwater in each wellfield, production wells in the wellfields of "South Hasa" and "East Ma'an" will be constructed in two stages. Each wellfield will be developed for 5 MCM/y by installing 10 wells in the first stage, and adding thereafter 5 MCM/y in the 2nd stage.

- For the purpose of optimal groundwater management of the proposed wellfields of "South Hasa" and "East Ma'an", management model simulation will have to be performed by using the data from the constructed wells mentioned above.

Lower Ajlun (A1-6) Aquifer

- The deep aquifer of the lower Ajlun (A1-6) will be promising in the area of the confined upper Hasa groundwater basin. It is recommended that a series of test well drillings and model simulations be carried out to evaluate the feasibility.

Groundwater Recharge Dam in the Western Highlands

- Intensive groundwater irrigation in the Shoubak area, where thickness of the saturated aquifer is not thick with complicated geological structures, lowers the piezometric surface in the northwestern part of the Jafr basin. Of the schemes formulated for the conjunctive water development, groundwater recharge dams are deemed to be effective for the area of the Western Highlands. It is recommended that further studies be made on the particular dam schemes whenever such irrigation development become needed.

- Domestic sewerage and/or irrigation return flow in the outcrop area of the B2/A7 in the Western Highlands shall be controlled to protect the quality of groundwater in the B2/A7 aquifer from the contamination.

Groundwater Monitoring

- WAJ's efforts in groundwater monitoring need to be continued. It is recommended that the amount of pumping discharge of each production well be monitored not only in respect of the government owned wells but also of the private owned ones.

- As to groundwater monitoring in the lower Ajlun (A1-6) aquifer, it is recommended that the water quality monitoring and isotope dating in the test well of JT-3 be carried out by using the depth water sampler.

- Prior to development of any potential wellfields, it is recommended that a monitoring well be constructed in the center of the group of wells.

Salt Accumulation Problem in Rijam (B4) Aquifer

- Salt accumulation problems in the Rijam (B4) aquifer are still critical. It is recommended that the monitoring work which comprises the measurement of both soil salinities and water salinities be continued. Counter-measure such as replacing the irrigation method from the existing gravity flow to the drip method, will be useful in reducing the salt accumulation in the Rijam (B4) aquifer.

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LIST OF ABBREVIATIONS (1/2)

JICA	=	Japan International Cooperation Agency
Government	=	Government of Jordan
MOWI	=	Ministry of Water and Irrigation
MOP	=	Ministry of Planning
WAJ	=	Water Authority of Jordan
JVA	=	Jordan Valley Authority
MOA	=	Ministry of Agriculture
NRA	=	Natural Resources of Authority
RSS	=	Royal Scientific Society
JNGC	=	Jordan National Geographic Center
JEC	=	Jordan Electricity Authority
JEPCO	=	Jordan Electric Power Company
S/W	=	Scope of Work
C/P	=	Counterpart Personnel
M/P	=	Master Plan
Pre-F/S	=	Pre-feasibility Study
F/S	=	Feasibility Study
KV	=	Kilo Voltage
KW	=	Kilo Watt
KVA	=	Kilo Voltage Ampere
hr/hrs	=	Hour/Hours
km^2	=	Square Kilometer
ha	=	Hectare
l/s	=	Liter per Second
m^3/h	=	Cubic Meters per Hour
m^3/s	=	Cubic Meters per Second
m^3/d	=	Cubic Meters per Day
bs/ft	=	Pound per Foot
MCM	=	Million Cubic Meters
MCM/y	=	Million Cubic Meters per Year
MCM/m	=	Million Cubic Meters per Month

LIST OF ABBREVIATIONS (2/2)

PG	=	Palestine Grid
E.L/G.L	=	Ground Elevation
S.W.L	=	Static Water Level
ppm	=	Parts per Million
mg/l	=	Milligram per Litter
T.D.S	=	Total Dissolved Solids
E.C	=	Electric Conductivity
VLF	=	Very Low Frequency
Al/Bslt	=	Alluvium/Basalt
O & M	=	Operation and Maintenance
M & I	=	Municipal and Industrial
API	=	American Petroleum Industry
FEM	=	Finite Element Method
FDM	=	Finite Difference Method
UNISSF	=	Unified Normal and Inverse Sub-Surface Flow Analysis Program
Fig.(s)	=	Figure(s)
Tab.(s)	=	Table(s)
Ref.(s)	=	Reference(s)

I. INTRODUCTION

I. INTRODUCTION

1.1 Background

The Hashemite Kingdom of Jordan is making steady in the economic development of the country, but is handicapped by the limited availability of water. Great efforts have been made in the water resources development sector with the allocation of JD 250 million in the 1981-1985 five-year plan or about one sixth of the national budget. Such efforts will be continued also in the future.

Among several measures taken by the Government of this sector, the Water Authority of Jordan (hereinafter referred to as WAJ) was established in 1983 mainly to have responsibility for the nationalization of water allocation in the entire Jordan. Then on 10th January 1988, the Ministry of Water and Irrigation (MOWI) was established. The WAJ and the Jordan Valley Authority (JVA) are functioning under the regulation of the new ministry.

Distribution of rainfall in Jordan is biased to the northern and north-western parts of the territory. Accordingly, studies on water resources and their development were commenced from such areas and were promoted approximately in the order of their amount of rainfall. In consequence, the areas which receive less rainfall were left for the future study. Notable wadi basins of such category were the Mujib basin, the Hasa basin and the Jafr basin. Of these, the study of the Mujib basin, which is located adjacent to the capital was carried out with bi-lateral foreign aid from Japan during the period from 1985 through 1987, and the latter two basins remained to be studied taking account of the following three previous studies of; i) the hydrogeological investigation which was initiated by United Nations Development Program in 1970 (Ref.1.1), ii) the national water master plan study which was conducted by the German Technical Cooperation Agency in 1977 (Ref.1.2), and iii) the groundwater resources study in the Shidiya area which was carried out by Natural

Resources Authority of Jordan (NRA) in 1986. (Ref.1.3)

The Government of the Hashemite Kingdom of Jordan (hereinafter referred to as "the Government of Jordan") decided to implement the the study on the water resources of the Jafr basin and the upper Hasa basin which are adjacent with each other, and requested the Government of Japan to provide the required the technical assistance. In response to this request the Government of Japan through the Japan International Cooperation Agency (hereinafter referred to as "JICA") the sole official agency for the implementation of the technical cooperation programs of the Government of Japan commenced to undertake the Study in close cooperation with the Government of Jordan through WAJ as an executive agency of the Study. In a short period of time, JICA organized a Preliminary Study Team and dispatched it to Jordan in February 1988. The Scope of Work (the S/W)for the Water Resources Study of the Jafr Basin (hereinafter referred to as "the Study") was agreed upon 25 February,1988. Then, JICA further organized a team for the Study (the Study Team) and dispatched it to Jordan on 6 July 1988. This Study has now been completed.

1.2 Concept and Objectives

Concepts

The basic concept of the Study is firstly to evaluate the potential of water resources including both groundwater and surface water, so that the results could be useful for the Government in planning the water allocation on the national basis, and to plan promising facilities for use of such water for the most beneficial purposes.

Objectives

The long-term development objectives are to develop economic and satisfactory water supply sources to sustain public water supply to the local cities and/or metropolitan area. These objectives are in accordance with the priorities expressed in the Government's Third Five Years Plan for the period 1986-1990 which put stress on the need to augment the supply of drinking water .

The objectives of this study were to execute hydrological and hydrogeological studies and to evaluate the potential of water resources in the Jafr Basin and upper Hasa Basin with an approximate area of 14,400 Km^2. (Hereinafter referred to as "the Study Area", See Location Map)

The Study will also contribute to the goal and targets set by the Government's National Water Carrier Scheme which integrates national water resources in Jordan.

1.3 Study Tasks

The Study comprises four stages of the investigations 1st through 4th as follows and as shown on Fig.1.2:

<u>The First Stage Tasks</u> ; (July 1988 - March 1989)

The 1st stage field investigation comprised data collection and field investigations. The data collection and review of existing reports on topography, geology, hydrology, hydrogeology and water resources development, which were performed with close coordination with WAJ, included following;

- Topographical maps (1/50,000), aerial photos (1/50,000) and Landsat imagery (1/750,000)
- Geological maps (1/50,000 - 1/1,000,000) and hydrogeological maps
- Land use map and population data
- Meteorology
- Soil moisture
- Stream flow and suspended solid in the flash flood
- Well inventory

- Test well drillings and pumping test
- Water quality test

After field reconnaissance surveys and examining existing data, the Inception Report was submitted to the WAJ in August 1988.

Geological and hydrogeological mappings were performed prior to geophysical prospecting by VLF (Very Low Frequency) method. The geological mapping was carried out to examine the stratigraphy, micro paleontology and geological structures of the sequences from lower Ajlun (A1-6) formation to alluvial, which includes the survey for the proposed groundwater recharge dams. The VLF survey was performed to delineate the salt-accumulated areas in the Rijam (B4) aquifer and to examine the effects by faults such as "Salwan" and "Karak - Wadi Al Fiha" on the hydrogeology of the shallow units. After geological reconnaissance, a technical specification was prepared for tendering for test well drillings following WAJ's tender procedure. The test well drillings included four test wells and three observation holes with a total depth of 2,940 m. These were carried out in the area along the "Salwan" fault and "Karak - Wadi Al Fiha" fault where neither geological nor hydrogeological data could be available from the previous studies. The drilling work was carried out by local contractor "Equipment and Sales Co.," under the supervision by JICA drilling expert. The exploratory drilling was aimed to assess the aquifer parameters and the geological and/or the hydrogeological discontinuities in the B2/A7 and/or A1-6 units. During this period, groundwater monitoring, which comprised water level measurements and water samplings and testings, was carried out in cooperation with WAJ's monitoring department and laboratory, including installation of four automatic water level recorders JT-1, JT-3,JO-3 and JO-5.

Prior to hydrogeological analysis, the hydrological analysis was performed to evaluate the potential of surface water. The analysis was based on the existing data, including;

- Runoff analysis by using tank model method
- Flood frequency analysis
- Sedimentation analysis

A seminar on surface hydrology was held in November 1988, to discuss the reliability of the existing data collected and the method of analysis to be carried out. The hydrological data book was submitted to WAJ counterpart team, including the mini-floppy diskettes which store all the raw data such as rainfall and flow discharge by using the IBM-PC compatible data base"Lotus 1-2-3".

The 1st stage analysis compiled the results of the investigation and the analysis mentioned above, and the Progress a Report was submitted to the Jordanian side in March 1989.

The 2nd Stage Tasks ; (May 1989 - September 1989)

The 2nd stage field investigation was initiated by discussing the Progress Report. The hydrogeological analysis was carried out to construct the groundwater simulation models of both B2/A7 and A1-6. The computer program of UNISSF, which was designed for the FEM simulation model,was transferred to WAJ's VAX-8200 computer system. During this period, groundwater monitoring was also continued.

The first seminar on the groundwater model simulation was held in July,1989, to transfer the computer program of the UNISSF which was written by FORTRAN language and its use in the B2/A7 steady state modeling. Prior to transfer of the UNISSF program, a simplified FEM groundwater simulation program, written in BASIC language, was demonstrated to show use of the graphic display (contour mapping) of the IBM-PC compatible micro-computer. The simulation manual version (1.0), which explains the method of the steady state model calibration, was submitted to WAJ counterpart team. The manual (ver.1.0) comprises the method of transferring micro-computer data base (IBM-PC compatible) to VAX-8200 by means of RS-232C data communication system. The mini-floppy diskettes, which store the input data such as mesh grid, boundary conditions, aquifer parameters and geologic conditions, were also handed over to WAJ.

The 2nd stage analysis is carried out to delineate the potential aquifers and well fields. Water demand and frames of the water resources development plans were studied. Potential analyses were carried out by using the simulation models including;

- Steady state calibration of the groundwater simulation models (B2/A7, A1-6)
- Non-steady calibration of the groundwater simulation model (B2/A7)
- Simulations for alternative groundwater development plans
- Hydrochemical analysis and simulation of the B4 aquifer (salt-water balance simulation by using tank model)

The 2nd stage analysis compiled the results of the investigation and the analysis mentioned above, and the Interim Report was submitted to the Jordanian side in October 1989.

<u>Third Stage Tasks</u> ; (October 1989 - January 1990)

The 3rd stage filed investigation comprised discussion on the Interim Report and alternatives of the water resources development plans, groundwater monitoring and transfer of the computer simulation models and the input data.

The second seminar on groundwater model simulation was held in October 1989, to transfer the simulation models of both B2/A7 and A1-6. The simulation manual version (2.0), which explains the method of non-steady state model calibration for the B2/A7, was submitted to WAJ counterpart team. The 2nd seminar also demonstrated the method of using computer plotter (CALCOMP-1043) which is installed on the 7th floor of WAJ computer room. The mini-floppy diskettes which store the input data of i) mesh grid, ii) boundary conditions, iii) aquifer parameters, and ix) geologic conditions were also handed over to WAJ.

The 3rd stage analysis included 1) conceptional design of the water source facility and its preliminary cost estimate for the selected alternatives, 2) water demand and model predictions, 3) master plan study of the water resources development, 4) institutional study on the groundwater monitoring plan for the selected plan and 5) compilation of draft final report.

The Fourth Stage Tasks ; (February 1990 - March 1990)

The Draft Final Report was explained to and discussed with the Government. The 3rd computer simulation seminar was held to transfer the technology of operating the simulation models. A final report is herewith prepared, scrutinizing the Government's comments.

1.4 Personnel

The Study Team organized by JICA has 6 members. The members with their assignment schedule are shown on Fig.1.1.

The Study Team received counterpart services from the Jordanian side through the Department of Water Resources Study of WAJ. The counterpart personnels were assigned from the said Department including the senior members listed in Table 1.1.

Furnished office space was provided to the Study Team during its stay in Jordan mainly in the said Department of WAJ. Two 4-wheel drive Nissan Patrols were procured by JICA, while the drivers and fuel were provided by WAJ.

1.5 Acknowledgments

In undertaking the Study, the Study Team has attached great importance to the incorporation of the views of MOP and WAJ. The contribution to the Study by the officials of the Government of Jordan who have provided information and data, participated in meetings and discussions, given valuable advice and provided other forms of assistance to the Study are gratefully acknowledged.

Special gratitude is expressed to all the members of the Department of Water Resources Study including those who worked as counterpart personnels, to the Department of Drilling of WAJ for providing data and records, and to other Departments of WAJ for giving the information.

Heartfelt thanks are also given to the following:

- Ministry of Water and Irrigation
- Ministry of Planning,
- Ministry of Public Works,
- Natural Resources Authority
- National Geographic Center
- Central Bank of Jordan,

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II. STUDY AREA

II. STUDY AREA

2.1 Socio-economy

2.1.1 Background

The Hashemite Kingdom of Jordan is located in the northwestern part of the Arabian peninsula, which extends from 29 to 33 degrees of north latitude and from 35 to 39 degrees of east longitude. The country which covers an area of about 89,206 km^2 is bounded by Syria on the north, by Iraq on the east, by Saudi Arabia on the south and southeast and West Bank on the west. Jordan, which has a relatively high population growth rate and a little suitable land for agricultural use and is not an oil-producing country, is in financial difficulties. To relieve such difficulties, the Government has made intensive efforts to increase the export of commodities by developing industries, improving the agricultural technology and raising the educational levels. Water, which is essential for development of industry and agriculture, however, is so scare in Jordan as to be insufficient even for domestic purposes.

2.1.2 Population statistics

The population of Jordan was approximately 2.9 million in 1987 and must have exceeded 3 million in 1988. The annual rate of population increase in recent years has been 3.6-3.8%.

Jordan is divided into eight Governorates (Gov.), with Amman Gov. which includes the capital city is the most densely populated with 41.5% of the national population. The three Govs. of Amman, Zarka and Irbid contain as much as 80.3% of the national population leaving the other Govs. populated sparsely. The population from 1983 through 1987 by Gov. is shown on Table 2-1.

The Study area is located mostly in the Ma'an Gov. and partly in the Tafila Gov. As the Study area belongs to the arid area, the population is very sparse. In year 1987, the populations of the towns and villages in the Study area within the Ma'an Gov. were 15,815 in Ma'an, 1,630 in Jafr, 2,502 in Husseiniya and 195 in Mohamadya. These populations fluctuate considerably since the bulk of the populations are nomads. In the Hasa town, no population statistics are available, yet the population is estimated at some 5,000 in the town and some 2,000 at the Hasa phosphate mine.

2.1.3 Agriculture

As the Study area is extremely arid, the land use for agriculture is to be found. In the upper Hasa basin almost no agricultural land use is observed. In the Jafr basin, some oasis agriculture is being practiced near Jafr town, and several scattered farm projects are to be found in the western part of the basin. These projects do not depend on rainfall but the tube wells.

In the northwestern part of the Jafr basin where the ground elevation exceeds 1,200 m, extensive agriculture development is being carried out to take advantage of the higher rainfall of more than 200 - 300 mm per annum and the cool weather. The Abu Makhtoub and Shoubak project, which extends over 633 ha, depends on 17 wells owned privately by 14 farms for irrigating apples and horticulture.

The Husseiniya project (100 ha) and the Mohamadya project (100 ha) located between Hasa and Ma'an towns depend on two and three tubewells respectively for cultivation of the fodder grasses, fruit trees and vegetables. The Al'Qasimya project (117 ha) and the Wuheida projects (171 ha) located to the southwest of Ma'an town depend on two tubewells each for irrigating apples and grapes.

The Al'Jafr project (245-100 ha) located near Jafr town depends on four shallow tubewells in the Rijam aquifer for supplying domestic water to the town as well as for irrigating fodder crops. One of these wells has suffered from salinization, and a study on this phenomenon is treated in Chapter V of this Report.

2.1.4 Manufacturing industry

Near Hasa town, there is the Hasa Phosphate Mine producing more than 3.4 million tons a year of natural phosphate. This is the largest phosphate mine in Jordan, and contributes greatly to hard currency earnings. This mine uses 10 tubewells. The well water is used solely for the self-consumption especially for ore washing.

Near Husseiniya town, there is a factory for bottling mineral water. The water depends on tubewells owned by the bottlers.

In Ma'an town, there are small factories including one glass factory. The water source depends on the city water supply.

The Shidiya phosphate mine, which is located to the southeast of Ma'an town will be the biggest mine in the Hashemite Kingdom of Jordan, when it starts operation.

2.1.5 Public facilities

The Desert Highway which traverses the nation in a north-south direction runs through the western side of the Study area. The King's Highway which has been maintained since historical times lies on the western boundary of the Jafr basin. There is a motorable road from Ma'an town to Jafr town along, and from there to Azraq along a newly constructed road. The above-mentioned roads are all paved with asphalt and maintained reasonably. A few feader roads are available in between these roads and highways.

There is an existing railroad from Hasa mine to Aqaba sea port. This railroad is used solely to transport the phosphate ore for export.

Most of the towns and villages are supplied with electricity from the national grid, and likewise with the domestic water supply.

2.1.6 Water resources development

Water resources in Jordan are being exploited for the use of drinking and domestic uses , industry and irrigation. It is said that 96 per cent of the Kingdom's population is now supplied with drinking water from springs and underground artesian wells. A series of water resources development projects have been carried out including 20 MCM/y of Wadi Al Araba groundwater project near Irbid, 15 MCM/y of Qastal groundwater project near Amman, 14 MCM/y of Zarqa groundwater project, 45 MCM/y of Deir Alla (canal) base flow water project, 3.5 MCM/y of Sultani groundwater project near Karak, 1.5 MCM/y of Shoubak groundwater project, and 17 MCM/y of Disi groundwater project.

2.1.7 Water Demand

According to an estimate by the Ministry of Water and Irrigation in 1988, Jordan is expected to require nearly 266 MCM of water for annual consumption by the year 2005. This suggests a shortage of 75 MCM per annum and that intensive efforts will have to be made to find new water resources to meet the growing demand on water for different purposes.

Water demand in the Study area is largely dependent on the operation program of the Shidiya phosphate mining development project, which will require 6 MCM/y by the year 1992, and 20 MCM/y for full scale development.

2.2 Present Condition

2.2.1 Topography

The Hashemite Kingdom of Jordan covers an area of approximately 89,206 km^2 in the northwestern part of the Arabian Peninsula. It has been divided into physiographic provinces, which coincide with the seven geologic provinces: "Southern mountain desert", "Mountain ridge and northern highlands east of the rift", "Central plateau (includes Al Jafr and Al Azraq-Wadi as Sirhan basin)", "Northern plateau basalt", "Northeastern plateau","Wadi Al Arab-Jordan rift" and "Highlands west of the rift".(Ref.2.1, see Fig.2.1)

The Study area, which covers the two watersheds of "Jafr basin" and "upper Hasa basin", is located in the southern part of the Central Plateau. The Jafr basin, which is about 150 km long NW-SE and about 100 km wide, displays a typical centripetal drainage pattern with all wadis draining from the encircling highlands to a central playa. The drainage system has a catchment area of 13,450 km^2 Km with an extensive mudflat (240 km^2). The upper Hasa basin with a catchment area of 2,198 km^2 shows topography like a centripetal drainage pattern with a playa "Qa El Jinz", but it is drained by wadi Hasa to the northwest into the Dead Sea. (See, Location Map)

The highest altitudes in the Study area (1,733 m) is in the western mountain ridge of the Jafr watershed, while the lowest (845 m) is in the center of the playa "Qa El Jafr".

2.2.2 Geology

In the study area, the geology is of sedimentary origin, ranging in age from Cambrian to Recent except in the north-western areas, where volcanics of the Quarternary age occur. The sedimentary succession which is between 2,000 and 3,000 m thick is mainly due to a series of regional regressions and transgressions of the Tethys sea. The lower part of the sedimentary sequence comprises mainly sandstones of Paleozoic and lower Mesozoic age, while the upper part is mainly composed of limestones, marls and cherts of upper Mesozoic and Cenozoic age. (Refs. 2.2 to 2.6)

Lithologic Composition

The Disi group, which is the oldest succession unconformably overlying the basement complex, was exclusively continental in the Cambrian but became mixed marine and deltatic and finally fully marine in the early Ordovician when the first major transgression of the Tethys across

Jordan occurred. The Khreim group, which comprises mainly fine-grained sandy and argillaceous materials, were deposited in an unstable shallow marine environment at the unstable shelf edge of the Tethys during the middle and late Ordovician and the early Silurian. These sedimentary basins were centers of subsidence throughout the Paleozoic.

From the Silurian through the late Jurassic, the Tethys sea underwent a series of discontinued transgressions and regressions, however, regional crustal epeirogenic movements uplifted and tilted the southern Transjordan block to the east, by following the erosion of the Disi and Khreim.

The Kurnub group, which is composed of sandstones with shales, shows the marine to brackish influence of the major Tethys transgression after the Silurian Age.

Beginning in the late Cretaceous (Cenomanian), a regional transgression started to spread, however, the continental depositional environment of sandy sedimentation, which formed in the early Cretaceous, continued in the late Cretaceous, including the Santonian. The marine calcareous, marly and siliceous rock units of the Cenomanian, Turonian, Santonian, Campanian and Maestrichtian overlay these continental sandstones with onlap toward the southeast. Great thicknesses of sediments which accumulated in the areas occupied by the Tethys sea such as along the Jafr basin. In the west, the Ajlun formation is a calcareous marine feces, but southeast of the oscillating Tethys sea, east of the Jafr basin becomes a continental sandy feces. In the late upper Cretaceous (Campanian and Maestrichtian) when the Mesozoic extent of the Tethys sea was at its greatest, the shallow marine marls and limestones of the lower Belqa (the Amman formation and parts of the Muwaqqar) were laid down. These sediments transgressively overlap the lower parts of the upper Cretaceous sequence to the southeast. A thick pile of bituminous shales, which belong to the Muwaqqar of the middle Belqa continued into the early Eocene, was accumulated in the El Jafr basin in particular. The shallow marine limestones of the Rijam series, which are the last sediments of the Belqa, were deposited in the late Eocene.

Geologic groups comprise "Disi", Khreim", "Kurnub", "Ajlun" and "Belqa". None of the deep test wells which were drilled in the Study area penetrated the groups of "Disi", "Khreim" and "Kurnub". The Ajlun group is composed of two formations of "Lower Ajlun (A1-6)" and "Wadi Sir (A7)", while the Belqa group includes three formations of "Amman (B1/2)", Muwaqqar (B3)" and "Rijam (B4)" The Ajlun group is collectively referred to as the "A(1-7)" and the Belqa as the "B(1-4)".

In the southern area of the central plateau, a formation name of the "Fassua" for the entire Ajlun was proposed by Weisman in 1966, because of the difficulties of distinguishing the formation units in the Ajlun group. The "Fassua" formation which has its type section on the escarpment near Batn el Ghul in fact represents only the lower A1 to A6 formations of the Ajlun group. Since the Wadi Sir (A7) formation is of importance to the Study and can be identified over most of the area, the multiple formation name "Fassua" was abandoned in favor of more descriptive terminology of lower Ajlun referred to as A1-6 formations, and the Wadi Sir (A7) for the uppermost Ajlun group.(See Table 2.2)

Lower Ajlun (A1-6) Group

The earliest late Cretaceous sedimentation in west, north, and central Jordan is marked by a marine calcareous facies, whereas in the southeast of Jordan, deposition of sandy sediment continued in a continental environment. Alternating limestone, dolomite, sandstone, marl, shale and very few cherts were deposited on top of the Kurnub group of the lower Cretaceous. A deposition from the lower to middle Cretaceous is interpreted to transgress the time boundary between the two groups.

In the Study area, the lower Ajlun (A1-6) has littoral sandy facies almost entirely, which contains some limestones in the southeast and become more shaly and marly in the east. In the east of the Study area, the lower Ajlun sequence thins out and becomes diachronous with the Subeihi formation of the upper Kurnub. In general, the formation is up to about 400 m thick in the Jafr trough but becomes thinner to the south. The thickness is about 300 m in the northeast of the Jafr basin, whereas it is about 200 m in the southern area such as in Shidiya.

The elevation of the top of the Kurnub (equivalent to the bottom of the Lower Ajlun) formation is shown in the structure contour map of Fig.2.3. Fig.2.4 shows the isopach map of the lower Ajlun formation. From the map, the lower Ajlun (A1-6) appears deepest at elevation 100 to 400 m in the Jafr trough. The formation thickness is about 250 m in the Jafr trough but less than 150 m in the Shidiya. South of Shidiya, the formation decreases in thickness to the south and finally disappears at the boundary of Jafr watershed.

Wadi Sir (A7) Formation

The Wadi Sir (A7) formation comprises the uppermost part of the Ajlun group. It outcrops in the Western Highlands but disappears in the southern escarpment. In the Study area, the sequences of A7 are almost entirely littoral facies, which are mainly composed of sandstone, calcareous sandstone, sandy limestone, marly limestone and limestone. In the Western Highlands, the formation is mainly limestones with chert bands but becomes sandy to the south and to the east. In the northern Study area, lithological facies are calcareous sandstones and/or sandy limestones, whereas it changes predominantly sandy nature in the southern Jafr basin.

The elevation of the top of the lower Ajlun (A1-6) formation is shown in the structure contour form in Fig.2.5, and the isopach map of Wadi Sir (A7) formation in Fig.2.6. From the maps, the A7 formation appears deepest at elevation 400 to 750 m in the Jafr trough. The formation thickness is about 50 to 100 m in the Study area, but less than 50 m in the southern Jafr such as in Shidiya area. South of Shidiya, the formation decreases in thickness to the south and finally disappears at the boundary of Jafr watershed.

Amman (B2) Formation

The lowest part of the Belqa group is composed of two formations such as Ruseifa (B1) and Amman (B2). The Amman (B2) formation is a litho-stratigraphically continuous unit, and has been found to occur over the study area, while the Ruseifa (B1) formation is thin and not a continuous unit in the sedimentary sequence. Because of the difficulties in distinguishing the formation unit of the Ruseifa (B1), a formation name of Amman (B2 and/or B1/2) is used to synthesize the geological unit of B1 and B2.

The Amman (B2) formation comprises two members of upper (B2b) and lower (B2a). The upper (B2b) is composed of phosphorite member of Campanian Age, while the lower (B2a) consists of silicified limestone member of Santonian to Campanian Age. The silicified limestone member intercalates alternating this bedded silicified limestone with chert, marly limestone, marl and limestone, while the phosphorite member consists of alternating thin-bedded limestone, more-or-less silicified or calcified phosphorite layers and coquina beds.

The formation outcrops in western and southern part of the Study area forming a hard, erosion resistant cap-rock to the underlying Ajlun group.

The elevation of the top of the Wadi Sir (A7) formation is shown in the structure contour map of Fig.2.7, and isopach map of Amman-Ruseifa (B1/2) formation in Fig.2.8. From the maps, the B2 formation appears deepest at elevation 450 to 850 m in the Jafr trough. The formation is up to 50 to 100 m or more thick in the Jafr trough, while it is less than 50 m thick in the central area such as in Al Jafr playa and southern part of the Jafr basin.

Muwaqqar (B3) Formation

The Muwaqqar (B3) formation comprises the upper part of the Belqa group of Maestrichtian Age. The formation consists of marl-chalk members such as soft chalk, marl, bituminous marl and shale.

The Muwaqqar was deposited mostly in the late Mesozoic, but its deep portion in the northwest Jafr trough continued being deposited into the upper most Cretaceous.

The formation outcrops extensively throughout the Study area except in the Western Highlands and southern part of the Jafr basin. In the south, the Muwaqqar consists mainly of marls and chalky limestones. While in the central and northwestern area, the formation thickens rapidly with a distinctive sequence of bituminous marls and shales. These thick argillaceous strata are the sediments in the deep-sea environment.

The elevation of the top of the Amman (B2) formation is shown in the structure contour map of Fig.2.9, and isopach map of Muwaqqar (B3) formation in Fig.2.10. From the maps, the B3 formation appears deepest at elevation 500 m in the northwestern Jafr basin, where the thick sequence, is restricted to the Jafr trough that strikes northwest, with a maximum thickness of 450 m in the deepest trough.

Rijam (B4) Formation

The Rijam (B4) formation comprises the upper most Belqa group of upper most Cretaceous to lower Eocene. The formation consists of massive limestone intercalating with crystalline chert limestone and marly limestone.

The formation outcrops extensively in the northern part of the Jafr basin. The deposit is restricted to the area from the center (Al Jafr) to the northwestern Jafr basin mainly along the Jafr trough.

The elevation of the top of the Muwaqqar (B3) formation is shown in the structure contour map of Fig.2.11, and isopach map of Rijam (B4) formation in Fig.2.12. From the maps, the B4 formation appears deepest at elevation 800 m in the central Jafr basin (at Al Jafr air port), where the thickness is approximately 50 m. The sequence is restricted to the Jafr through, and thickens to the northeast from 50 to 100 m or more.

Geological Structure

In the Study area, four major structural provinces may be distinguished according to their structural evolution, types of deformation, and pattern; namely i) north-west striking normal faults, ii) west-east fault, iii) north-south striking fault zone (frexure) and iv) Jafr trough.

North-West Striking Normal Faults

The most prominent fault of this area is the "Karak - Wadi Al Fiha" fault, which extends to more than 300 km from Karak in the northwest to Saudi Arabia in the southeast. The fault is not a continuous system, but consists of a series of the discrete faults.

The fault intersects the eastern boundary of the Study area from northwest to southeast, which is composed of a series of graben-horst structures with vertical displacement. The displacement is estimated to be about 100 m such as at the northeastern part of the Jafr basin as seen in Fig.2.13. The fault appears to be diminishing southeastward, and it may die out in that direction.

West-east Faults

These occur in the northwestern part of the Jafr basin. Of significance is the "Salwan" fault zone which intersects the northern part of the Jafr basin from west to east. The "Salwan" fault zone is extensive, but it is not a continuous structure which is frequently cut by a series of north-south trending discrete faulting systems. It is well defined to the north of Shoubak, but disappears north of Husseiniya. To the northeast of the Jafr basin, the faulting system can be traced as "horse tail" faults aligned WNW-ESE, which parallel the long axis of the Jafr trough. The lineaments seem to continue into the Bayir Block by crossing the "Karak - Wadi Al Fiha" fault zone. The maximum vertical displacement is estimated to be about 200 m at where the adjacent Jafr trough deepens the depth up to 500 m. (See Figs.2.14 to 2.16)

North-South / North-West Striking Faults

These are sub-parallel to the Wadi Araba-Jordan Garden and form small graben and horst structures. Of significance is the "Arja-Uweina" flexure/fault zone which extends from Jabal El Batra in the south to a few kilometers west of Jebel Uneiza in the north. At its northern end it appears that this tensional fault system has allowed the intrusion of a basaltic dyke which follows the alignment of the fault but becomes truncated by the east-west trending "Salwan" fault.

Jafr Trough

The most prominent geological feature in the Jafr basin is the Jafr Trough, which is bounded by the two parallel faulting zones with approximate WNW-ESE strike. The formations in the trough are controlled by the post Paleozoic sedimentations, of which the geological development can be traced by a series of increasing in the thickness of the progressively younger strata. The sediments thicken at the center of the trough where the Muwaqqar (B3) formation in the Maestrichtan epoch exceeds a thickness of 450 m.

2.2.3 Drainage

The Jafr basin is located in the southern part of the central Jordan plain and lies to the east of the Western Highlands. The basin has an area of 13,500 km^2, most of which is classified as arid desert with mean annual rainfall of about 50 mm. The basin displays a classic centripetal drainage pattern with all wadis draining from the encircling highlands to the central El Jafr Playa, the largest concave in Jordan. The catchment lies at elevations between 850 m in the El Jafr Playa and 1,750 m in the Western Highlands. (See Fig.2.17)

The Upper Hasa basin is separated from the northern Jafr Basin by watershed. The catchment area is about 2,200 km^2, and lies at elevations between 400 m at the basin outlet near Tannour and 1,250 m in the Eastern Highlands. The wadis in the Southern-western Highlands are characteristically narrow and moderately incised, while wadis are flat in the eastern part of the basin where the elevation is about 900 m. All the wadis in the upstream reaches drain flushing floods to the central playa named Qa El Jinz. (See Fig.2.17)

2.2.4 Climate

The whole of eastern Jordan lies within the Mediterranean bioclimatic region and the study area has a Mediterranean Saharian climate of the warm variety (Long,1957), being classified as arid (Miller,1951).

Climatological data of the study area, except rainfall, are summarized for the period between October 1977 and September 1988 (See Table 2.3).

Temperature

According to Table 3.1, the annual minimum temperature is recorded in January, ranging from 3.9° C at Hasa to -2.6° C at Udruh on average, with the annual maximum temperature recorded in July or August, ranging from 35.5° C at Jafr to 27.4° C at Shoubak on average. Relative humidity is as low as 30's or 40's in percent in May to October and as high as 60's or 70's in percent in December to January.

Rainfall

There are 53 rainfall gaging stations in and around the study area which locations are shown on Fig.2.18, and the gaging type is shown in Table 2.4 together with dates opened and closed.

An isohyetal map of annual rainfall of the study area was made from available rainfall data between October 1937 and September 1988. (See Fig.2.19). From the isohyetal map , it is found that the annual rainfall decreases from 300 mm in the western watershed to less than 50 mm in its eastern part.

Annual rainfall of the Upper Hasa basin, the Wadi Jurdhan and the Jafr basins was estimated by the Thiessen method and by applying long-term annual rainfall for the period between 1937/38 and 1987/88 of gaging stations within each polygon.

Accordingly, annual rainfall of the Upper Hasa basin, the Wadi Jurdhan and the Jafr basin is estimated at 89 mm, 129 mm and 52 mm, respectively.

From the view point of annual rainfall pattern, a year is divided into two distinct seasons, namely, the rainy season from October to May and the dry season from June to September.

Evaporation

As may be seen from Table 3.1, the annual total evaporation measured by a class-A pan ranges from 1,800 mm at Shoubak to 4,200 mm at Jafr. At all the stations, about 70 % of annual evaporation is recorded between April and September.

2.2.5 Present use of water resources

Present use of water resources in the Study area is dependent on the groundwater resources in the B2/A7 aquifer. A very small amount of 1.1 MCM/y, however, is being pumped from the shallow unconfined aquifer of B4 to irrigate the pilot firms. Abstractions are preliminary estimated by WAJ at 18.4 MCM/y in total, which includes the biggest consumer of the Hasa phosphate mine of 7.4 MCM/y, and Shoubak irrigation of 3.3 MCM/y. No surface water is used, whereas 0.75 MCM/y of spring water is being used for local villages and firms in the Western Highlands.

EFERENCES (2)

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2.2 United Nation (FAO), 1970, "Investigation of the Sandstone Aquifers of East Jordan, Main Report and Annex I"

2.3 German Agency for Technical Cooperation Ltd., Federal Republic of Germany, 1977, "National Water Master Plan", Vol.I,II,III,IV,V,VI and VII

2.4 Howard Humphreys, 1986, "Groundwater Resources Study in the Shidiya Area"

2.5 The government of Jordan, 1958, "Geological Map of Jordan (Aqaba-Ma'an, S=1/250,000)

2.6 The government of Jordan, 1975, "Geological Map of Jordan (S=1/500,000)"

III. WATER RESOURCES

III. WATER RESOURCES

3.1 Flood Analysis

3.1.1 Duration of storms

A. Duration of storms of the Upper Hasa basin

Concerning areal distribution of rainfall within the basin, it is observed that floods with large peak discharges are caused by rainfall which is concentrated in limited areas within the basin.

Though no data are available to clarify a depth-duration relationship on an hourly basis for upstream areas of the Upper Hasa basin, it seems relevant to apply hourly rainfall data of any of the three stations (namely, CF0007, CF0008 and DB0002) to determine duration of storms of the Upper Hasa basin. This is because most of the runoff at the basin outlet is considered to be caused by rainfall which precipitates in the western half of the Upper Hasa basin as understood from the isohyetal map (Fig.2.19).

On average, the duration of storms is 20 hours for station No. CF 0007, 28 hours for station No. CF 0008 and 32 hours for DB 0002. This means that the duration of storms tends to become longer in the western part of the basin where more annual rainfall is observed. In this analysis, the duration of storms used in estimation of probable floods is chosen at 28 hours which is the average duration of storms for station No. CF 0008, because this station is intermediate in terms of annual rainfall amount and duration of storms among the three stations.

B. Duration of storms of wadi Jurdhan

There are 4 rainfall stations in and around the wadi Jurdhan. Among these, stations No. G 0003 and G 0010 which are located near the basin outlet in the eastern part have a shorter duration of 15 to 16 hours than stations No. DG 0001 and DH 0001 which are located near the western watershed outside the wadi Jurdhan and with storm durations of 22 to 24 hours.

The long-term annual rainfall of stations G 0003 and G 0010 is less than 50 mm while that of stations DG 0001 and DH 0001 is about 180 mm. From this, it is considered that most of the runoff at the basin outlet is considered to be caused by rainfall which precipitates in the western part of the Jurdhan basin and whose rainfall pattern in terms of duration and depth-duration relationship is considered more similar to those of the stations No.DG 0001 and DH 0001.

In this analysis, the duration of storms used in estimation of probable floods is chosen at 24 hours. This is the average duration of storms for station No. DH 0001 because the depth-duration relationship of station No. DH 0001 is obtained for a larger amount of rainfall than station No. DG 0001 though the long-term annual rainfall of these stations is nearly equal.

3.1.2 Probable rainfall

A. Probable rainfall of major rainfall stations

Relationships between rainfall intensity, duration and frequency of 40 rainfall stations in Jordan are tabulated and graphically shown for duration of 5 minutes to 24 hours and return periods of 2 to 500 years (See Ref.3.1). Such relationships of 8 rainfall stations in and around the study area (namely, CD 0013,CF 0007, CF 0008, DB 0001,DC 0002,DG 0001,DH 0003 and G 0003) are available in this study paper (See Table 3.1).

B. Probable rainfall of Upper Hasa basin

Probable rainfall of the Upper Hasa basin is obtained by multiplying probable rainfall of the rainfall station No. CF 0008 with the ratio of long-term annual rainfall between rainfall station No. CF 0008 and the Upper Hasa basin. Long-term annual rainfall between year 1937/38 and

1987/88 is 136 mm for rainfall station No. CF 0008 and 89 mm for Upper Hasa basin.

C. Probable rainfall of wadi Jurdhan

Probable rainfall of the Jurdhan basin is obtained by multiplying probable rainfall of the rainfall station No. DG 0001 with the ratio of long-term annual rainfall between the rainfall station No. DG 0001 and the wadi Jurdhan. Long-term annual rainfall between year 1937/38 and 1987/88 is 180 mm for the rainfall station No. DG 0001 and 129 mm for the Jurdhan basin.

3.1.3 Unitgraph

A. Unitgraph of Hasa river

Hydrographs of 4 single-peaked large floods (namely, floods No.H15,H17,H28 and H45 in Fig.3.1) are converted to hydrographs caused by 1-mm-rainfall after deducting base runoff. The peak discharge of hydrographs before and after the conversion and the time from start of rise to peak are shown as below.

Flood No.	Peak Discharge (m^3/sec)		Time from start of rise to peak (hr)
	Observed Flood	Flood Caused by 1 - mm Rainfall	
H 15	78	216	3
H 17	71	128	5
H 28	80	130	7
H 45	290	50	7
-	-	-	5 (1)
-	-	-	12 (2)
-	-	-	8 (3)

Note :

(1) Time of concentration is estimated by Kraven's formula.

(2) Time of concentration is estimated by Bayern's formula.

(3) Time of concentration is estimated by the formula derived by the California Highways and Public Works.

(4) Time from start of rise to peak (T_p) is estimated by T_p=0.5+0.6 x T_c which is an empirical relationship derived by the Soil Conservation Services of U.S. Dept. of Agriculture. T_c is time of concentration.

A unitgraph, shown in Fig.3.3, to estimate probable floods was constructed from the hydrograph of the flood No. H 45 which has the second largest peak discharge of the 64 flood hydrographs collected by this study.

B. Unitgraph of wadi Jurdhan

Hydrographs of 4 large floods with a single peak (namely, floods No.J3,J8,J21 and J24 in Fig.3.2) are converted to hydrographs caused by 1-mm-rainfall. Peak discharge of hydrographs before and after the conversion, time from start of rise to peak are shown as below.

Flood No.	Peak Discharge (m^3/sec)		Time from start of rise to peak (hr)
	Observed Flood	Flood Caused by 1 - mm Rainfall	
J 3	30	30	2.0
J 8	120	26	1.5
J 21	77	17	3.5
J 24	33	20	1.0
-	-	-	2.1 (1)
-	-	-	3.5 (2)
-	-	-	3.3 (3)

Note :

(1) Time of concentration is estimated by Kraven's formula.

(2) Time of concentration is estimated by Bayern's formula.

(3) Time of concentration is estimated by the formula derived by the California Highways and Public Works.

(4) Time from start of rise to peak (T_p) is estimated by $T_p = 0.5 + 0.6 \times T_c$ which is an empirical relationship derived by the Soil Conservation Services of U.S. Dept. of Agriculture. T_c is time of concentration.

A unitgraph, shown on Fig.3.4, to estimate probable floods was constructed from the hydrograph of the flood No. J8 which has the largest peak discharge of the 64 flood hydrographs collected this time.

3.1.4 Probable floods

A. Method of estimation of direct runoff from rainfall

The method used for estimation of direct runoff from a given amount of rainfall is taken from Ref.3.2. This method was originally developed by the Soil Conservation Service, the United States Department of the Agriculture in 1956.

In this study, for the Upper Hasa basin, the Jurdhan basin and the Jafr basin, the hydrologic soil group is chosen to be "Group B" which is classified as "soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures and which have a moderate rate of water transmission". The pattern of land cover is chosen to be fallow. This choice is based on a study of hydrological soil classification in Ref.3.3

The antecedent moisture condition is chosen to be AMC-II which is quoted as " the average case for annual floods, that is, an average of the conditions which have preceded the occurrence of the maximum annual flood on numerous watersheds" for both the Upper Hasa basin and the Jafr basin.

Other study reports on Jordan estimated the amount of abstraction which principally consists of interception, infiltration and surface storage as below.

Reference No.	Initial Abstraction (mm)	Abstraction after Initial Abstraction (mm/hour)
4	12	5
5	(Unknown)	5
6	10	4

In this study, initial abstraction and abstraction after initial abstraction are estimated as below.

Return Period	Initial Abstraction (mm)		Abstraction after Initial Abstraction (mm/hour)	
(Year)	Upper Hasa	Jurdhan	Upper Hasa	Jurdhan
2	8.3	8.3	0.27	0.48
5	8.3	8.3	0.54	0.69
10	8.3	8.3	0.65	0.79
25	8.3	8.3	0.77	0.90
50	8.3	8.3	0.84	0.98
100	8.3	8.3	0.88	1.03
200	8.3	8.3	0.93	1.07
500	8.3	8.3	0.98	1.13

B. Probable floods of Hasa river at Hasa water stage gaging station

From the aforesaid unitgraph and probable rainfall, probable floods and runoff coefficients are estimated as shown on Table 3.2 and Fig.3.5.

In a previous study report (Ref.3.4), runoff coefficients vary from about 20 % for short return periods to about 50 % for 100-year probable floods, which shows good agreement with the results obtained by this study. Also, the peak discharges estimated by this study are plotted in Fig.3.7 with estimates by previous study reports of Jordan and actual flood records in the Levant. From Fig.3.7, the peak discharges estimated by this study are considered reasonable.

C. Probable floods of wadi Jurdhan at water stage gaging station by Desert Highway

From the aforesaid unitgraph and probable rainfall, probable floods and runoff coefficients are estimated as shown on Table 3.3 and Fig.3.6. As described in Sec.3.1.3, the unitgraph of wadi Jurdhan is derived from a historical large flood in March 1966 when the reliability of the water stage record is said to have been still high.

In a previous study report (Ref.3.4), runoff coefficients vary from about 20 % for short return periods to about 50 % for 100-year probable floods, which shows good agreement with the results obtained by this study. Also, the peak discharges estimated by this study are plotted on Fig.3.7 with estimates by previous study reports of Jordan and actual flood records in the Levant. From Fig.3.7, the peak discharges estimated by this study are considered reasonable.

D. Probable floods at 8 recharge dam sites

By this study, construction of recharge dams is proposed at 8 sites for which location, drainage area and annual rainfall are shown on Fig.4.1 and Table 3.4.

Probable floods of recharge dam sites are estimated by the following equation.

$$Q_x = Q_o \times C$$

$$C = \frac{Al_x^{\ bx}}{Al_o^{\ bo}} \times \frac{R_x}{R_o}$$

$$A1 = 0.62137^2 \times A2$$

where

C	:	Adjustment factor of probable floods
Q (m^3/sec)	:	Peak discharge of a probable flood
A1 ($mile^2$)	:	Drainage area
A2 (km^2)	:	Drainage area
R (mm)	:	Annual rainfall
Subscript o	:	Values of the wadi Jurdhan at the water stage gauging station
Subscript x	:	Values of recharge dams

and

$$b = 0.894 \times A2^{-0.048}$$

Adjustment factors of probable floods are calculated as shown on Table 3.4. Peak discharges of probable floods at 8 recharge dams thus estimated are shown on Table 3.5.

3.2 Runoff Analysis

3.2.1 Estimate of daily rainfall

Estimate of basin rainfall is made by the Thiessen method after estimating missing rainfall data. There are absences of daily rainfall data for a considerable period for some rainfall stations. The absences of rainfall data of a certain station are filled by data of a station with which the best correlation is obtained on a monthly basis. Prior to the correlation analysis, selected rainfall stations in and around the study area were divided into 4 groups with regard to the availability of daily rainfall data, and the amount of annual rainfall and their closeness as follows.

Group No.	Characteristics of Group
1	Located in and near the Jafr basin and annual rainfall of most stations with missing data is more than 100 mm
2	Located in and near the Upper Hasa basin and annual rainfall of most stations with missing data is more than 100 mm
3	Located in and near the Jafr basin and annual rainfall of most stations with missing data is less than 100 mm
4	Located in and near the Upper Hasa basin and annual rainfall of most stations with missing data is less than 100 mm

Simple correlation factors and linear regression formulas thus derived are shown on Table 3.6 for the 4 groups.

3.2.2 Simulation model

A. Basic component of tank model

The tank model is a widely practiced tool to estimate long-term runoff data or runoff data from rainfall data during ungaged periods and/or of ungaged areas. The tank model is normally composed of three or four tanks connected directly with each other by bottom outlets, thus upper tanks emit and lower tanks receive the amount of water in proportion to the water level in upper tanks. Each tank has side holes, which pass the runoff to rivers. The outflow from each side hole is proportionate to the height between the hole and water surface. Provided that a tank is accommodated with one bottom hole and two side holes, the rule for outflow computation is as follows.

$y = 0 \qquad (X <= h1)$

$$y = a1(X - h1) \qquad (h1 < X <= h2)$$

$$y = a2(X - h2) + a1(X - h1) \qquad (h2 < X)$$

$$Z = bX$$

$$X^* = X - y - Z + I$$

where

X : Water depth of i-th day

X^* : Water depth of (i+1)-th day

y : Outflow from side holes of i-th day

Z : Outflow from a bottom hole of i-th day

I : Inflow of i-th day

a1,a2 : Discharge coefficients of side holes

b : Discharge coefficient of bottom hole

h1,h2 : Height of lower and upper side holes

In order to effectively trace hydrological conditions of the study area where there is a dry season regularly and streamflows diminish to a considerably low level or completely dry up in the dry season, the tank model is furnished with a structure to simulate the moisture content in the top tank. This structure is composed of two moisture-bearing zones, which contain moisture up to the capacity of saturation . The moisture contents in two zones are expressed as height, which are called primary soil moisture depth and secondary soil moisture depth,respectively. Between the above two zones, transfer of water contents takes place, as expressed below.

$$T2 = TC\ (XP/PS - XS/SS)$$

where

T2 : Transfer of moisture between primary and secondary zones (if positive, transfer takes place from primary to secondary, and vice versa)

PS : Capacity of primary soil moisture

SS : Capacity of secondary soil moisture

XP : Primary soil moisture

XS : Secondary soil moisture

TC : Transfer coefficient

If the primary soil moisture is not saturated,i.e., $XP<PS$, water is

supplied to the primary moisture zone from the lower tanks as a result of capillary attraction, amount of which is computed as below.

$$T1 = TB\ (1 - XP/PS)$$

where

T1 : Transfer of moisture from lower tanks to primary soil moisture

TB : Transfer coefficient

The basic components of the tank model are depicted in Fig.3.8.

B. Tank model of study area

Based on available rainfall data between October 1937 and September 1988, an isohyetal map of annual rainfall of the study area was prepared (See Fig.2.19). As seen from the isohyetal map, nearly 70 % of the study area has an extremely arid climate with annual rainfall less than 50 mm.

Topographically, there are wadis where B2/A7 and/or B4 aquifers directly outcrop, causing direct recharge of aquifers along riverbeds by rainfall and there are areas where the aforesaid aquifers form sub-surface layers (See Fig.3.9). The distribution of outcrops and sub-surface layers of such aquifers is not uniform over the study area. Taking the Upper Hasa Basin for example, more than 80 % of B2/A7 and B4 aquifers forming outcrops and sub-surface layers exist in the rainy western half of the basin where long-term annual rainfall is more than 50 mm. For the Jafr basin, about 70 % of such permeable sub-surface layers exist in the area with annual rainfall less than 50 mm.

For the purpose of describing such distribution of rainfall and permeable layers in the study area more accurately, the tank model of the study area is separately constructed for a rainy area and a rain-scarce area, the two areas being bordered by an isohyetal line of annual 50-mm-rainfall (See Fig.3.10).

The effect of groundwater recharge through riverbeds is estimated by the

Wedernikow's formula assuming a steady state unsaturated condition as below.

$$Q = k \times (b + 2h) \times A$$

where

Q : Amount of recharge

k : Coefficient of conductivity

h : Water depth of streams

b : Surface width of streams

A : Area of recharging

It is assumed that the recharge through riverbeds of B2/A7 and B4 formations begins when daily rainfall lasting 1 to 2 days is more than 8 mm. The initial abstraction of 8 mm is estimated by the method developed by the Soil Conservation Service, the United States Department of Agriculture as outlined in Section 3.1.4.

In addition, rainfall with strong intensity which directly precipitated over impermeable riverbeds is assumed to reach the basin outlet without any loss.

3.2.3 Input data

Daily rainfall of areas of interest is estimated by the Thiessen method as explained in Section 2.2.4.

Evaporation used in the runoff calculation is based on the class-A pan evaporation of the Hasa evaporation station.

The area of B2/A7 and B4 aquifers forming outcrops and sub-surface layers are estimated from Fig.3.9.

The capacities of primary and secondary soil moisture (PS and SS) are estimated from soil moisture content of a 50-cm-thick surface layer measured at a farm in Shoubak (See Fig.3.11). From Fig.3.11, soil moisture content at Shoubak is estimated at 25 mm at the end of dry season in September and 50 mm at the very height of rainy season in March, and the difference of the two extremes equal to 25 mm is considered as the sum of PS and SS for Shoubak. The sum of PS and SS is derived for the Upper Hasa and the Jafr basins from the data of Shoubak, assuming that the total sum of PS and SS is inversely proportionate to annual rainfall and that the ratio of PS and SS is one to four. As a result, PS and SS for the Upper Hasa and Jafr basins are estimated as follows.

	PS (mm)	SS(mm)
Upper Hasa basin	17	66
Jafr basin	30	120

It may be noted that, about the sum of PS and SS of western parts of the Jafr basin, Ref.3.5 is quoted as reading that " the average soil moisture deficit at wadi alluvium fans in the basin reaches 200 mm during October - May"

3.2.4 Calibration

A. <u>Reliability of discharge data of wadi Jurdhan</u>

There are two water stage gaging stations in the study area, one in the Upper Hasa basin and the other in the Jurdhan basin. Based on observed discharge data, runoff characteristics of these two sites are compared with that of the Mujib basin as shown on Table 3.7. As understood from Table 3.7, runoff coefficient of the Jurdhan basin is unreasonably low though annual rainfall of the Jurdhan basin is comparable with that of the Mujib basin.

Observed discharges and runoff coefficients of wadi Jurdhan are tabulated in Table 3.8 for the period from the start of water stage measurement in 1963/64 to 1985/86. According to Table 3.8, no discharge is recorded due to malfunction of recording apparatus after 1982/83 though a considerable amount of annual rainfall data are available.

According to an on-site inspection made in September 1988, the water stage gaging station of the wadi Jurdhan is installed at a place where frequent scour or deposition of sediment is likely to take place, resulting in frequent changes of stage-discharge relations and, hence, maintenance of a stable water rating seems difficult unless provided with an artificial control like a low concrete weir constructed at the water stage gaging station of the Hasa river near Tannour.

For the above reasons, reliability of the discharge data of the wadi Jurdhan collected by this study is considered too low to be used for the calibration of the tank model for the study area.

It would be desirable that the water stage gaging station of wadi Jurdhan be equipped with an artificial control or be shifted to an appropriate site to have a more accurate stage-discharge relation.

B. Calibration of tank model

For the aforesaid reason,the tank model for the Jafr basin and the recharge dam sites is calibrated by using rainfall-runoff relations of the Upper Hasa basin which is considered far more reliable than that of the wadi Jurdhan. Calibration of the tank model is made by the comparison of average annual runoff volume and hydrographs of observed discharges and calculated discharges.

Being calibrated by rainfall-runoff relations of the Upper Hasa basin, the final values of parameters of the tank model are calculated as tabulated in Table 3.9. The calculated average annual runoff of the Hasa river is compared with the observed one (See Table 3.10).

3.2.5 Estimated runoff volume

Estimated runoff volume of the Upper Hasa basin, the Jafr basin and the recharge dams is summarized for the period between 1963/64 and 1985/86

(See Table 3.11).

Annual runoff volume of the Jafr basin is estimated at 22.9 MCM (Runoff coefficient = 3.3 %), which is comparable with the estimate by Ref.3.3 (7.18 MCM in dry years, 31.51 MCM in wet years and 14.97 MCM in average years), Ref.3.5 (10 to 16 MCM) and Ref.3.6 (16.2 MCM).

Of the Jafr basin, the annual groundwater recharge through the riverbed is preliminarily estimated at 6.7 MCM for B2/A7 aquifers and 2.0 MCM for B4 aquifers.

3.3 Sediment Analysis and Water Quality

3.3.1 Sediment analysis

Suspended sediment data are plotted as shown in Figs.3.12 and 3.13 respectively to determine a relation between water discharge and suspended sediment discharge, which are given by:

$$Qs = 5.12\ Q^{1.24}$$ for the Hasa river, and

$$Qs = 5.96\ Q^{1.34}$$ for wadi Jurdhan,

where

Qs (kg/day) : Suspended sediment discharge, and

Q (m^3/sec) : Water discharge

The unit weight of suspended sediment is estimated at 1.04 ton/m^3 based on a sieve analysis of samples collected at Ghor Safi of the Hasa river on January 23,1972.

As no in-situ survey related to the estimate of bed load was conducted, the proportion in volume of bed load to suspended load is assumed to be 30 % the same as that assumed in Refs.3.7 and 3.8. The result of sediment analysis is shown on Table 3.11. The ratio of annual total sediment load (i.e. suspended load plus bed load) to annual total inflow varies from 0.8 % to 1.9 % , which might be comparable with 0.4 % of the

Maqarin dam (Ref.3.8), 1.02 % of the King Talal dam and the Wadi Arab dam (Ref.3.9), 4 % of the Kafrein reservoir (Ref.3.3) and 1.4 % of the Sultana reservoir (Ref.3.10).

3.3.2 Water quality

A result of water quality test for which sampling was made at Ghor Safi of the Hasa river on March 19, 1973 is shown on Table 3.12, according to which water is ranked as C2 to S1 as water for use of irrigation.

3.4 Hydrogeology and Aquifer Unit

3.4.1 Aquifer conditions

Aquifers have been recognized in argillaceous, arenaceous and/or carbonate rocks of the Cambrian to Paleogene age such as Disi, Kurnub, lower Ajlun (A1-6), Amman-Wadi-Sir (B2/A7), and Rijam (B4). In the course of the present Study, attention was focused on the aquifers in Ajlun and Belqa group such as A1/6, B2/A7 and B4.

The Study area includes both Jafr basin and upper Hasa basin. In the southern part of the Jafr basin, to the south of the Shidiya phosphate mines, the B2/A7 and A1-6 are both thin and unsaturated. In the central part of the Study area, the B2/A7 is confined by overlying thick impervious argillaceous unit of the Muwaqqar (B3) formation, while the surrounding areas are unconfined. Except the area along the Jafr trough, the confined B2/A7 aquifer is promising to be developed. The A1-6 is highly confined in the area of the north of the Salwan fault, which is conceived to be a promising aquifer. The B4 aquifer exists in an independent regional shallow sedimentary basin which overlies the impervious Muwaqqar (B3) formation. In the central part of the sedimentary basin, the B4 is saturated with water table condition, while it is unsaturated in the surrounding areas. The aquifer receives limited recharge through the wadi beds during the occasional floods, of which potential is evaluated to be limited and small.

3.4.2 Lower Ajlun (A1-6) aquifer

The lower Ajlun (A1-6) underlies the Amman - Wadi Sir (B2/A7) aquifer, which is comprised of multi-layered units of sandstones, marls, clays and shales. The hydrogeology of the lower Ajlun (A1-6) including the southern part of the Jafr basin was examined by NRA in 1985 by installation of a series of multiple piezometers. In this investigation, the emphasis was put on the northern part of the Jafr basin, north of the "Salwan" fault and west of the "Karak - Wadi Al Fiha" fault, where the aquifer was conceived to be highly confined but neither hydrogeological nor hydrochemical data could be obtained.

In the northern part of the Study area, i.e. north of the "Salwan" fault and the west of the "Karak - Wadi Al Fiha" fault, the lower Ajlun (A1-6) is composed of two lithological units; i) mainly arenaceous facies in the upper part of A4-6 and ii) mainly argillaceous facies in the lower part A1-3. The upper most part of the lower Ajlun formation comprises A5/6, which is composed of alternating marly sandstone, sandy marl and marl with a thickness of about 100 m in total. The A5/6 acts as a capping layer to confine the underlying aquifers such as A4 and A2. The main aquifer is recognized to be the A4 formation which consists of an uniform unconsolidated sandstone unit with uniform grain size of medium to coarse. The A4 is only 20 m thick, but it is pervious and highly confined with an aquifer pressure of 30 Kg/cm^2. The A1-3 is an argillaceous unit, which mainly consists of alternating shales and clays, intercalating some impure layers of sandstones and limestones. The variation in lithological facies in the lower section of A1-3 gives complexity to its hydrogeology. No promising aquifers may be distinguished in A1-3.

The regional groundwater flows in A1-6 aquifer are confined by the three major fault systems, the "Arja -Uweina" flexure, "Salwan" fault and "Karak - Wadi Al Fiha" fault. These faults act as impervious barriers, since displacements exceed the total thickness of the A4 formation. (see Fig.3.14) In the Western Highlands, the groundwater flows from southwest to northeast in and along the Arja - Uweina flexure. In the northern part of the Study area, north of the "Salwan" fault and the west of the "Karak - Wadi Al Fiha" fault, the groundwater flows from west to east with a piezometric elevation at 890 m. While south of the Salwan fault, the piezometric elevation is as low as 750 m. The regional piezometric level of the A1-6 is shown in Fig.3.15.

The water salinity is as low as 330 mg/l of T.D.S to the north of the Salwan fault. This may be largely due to the arenaceous character of the hydrogeology in the upper part (A4-6) of the lower Ajlun (A1-6). Where the groundwaters are in a stagnant environment in the confined area east of the "Arja - Uweina" flexure and south of the "Salwan" fault, the water salinity is as high as or more than 1,000 mg/l of T.D.S.

The hydrogeological map of the lower Ajlun (A1-6) is shown in Fig.3.16.

3.4.3 Amman - Wadi Sir (B2/A7) aquifer

The Amman - Wadi Sir (B2/A7) aquifer underlies the Muwaqqar (B3) formation, which is composed of two formations, namely ; i)the silicified chert limestone unit of the Amman (B2) and ii) older sandy limestones and calcareous sandstones of the Wadi Sir (A7). The two aquifers conceived as having hydraulic continuity, and are regarded as a single hydraulic system. The Amman (B2) formation is well jointed and fissured both at outcrops and at depth. The sandy limestones and sandstones in the Wadi Sir (A7) are variable in their texture, well to loosely cemented. The sandstones become friable in their more arenaceous facies. Eastwards, the limestones become more calcareous and/or sandy.

South of the Salwan fault, the B2/A7 aquifer has an average thickness of 100 m, comprising the Amman (B2) 40 m thick, and the Wadi Sir (A7) 60 m thick. Whereas north of the Salwan fault, B2/A7 aquifer is as much as about 200 m thick, comprising the Amman (B2) of 100 m and the Wadi Sir (A7) of 100 m. In general, the B2/A7 thins to the south and thickens to the north.

The piezometric elevations of the groundwater surface in the Western Highlands are as high as 1,200 to 1,500 m, while they are as low as 800 to 900 m immediately east of the "Arja - Uweina" flexure. In the central area of the Jafr basin, the piezometric elevations are in the range of 750 and 800 m with a nearly flat hydraulic gradient on an average of 0.0003. The "Arja - Uweina" flexure acts as a hydraulic barrier to the regional groundwater flows following abrupt drops in the piezometric elevations over a short distance. North of the Salwan fault, the piezometric elevations gradually decrease from west to east and/or northeast. The piezometric elevations are as high as 1,200 to 1,400 m in the Western Highlands, while they are 800 to 1,000 m eastwards from the Husseiniya with an hydraulic gradient on average of 0.005. The measurements of the piezometric heads in and around the "Karak - Wadi Al Fiha" fault using the observation boreholes of JO-3 and JO-4 indicate that the fault is not an impervious barrier with hydraulic discontinuity. The displacement of the fault is about 100 m which is half of the total thickness of the B2/A7 aquifer as shown in Fig.3.14.

The regional groundwater flows in the B2/A7 aquifer are confined by the two major faulting structures "Arja - Uweina" flexure and "Salwan" fault. These faulting structures act as impervious barriers, but they are not continuous barriers because of their complicated structures. In the Western Highland, the groundwater flows from west to east intersecting the "Arja - Uweina" flexure which is composed of a group of discontinuous faults. In the northern part of the Jafr basin, the "Arja - Uweina" flexure acts as an impervious barrier intersecting flows to the east. The flows of groundwater turn from the west to the northwest direction passing through the basin boundary between Jafr and upper Hasa. To the north of the Salwan fault, the groundwater flows from west to northeast and east, and flows out through the "Karak - Wadi Al Fiha" fault which is not a continuous faulting system and acts as a semi-pervious barrier with hydraulic continuity in B2/A7. The regional piezometric level of the B2/A7 is shown in Fig.3.17.

The Amman - Wadi Sir (B2/A7) aquifer is conceived as a single hydraulic system with hydraulic continuity between the B2 and the A7. In the JT-1 test well which was drilled in the northwestern part of the Jafr basin, however, different piezometric heads were measured in each formation unit of B2 and A7. Drilling with chemical foam jammed at a depth of 358 m which is in the lower part of the B2. No flow return could be obtained due to the substantial circulation losses in the fractured B2 formation. Just after penetrating into the top of the A7 formation at a depth of 387 m, however, the piezometric head in the borehole recovered instantly from 220 to 185 m. Between 380 and 387 m deep, the lithology changed to marls, that were conceived to be part of the B1 formation which confines the underlying A7 aquifer unit. North of the Husseiniya, B2 is slightly confined, while A7 is highly confined with a piezometric pressure of 20 Kg/cm^2 or more.

Due to the variation in lithology, diagenetic and structural phenomena, the transmissivities and/or permeabilities of the B2/A7 aquifer are extremely variable. The transmissivities vary between less than 1 and more than 10,000 m^2/d depending on the size of fissures and caves in the carbonate rocks. The lower transmissivity zones such as less than 50 m^2/d are regionally mapped in the southern and western parts of the Jafr basin, where the aquifer thickness decreases to less than 50 m. The higher transmissivity zones such as more than 100 to 200 m^2/d which locally includes extremely high values of more than 1,000 m^2/d are regionally mapped in the zones corresponding to the major groundwater flow passes such as passing through "Wuheida" - "Ma'an" - "Al Jafr" and "Husseiniya" - "Jurf ad Darawish" - "Hasa". The regional transmissivities of the B2/A7 are mapped in the Fig.3.18.

The hydrogeological map of the Amman - Wadi Sir (B2/A7) is shown in Fig.3.19.

3.4.4 Rijam (B4) aquifer

The Rijam aquifer has been studied since 1967 as reported by Abu Ajamieh ,1967 (Ref.3.11), Parker,1970 (Ref.3.12), AHG, 1977 (Ref.3.13) and NRA, 1985 (Ref.3.14). The present report summarizes of these previous studies and includes the result of the VLF survey which was carried out during this investigation.

The Rijam (B4) aquifer comprises crystalline limestone, chalk and chert bands, and is underlain by chalky marls and thick impervious shales of the Muwaqqar (B3) which form the base of this aquifer. It occurs in the center to the northern part of the Jafr basin with elevations of less than 1,200 m. The sequence is thick in and around the Jafr trough with a maximum thickness of about 100 m at the northwestern edge, while it becomes as thin as about 50 m or less in the southeastern part of the Jafr trough. The B4 wedges out eastwards and southwards of the Al Jafr town.
The aquifer is saturated only in the central part of the Jafr basin where the ground elevation is less than 930 m as seen in Fig.3.20.

The Rijam (B4) aquifer receives limited recharge by infiltration of the flood runoff through the wadi courses such as in the lower reaches of wadi Nijl, wadi Arja, wadi Jurdhan, wadi Wuheida, and wadi Husseiniya. The groundwater flows from north east to southeast following the main wadi courses such as shown in Fig.3.21. The hydraulic gradient is as relatively flat as 0.001 in the eastern part of the saturated B4, while it becomes steeper to upstream to the west.

The transmissivities vary between 16 and 10,000 m^2/d, which indicate the karstic nature of the Rijam limestones. The higher transmissivities are mapped locally in the area of 1 to 10 km northwest of the Jafr town where the gradient of the groundwater table flattens to 0.001. Fig.3.22 shows the regional transmissivities of the Rijam (B4) aquifer.

3.5 Quality of Groundwater

3.5.1 Hydrochemistry

In the course of the study, the hydrochemistry of the following three aquifers was examined by taking account of the following conditions;

The Lower Ajlun (A1-6) ; Hydrochemistry of the groundwater basin has not been studied except for a limited area in the southern part of the Jafr basin.

The Amman - Wadi Sir (B2/A7) ; The aquifer is believed to satisfy the quality requirements.

The Rijam (B4) ; Part of this aquifer has been contaminated by irrigation return with high salinity.

3.5.2 Lower Ajlun (A1-6) aquifer

The lower Ajlun (A1-6) has not been regarded as a promising aquifer due to the lack of information on both hydrogeology and hydrochemistry.

In 1985 NRA carried out a series of chemical analysis on the water samples from the project boreholes. The boreholes, which penetrate the whole of the lower Ajlun (A1-6) in and around the Shidiya area in the southern part of the Jafr basin, is composed of alternating sandstones and shales with rather low apparent resistivities of less than 100 ohm-m. The values of E.C are in the range between 1,000 and 2,750 micromho/cm and of T.D.S between 700 and 2,000 mg/l, which follow the slightly saline water environment and/or the stagnant water environment. At the southwestern edge of the A1-6 aquifer where the narrow bands of outcrop receive rainfall, the groundwater is fresh with T.D.S of 600 to 700 mg/l, while the water salinity increases to 1,728 to 2,048 mg/l towards the east basin boundary.

The spatial variation of water salinity (T.D.S) in the carbonate rocks is dependent on the aquifer characteristics such as formation lithology, recharge area and distance of groundwater flow. North of the Salwan fault, the groundwater in the lower Ajlun (A1-6) aquifer is mainly derived from the A4 formation which is arenaceous consisting of medium to coarse homogeneous sandstones with a very high aquifer pressure of 30 kg/cm^2, which explains the very low range in water salinity such as

T.D.S of 326 mg/l. The sand layer in the A4 acts as a sand filter to percolating groundwater flow in the lower Ajlun. The following is a summary of the chemical analysis of a water sample from JT-3;

Well No.	E.C m.mho/cm	T.D.S mg/l	pH -	Ca^{++} mg/l	Mg^{++} mg/l	Na^{++} Mg/l	K^{+} mg/l	Cl^{-} mg/l	$SO4^{--}$ mg/l	$CO3^{--}$ mg/l	$HCO3^{-}$ mg/l
JT-3	0.510	326	7.3	46.5	21.2	20.7	14.9	25.9	33.6	0.0	235.5

The water sample of JT-3 is situated in an area of "carbonate hardness" as classified in the Piper's tri-linear diagram. The quality is excellent in meeting drinking water standards, and is suitable for most uses.

A water salinity (E.C) map of the lower Ajlun (A1-6) is shown in Fig.3.23.

3.5.3 Amman - Wadi Sir (B2/A7) aquifer

The Amman - Wadi Sir (B2/A7) has been identified as a promising aquifer to satisfy the water requirements of the Study area. The hydrochemistry of this aquifer has been examined more detail than any other aquifers except for the areas of the northeastern part of the Jafr basin and the eastern part of the upper Hasa basin where no drillings were carried out before this study. The water samples of the B2/A7, which were collected from the test wells such as at JT-1, JO-3 and JO-5, were analyzed at WAJ's chemical laboratory in Amman. The following is a summary of the chemical analysis of the water samples;

Well No.	E.C m.mho/cm	T.D.S mg/l	pH -	Ca^{++} mg/l	Mg^{++} mg/l	Na^{++} Mg/l	K^{+} mg/l	Cl^{-} mg/l	$SO4^{--}$ mg/l	$CO3^{--}$ mg/l	$HCO3^{-}$ mg/l
JT-1	0.620	397	7.4	53.1	28.6	27.6	3.5	52.5	20.2	0.0	257.5
JO-3	1.000	653	7.2	86.2	46.6	62.1	5.9	105.3	129.7	0.0	340.5
JO-5	1.830	1,171	8.1	163.1	54.2	190.9	9.4	141.5	532.2	0.0	339.9

The regional E.C values in the B2/A7 aquifer are less than 700 micromho/cm in the Western Highlands, 1000 to 1,400 micromho/cm in the