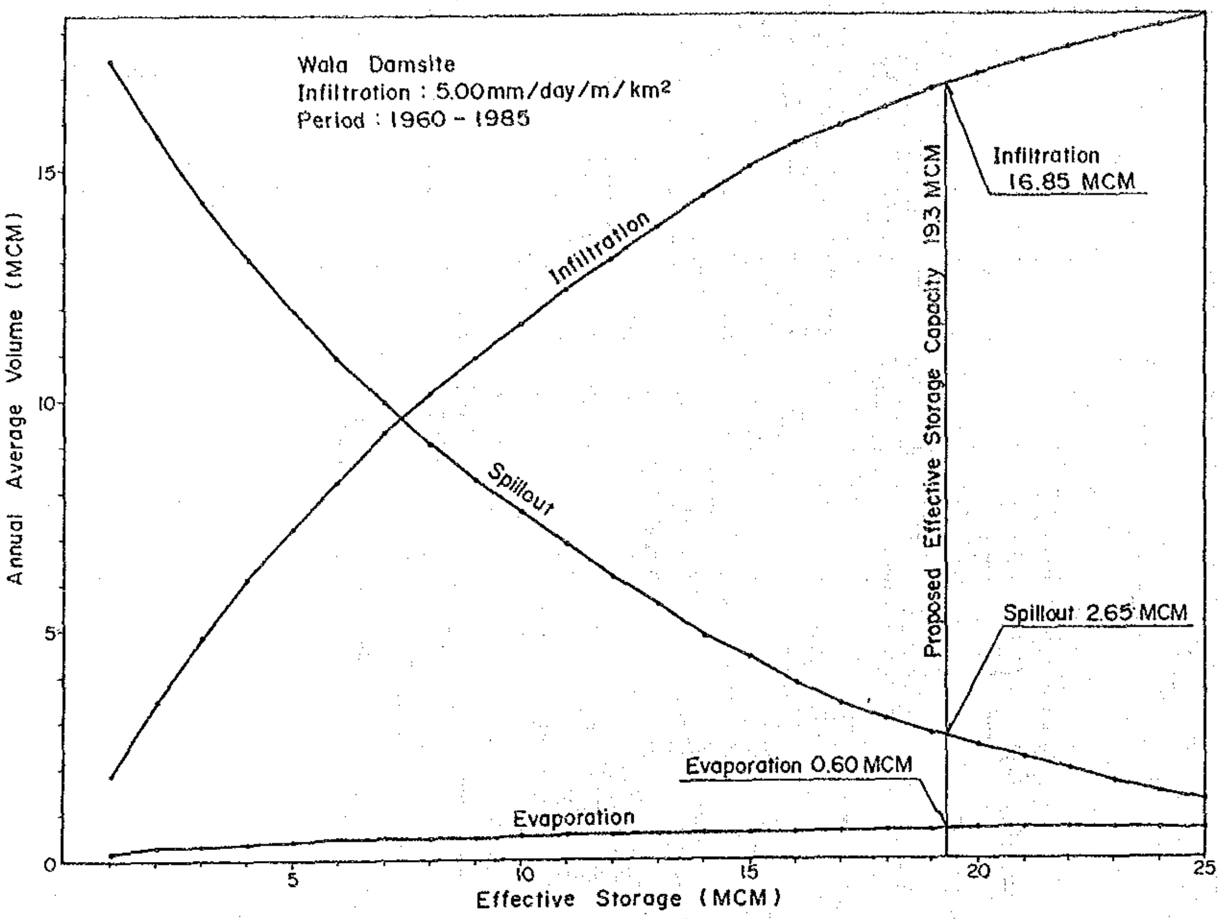

Fig.B-26 Effective Surface Water Resource at Wala Damsite (Recharge Dam)

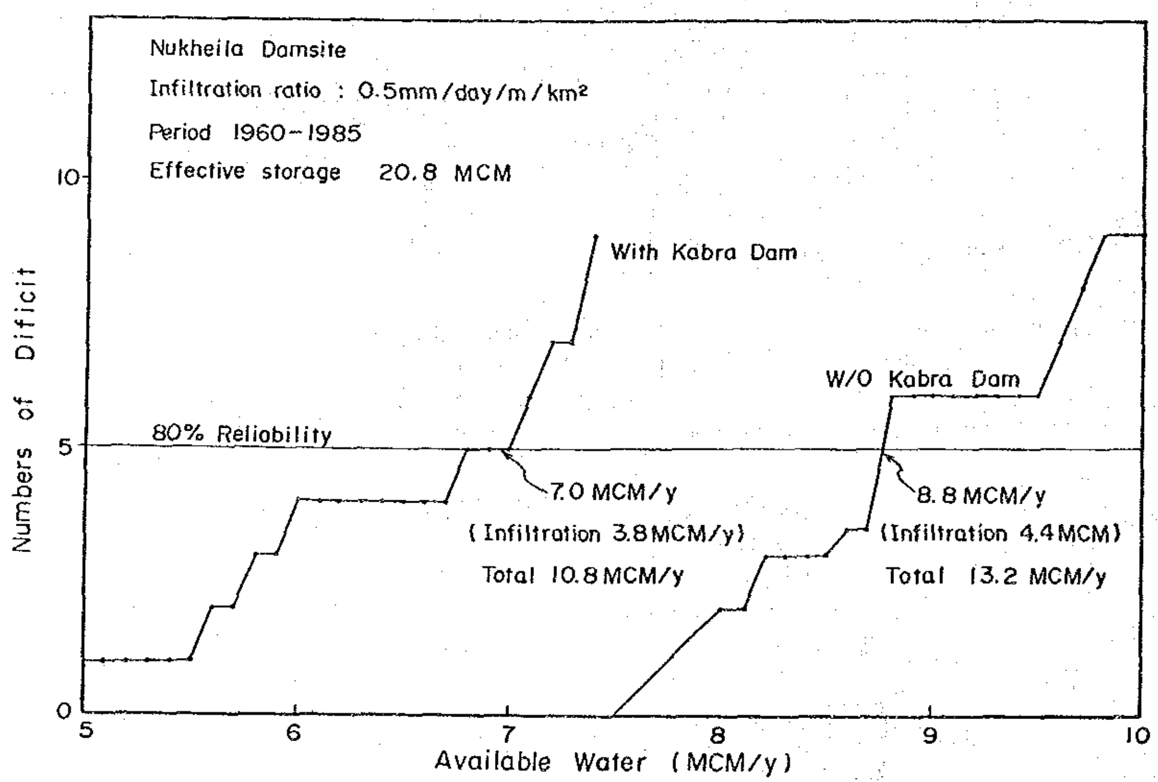

Fig. B-27 Effective Surface Water Resources at Nukheila Damsite

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
JAPAN INTERNATIONAL COOPERATION AGENCY

APPENDIX C

GROUNDWATER RESOURCES

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1. INTRODUCTION

Groundwater is the most commonly developed source of water supply in Jordan because it represents a reliable, economical, and local source of water supply that usually is of good quality. Although most of the water supply is dependent on regional shallow aquifers, the evaluation of groundwater availability from the B2/A7 aquifers in the Mujib basin area has taken an increasing importance in recent years because of increased competition in many areas for available water suppply, increased contamination and development of shallow groundwater resources.

The primary objectives of this study is to evaluate the potential of groundwater resources and to formulate the water resources development plan for the Mujib basin. General groundwater potential in the basin was preliminarily examined to delineate the economic aquifer which is to be developed for the purpose of immediate water supply to Amman. Taking account of the data availability, development possibility of the B2/A7 aquifer has been evaluated by using a computer simulation model. The groundwater model was programmed to estimate the hydraulic connection between groundwater flow and perennial base flow and/or flowing springs in the lower reaches of Wadi Wala (Heidan). A two-dimensional groundwater flow model based on a Galerkin finite-element discretization, was used to predict the future state of groundwater flow in the basin. From the simulation study, sustained yield from the B2/A7 aquifer were examined, taking into account the alternate plan of artificial recharge by using flood retention dams.

2. HYDROGEOLOGY

2.1 Geology

The Study Area is underlain by the Paleozoic, Mesozoic and Cainozoic sedimentary rocks with some basic and acidic intrusives. The Mesozoic system, especially Cretaceous carbonate sedimentary rocks are dominant in the Study Area.

The Cretaceous to Paleogene systems are divided into three groups, i.e. Kurnub (K), Ajlun (A) and Balqa (B) Group in ascending order. The Wadi Sir Formation (A7) in the Ajlun group, the Wadi Rusaifa Formation (B1) and the Amman Formation (B2) in the Balqa group of the middle to upper Cretaceous age, comprise the most important aquifer system of the B2/A7 in the Study Area. The B2/A7 aquifer is overlain by the Muwaqqar Formation (B3) which intercalates bituminous marl layer, and is underlain by thick impervious marly shale to marl layers in the A6 Formation. The strata of the B2/A7 system primarily consist of a thick and extensive sequence of limestone, chert and, marl intercalating sandstone, shaly marl and some phosphate. The term "B2/A7" is used in this report to refer to either B2 Formation or A7 Formation or both where distinction between the two names is not necessary.

The middle to lower Cretaceous and the pre-Cretaceous sedimentary and intrusive rocks outcrop on the valley slopes in the lower reaches of Wadi Wala and Wadi Mujib. The Tertiary carbonate rocks are found at some locations along the eastern boundary of the Study Area. The Peistocene basalt flows associated with plugs, cones and vents are present in places in the western part of the Study Area. The Quaternary fluviatile deposits, mantle rocks and mudflat pelitic sediments have accumulated over extensive areas in the desert and obscure the older formations. These deposits are normally relatively thin. The mudflat deposits have developed over extensive areas where the drainage is restricted. These sediments are commonly saline due to the poor drainage. The regolith or mantle rocks consist mainly of cherts and extensive pavements of this material, are present on the plateau. Hydrogeological map of the Study Area is shown in Fig.C-1.

The Paleozoic to Cainozoic sedimentary rocks in the Study Area generally have a structure of monoclinol flexures at a low angle, which is disturbed by faults. The dominant fault directions in the area range from NW-SE to NNW-SSE. Siwaqa fault, which is the most remarkable fault in the area, runs SW-NE to W-E. The fault systems correlated to the rift also occur to the west of the area. Fig.C-2 shows the summary of basin geology which is compiled in the three dimensional structure form of fence diagram.

2.2 Aquifers

The Mesozoic sediments form a sequence of aquifers and aquicludes. Four aquifer units of "B2/A7", "A4" and "A2" and"K" have been recognized in the Study Area. Among them, the B2/A7 aquifer system has regional and economic importance. Other aquifer systems of A4, A2 and K may have a groundwater potential, but not considered in detail in this report, taking into account the difficulties of data availability and economical feasibility of these deep or fossiliferous aquifers. The B2/A7 aquifer is considered to be a uniform aquifer unit with hydraulic connections, which spreads throughout the entire Study Area with maximum thickness of about 300m.

The B2 Formation is composed of following two typical sub-units; (1) B2b of the upper unit which consists of phosphate, chert, marl, limestone and Coquina bed, and (2) B2a of the lower unit which consists of chert, silicified limestone and chalky marl. The A7 Formation consists of following typical three sub-units; (1) A7c of the upper unit of alternating marly limestone and limestone, (2) A7b of the middle unit of limestone or dolomitic limestone, and (3) A7c of alternating marl, marly limestone and limestone. The B1 Formation, which is composed of alternating marl, marly limestone, chert and sandstone, is intercalated between the B2 and the A7. The B2a and the A7b are excellent aquifers with high permeability which varies both in horizontal and vertical planes due to joints, fractures and karstification of the limestones. Other sub-units of B1, A7a and A7c are aquicludes with less permeability due to their argillaceous rock facies. These geological features are shown in Fig.C-3.

2.3 Recharge and Flow System

The major sources of groundwater in the B2/A7 aquifer in the Study Area include recharge in and near the outcrop areas in the north-western and western edge of the highland. Much of the outcrops in the north-western and western edge of the highland are in an area which receive relatively high rainfall of more than 250 to 500 mm/year.

Most of the recharge enters the aquifer system in the structurally high outcrop areas in the north-western highlands, where A7 and/or B2 Formation crop out as shown in hydrogeological map of Fig.C-1. Of these areas, it appears that the three major areas producing the greatest recharge is the west flank of the mountainous blocks of Amman-Madaba, Libb-Dhiban and Karak-Mazar. The Amman Madaba groundwater mound is the biggest groundwater mound in the Study Area. Most of the groundwater flows southwards to Jiza and then south-westwards to the Wadi Wala (Heidan) along the main drainage system of Wadi Wala. The Libb-Dhiban groundwater mound is the smallest groundwater mound in the Study Area. Most of the groundwater flows down to the Wadi Heidan. The Karak-Mazar groundwater mound is developed on the mountainous area between Karak and Wadi Hasa. Most of the northeast directed flow from the Mazar groundwater mound is diverted either northwards or eastwards and continues to curve until the flow becomes generally north-east oriented in reaching Azraq.

Hydraulic gradients generally are steepest close to the recharge areas and tends to become much milder downwards. This pattern may reflect an interaction of several factors, including flow divergence, discharge from springs, and permeability changes. General pattern of steady state of groundwater flow is shown in hydrogeological map of Fig.C-1.

Major outflows from the B2/A7 aquifer are flowing springs and discharge to pumping wells. Most of the large springs that discharge regional flow within the Study Area are located in the lower reaches of Wadi Wala (Heidan). The spring discharge from the B2/A7 system in the Wadi Mujib is small compared with the Wala springs.

Some attempts were made to distinguish or evaluate various mechanism of recharge including (i) direct recharge by rain through the outcrops of the B2/A7 system, (ii) indirect recharge by rain through overlying surface soil layer and (iii) direct recharge by flood water through infiltration from the wadi beds. In general, these attempts are considered difficult to quantify the recharge volume, due to inadequate data of the field measurements. In this Study, groundwater recharge is estimated by model analysis using two coupled simulation models of sub-surface tank model and groundwater simulation model. Estimated groundwater recharge in the basin is 68.7 MCM/y, which is composed of (1) 52.2 MCM/y from the boundary of recharge mounds, (2) 14.2 MCM/y from infiltration through overlying soil layer and (3) 2.3 MCM/y from infiltration through outcrops in the wadi beds during flash floods, as shown in Table C-1.

The Siwaqa fault divides the groundwater basin into two, with Wala basin to the north and Mujib basin to the south. In addition, the Siwaqa fault is believed to form a hydraulic barrier with hydraulic connection between the two. Piezometric surface in the Wala basin is (1) rather deep at 150m in depth or more in the eastern part of desert, (2) 100 to 150m in depth in the central highland and (3) less than 100m in depth in the wadis at middle to lower reaches of Wadi Wala and Heidan. Southwards from the Siwaqa fault, groundwater table is rather shallow as about 100m in depth in the central part of the Mujib basin along the zone of Desert highway.

2.4 Well Inventory and Water Use

The Water Resources Department of WAJ maintains a series of inventory of wells, which comprises of records of 219 wells in the Study Area, including 155 private wells and 64 government wells. These records have been compiled and reviewed by using micro-computer data bank, of which outputs are presented in Tables C-2 to C-7. Wells drilled prior to the study are prefixed PVT (private), PP, S, W(Wala), SW(Siwaqa), AP(Lajjun) and AB(Abyad), and serially numbered. In addition, four test wells have been drilled under project supervision, and they are prefixed T(JICA) in a separate and serially numbered. These well data were installed in micro-computer (IBM-5550) data base.

Most of the private wells have been drilled in the northern part of the Wala basin. They are used for irrigation purposes, and are located mostly in the zone along Desert highway thru Qastal, Jiza, Wadi Hammam to Dabb'a. Some wells are located in the middle to lower reaches of Wadi Wala.

Government wells which are being used for water supply are mostly located along the Desert Highway thru Qastal to Sultana. At present, well fields of Qastal, Siwaqa and Qatrana are connected by water pipelines to Amman. Production wells in Sultani area are piped to Karak water supply. In Abyad area, wells drilled by the Government are being used for phosphate mining.

Fifteen test wells were drilled by WAJ in Wadi Heidan in 1984, to examine the groundwater potential in that area. However, withdrawals from the B2/A7 aquifer in and around that area has been believed to have a direct influence on base flow in the wadi. Strong attention has been given to the hydraulic connection between the B2/A7 aquifer and the flowing springs along the Wadi Heidan. A total of 17 exploratory wells were drilled by NRA in Lajjun area where oil shale mining is scheduled to be developed in the future.

The area presenting the greatest total withdrawal is located in the zone along Desert highway thru Qastal to Abyad. Based on the data from well inventory and other data from water works, this study assumed a total discharge of 32.5 MCM/y, which includes the withdrawal 2.0 MCM/y from Qastal (WAJ), 10.1 MCM/y from Siwaqa (WAJ), 3.0 MCM/y from Qatrana (WAJ), 1.4 MCM/y from Sultani (WAJ), 2.0 MCM/y from Ghureir (WAJ), 2.9 MCM/y from Abyad (Phosphate mining) and other 11.1 MCM/y (Irrigation). These pumping rates are used as the basis of the input parameter in the groundwater simulation model as described in following Clause 3.5.

2.5 Drilling Exploration

The drilling exploration of this study is concerned with uncertain areas where groundwater potential was deemed to be high but without adequate data from wells. Four areas were selected, including "Rumeil (T-1)", "Khan El Zabib (T-2)", "Siwaqa (T-3)" and "Qatrana (T-4)", of which location is shown in Fig.C-4. The drilling program includes four test wells and two observation holes with a total depth of 1683.5m. The drilling work was performed by the local contractor of "Naser Brothers for Well Drilling and Trade" under the supervision of the Study Team, that included drilling, well logging, pumping test and water quality test. The well logging was carried out by the Study Team in cooperation with WAJ's geophysical crew including logging of resistivity, gamma ray, water temperature, electrical conductivity and flow velocity. These results are presented in Fig. C-5 to C-8 of summary of well log.

Water samples were collected during pumping test, and were sent to the laboratory of WAJ in Amman. The chemical analysis was made for major constituents of calcium, magnesium, sodium, potassium, chloride, sulfate, carbonate, bi-carbonate, nitrate, electrical conductivity (EC) and total dissolved solid (TDS), and these results are shown in Table C-8.

Pumping tests were performed to estimate the aquifer parameters of transmissivity and storage coefficient in the B2/A7 aquifer. To assess the storage coefficient, two observation holes were installed beside the T-1 and the T-3 pumping wells at a distance of 20 m each. Analysis was performed using both modified equilibrium equation and conventional non-equilibrium equation. For the pumping test without observation hole, following modified form of equilibrium equation is used;

$$T = Q * \text{In } (R/r)/(2 \times 3.14 \ (H-h)) \ldots\ldots\ldots\ldots (C-1)$$

$$R = 2 * (H-h) * \text{SQRT}(T) \ldots\ldots\ldots\ldots (C-2)$$

From (2) and (3), unknown R is estimated by substituting R by x;

$$F(x) = \text{In}(x) - 3.14 * x^2/(2 * Q(H-h)) - \text{In}(r) = 0 \ldots\ldots (C-3)$$

Where:
- In : Natural log
- T : Coefficient of transmissivity (m^2/d)
- Q : Pumping rate (m^3)
- R : Radius of influence, x(m)
- r : Radius of the test well (m)
- H : Piezometric head before pumping (m)
- h : Piezometric head after pumping (m)
- SQRT: A square root
- * : Multiplying

Equation (C-3) is numerically solved by Newton-Raphson iteration method, by using the data of pumping rate, well drawdown and radius of well only. This simple numerical analysis is also included in the computer program for the data base of well inventory.

For the pumping test with observation hole (at T1 and T-3), conventional non-equilibrium equation is used to estimate the storage coefficient by applying Jacob method. Storage coefficients are estimated to be 0.0009 to 0.027 against the values of transmissivity of 35 to 556 m^2/d. Summary of analysis of the pumping test is presented in Table C-9.

2.6 Aquifer Properties

Measured transmissivities differ widely from well to well with values ranging from 5 to 26,000 m^2/d. The difference in the wide range in the permeability in the B2/A7 aquifer, is largely due to the karst features, including enlarged joints, sink holes, caves, and solution breccias that developed in and around the fault zones.

Most of the available measurements of transmissivities of the B2/A7 aquifer are summarized in Table C-10. Because the reported values are not always obtained by the same methodology, for the comparative purposes they are all converted to values of transmissivity which were estimated by modified equilibrium equation. It is clear from Table C-10 that the higher transmissivities are located along the zone of major Wadi system in the Wala basin and the zone of Desert Highway in the Mujib basin.

2.7 Potentiometric Data

The density of the potentiometric control points in the Study Area is dependent on the WAT's monitoring program; when the model was being constructed, there were 9 observation wells with automatic water level recorders from which accurate potentiometric data were available within an area of 6,600 km^2. Furthermore, the available potentiometric data were obtained from a variety of sources and were measured in a variety of ways. Hence, their degree of reliability vary greatly. Four groundwater gauging stations (T-1 to T-4) were added to the existing control points by the Study Team. These potentiometric data were used to enhance the reliability of the potensiometric maps for the B2/A7 aquifer. Piezometric surface in the B2/A7 aquifer is also shown in Fig.C-1.

Systematic groundwater monitoring has been carried out by WAJ's monitoring section of Water Resources Department since 1983. The monitoring work includes regular measurement of groundwater table and water quality. Automatic water recorders, 9 in number, have been installed in WAJ wells; 3 are located in Qastal, 2 in Heidan, 2 in Siwaqa and 2 in Qatrana. Most of the automatic measurement started in 1984 to 1985, except the Qatrana S-124 well which has the longest record since 1979. Groundwater hydrographs at 9 automatic gauging stations are shown in Fig. C-10.

From records at SW-7 observation well in the Siwaqa well field, rapid lowering of the piezometric surface, by 2 to 3 m of drawdown per year, has been measured since 1984. Close attention has been paid to the excess withdrawing from the Siwaqa well field.

2.8 Spring Discharge

Major outflows from the B2/A7 aquifer include underflow to the northeast in Azraq, discharge to pumping wells and flowing springs. Most of the large springs that discharge regional flow from the B2/A7 aquifer within the Study Area are located in the valley's outcrop areas in the Wadi Heidan. Hydrogeological occurrence of those major flowing springs are largely dependent on the geological structures of major faults. The biggest group of springs with annual average flow discharge of 15 MCM/y is located in the Wadi Heidan, where ground elevation is about 350 m and located at about 5 km westwards from the Wala bridge where King's highway crosses the wadi. A part of these spring water, which is preliminarily estimated to be 3 to 6 MCM/y in total, is being used for local irrigation in the Heidan area.

There are some small springs in the Wadi Mujib. Perennial flow discharge of these flowing springs from B2/A7 aquifer is preliminarily estimated to be about 5 MCM/y, which is being used fully for local irrigation. Springs from the A1-A6 Formation appear in and around the Mujib bridge, and they are fully used for local irrigation. These are negligible to minor contributor of base flow in the lower reaches. The details of the measurement of base flow are described in Clause 5.2 of Appendix (I)-B.

2.9 Water Quality

Water quality of groundwater in the B2/A7 aquifer is good to fair, compared with other sources such as sandstone aquifer in the Kurnub Formation. Total dissolved solid (T.D.S) and electrical conductivity (E.C) have been measured for most of the water samples. The T.D.S, which shows good correlation with E.C (T.D.S = 0.63 x E.C) is usually used for a major indicator of salinity of water. The low range in T.D.S less than 500 mg/l is found in the recharge mounds at the northeastern and southeastern ridge of the watershed. Rather fresh groundwater zones with T.D.S less than 750 mg/l are mapped in the zone along major drainage system in the Wala basin. Some patches less than 750 mg/l of T.D.S are also found in the major well fields along the zone of Desert Highway. Higher T.D.S of more than 1,250 mg/l is mapped on wide areas on the eastern desert. In the southern part of the Wala basin, T.D.S is rather high in the range between 1,000 to 1,250. T.D.S map of the B2/A7 aquifer is shown in Fig.C-11. Distribution of the T.D.S has a good correlation with either the distance from recharge mound or aquifer permeabilities.

Chemical analysis of the base flow have been performed by NRA and WAJ at confluence of Wadi Mujib and at Wadi Heidan since 1965. Quality of the flood flow has been measured using the water samples from impounded water at Qatrana dam in 1987. These results are presented in Table C-11. The T.D.S of water sample from Wadi Mujib is about 1,250 mg/l or more, while it is about 1,000 mg/l or less in the downstream of Wadi Heidan. In the upper Wadi Heidan, where flowing springs from the B2/A7 Formation are concentrated at an elevation about 350 m, the T.D.S is as low as about 500 mg/l. The T.D.S of flood water has been measured in September 1986, using the impounded water from Qatrana existing dam, and was found to be very low at less than 500 mg/l.

2.10 Groundwater Recharge and Well

The T.D.S of flood flow water is as low as less than 500 mg/l, which is an excellent source for the schemes of groundwater recharge and wells, if the higher suspend solid (SS) in the order of 1,000 mg/l is removed before injecting surface water into the B2/A7 aquifer. Groundwater recharge programs by well injection method are proposed at the potential sites of Qatrana, Sultani and Siwaqa, where existing or proposed damsites are located in the existing well fields. This recharge program is to combine two facilities of "flood flow storage dam" and "injection wells". Flood water during rainy season is first stored in the reservoir to remove the sands or suspended silt by natural precipitation and then introduced to the recharge well through filter unit by gravity flow as shown in schematic diagram of Fig. C-12.

A gravel filter unit is required to prevent the well logging by removing the fine silt. Among the three conceivable recharge programs, Qatrana scheme is one of the most promising, taking into account the effective stored flood water volume of 4.0 MCM and desirable siting of the existing dam on the center of flow pass in the Qatrana well field.

Available potential water of Wala flood storage dam scheme is estimated to be 17 MCM/y, which is a water leak through reservoir rims and foundation of B2a layer. A part of leaked water of 6 MCM will recharge the shallow aquifer of B2a and underflows on impervious B1 layer, and reappear on the river bed near the Wala bridge. Furthermore, artificial recharge of 5 MCM/y by using 11 injection wells which are located at downstream area of the damsite, will reinforce the groundwater potential of the Heidan well field in the downstream. Wala artificial recharge system is shown schematically in Fig. C-13.

The effect of these artificial recharge program is examined by the groundwater simulation model. The details of the simulation are shown in the following clause of 3.5 of groundwater management plan. Direct cost of the artificial recharge by injection wells at Qatrana, Sultani, Siwaqa C and Wala are preliminarily estimated to be JD. 65,700 to JD. 338,300 as shown in Table C-12.

3. GROUNDWATER MODEL SIMULATION

3.1 Mathematical Model

Groundwater flow in the B2/A7 aquifer is assumed to be governed by the two dimensional non-steady equation, which is called diffusion type of the partial differential equation with parameters of hydraulic conductivity and specific strativity. The numerical analysis of the simulation model has been performed by finite element method (FEM), which is now widely used to solve regional aquifer problems posed in a horizontal two dimension scale. Some advantages of the use of finite-element method over classical finite difference methods are the following;

(1) Ease of using a variable arbitrary discretization mesh.
(2) Ease of incorporating boundary conditions without special gradient approximations.
(3) Ease of dealing with heterogeneous-anisotropic domains.

Disadvantage of the finite-element methods over the classical finite difference methods is the requirement of huge random access memories and large computational time.

Solution of the partial differential equation is accomplished by the Galerkin finite element procedure, which is basically a rule for reducing the governing partial differential equations to a matrix statement involving a matrix of unknown elements and a matrix of unknown state valuables. The Galerkin technique is some what more general and is widely cited by those applying finite element methods to porous media flow problems.

3.2 Model Construction

The finite-element grid mesh of the Study Area, which is composed of triangular and/or quadrilateral elements, is shown in Fig. C-14. The area encompassed by the grid is about 6,600 km^2. The grid includes 835 quadrilateral (composites of four triangles) and triangular elements and 799 nodes. In general, the grid was designed to be finer where more data are available and/or where hydraulic gradients are relatively steep such as along the zones of Siwaqa fault and Faya linearment, and it is generally coarser in areas where few data are available and/or where hydraulic gradients are relatively small. In addition to these general grid work, finer meshes are given to the zone along Wadi Heidan, where more finer grids are needed to estimate the influence of groundwater withdrawal on the flowing springs in the wadi at elevation between 300 and 450 m. The distance between adjacent nodes varies accordingly from about 0.5 to 10 km. Nodes are located to coincide with observation and withdrawal wells, springs and hyraulic and geologic boundaries as shown in Fig. C-4.

Boundary conditions are either of the specified-flow or specified-head type. Model nodes along the western and northern boundaries of the Study Area, where annual rainfall exceeds more than 200 mm in the outcrop areas, are of specified-head type. Specified-flow is given to the nodes along the eastern boundary of the Study Area, where groundwater flows out to further east from the basin boundary. In addition to those conventional boundary conditions, recharge rates are given to the specified nodes, where groundwater recharge through the surfacial soil layers are estimated to be positive by the Tank Model simulation analysis (Refer to Appendix (I)-B). Major wadis of Heidan and Mujib have eroded canyons to cut the saturated zone of B2/A7 aquifer. In these areas, a plot of the land surface along the nodes was compared to the available head data, and a composit of these data was used as the initial specified image boundary.

Initial values for the specified-head boundaries were obtained by plotting head observations from wells and springs. The areas, where observed data were not available, interpolation was made by assuming that the head could be considered to vary linearly with distance. Wherever a head parameter coincided with an observation, the parameter was assumed to have prior information on the zonal parameters.

Major geologic features are illustrated in Fig. C-1. These, as well as data obtained from other sources, were used to create aquifer zones of constant permeability. As described in clause 2.2, B2/A7 aquifer unit is not composed of a single uniform layer but consists of alternating pervious, semi-pervious and impervious layers. It is rather difficult to distinguish the effective thickness of the pervious layers, however, in the model formulation, effective thickness of the accumulated pervious layer is assumed to be 100 m. From the analysis of pumping test data from 200 wells, zonal transmissivities in the order between 2 and 10,000 m^2/d were estimated for the model study. Zonal coefficient of permeabilities in the order between 2.3×10^{-5} and 1.2×10^{-1} cm/sec were created, for 18 zones. Although 18 zones were created, there are only three basic types of zones; (i) zones with higher permeability of more than 5×10^{-3} cm/sec in the area along the major drainage system of the Wadi Wala and along the zone of Desert Highway from Siwaqa to Abyad. (ii) zones with lower permeability less than 5×10^{-3} cm/sec in the remaining part of the Study Area and (iii) linear features, termed here "linearments", that could be barriers to flow as indicated by zones of very steep gradient of piezometric surface, with very low permeability in the range between 2×10^{-5} to 2×10^{-4} cm/sec. Other stratigraphic variations were not separated out as zones because it was not clear how these features affected permeability and because there was no clear evidence in the observed head data of large-scale permeability variations. Zonal permeabilities are regarded as relative parameters used in the model. Because the existing estimates of permeability are scattered and few and because their reliabilities are unknown, this study assumes there is no prior information on the zonal permeabilities.

3.3 Model Calibration

The objectives of this study are (i) to demonstrate the simplest simulation model that could account for the principal features of flow in the B2/A7 aquifer and (ii) to examine the possibility of future development of groundwater resources in the basin. Accomplishment of the first aim requires postulating several alternative models and choosing the best one according to appropriate criteria. The second aim requires postulating several alternative identifications and choosing the best parameters according to the monitored data.

3.3.1 Steady state model calibration

The first step of the model calibration was performed by the two dimensional steady state equation using parameters of aquifer permeability and source-sink strength (positive for a source). Hydraulic head in the aquifer is computed by the Galerkin finite element procedure with given boundary condition as described in the preceding clause of 3.2. Identification of the steady state model was carried out by comparing the computed heads and spring discharge with observed data at representative points in the basin. The computed residuals results from two different sources of error, measurement error and lack of model fit. In general, it is rather difficult to distinguish the difference in the two sources of error.

In the model formulation there is assumed to be a steady state. In general, there are two kinds of steady states; the first is the steady state without any pumping, and the second is the steady state with some amounts of groundwater withdrawal, of which hydro-static level is still constant with annual recovery by natural recharge. The second category of the steady state is adopted in this study, by assuming the two dimensional steady state of partial equation with given boundary conditions and permeabilities. A steady state condition in the basin has been assumed the time before starting intensive pumping by WAJ in 1984. Record of groundwater level at Qatrana thru 1979 to 1983, indicates a constant water level with elevation at 686 m as shown in Fig. C-10, that is a static water level with pumping about 2 MCM/y by some wells for local water supply and irrigation in that area. In the Wala basin, no continuous monitoring record is available before for period before 1984, however, indirect information of the flowing springs in the Wadi Heidan can be used to interpret the static water level in the groundwater basin. From the WAJ's monitoring record at Heidan springs, a significant change in decreasing and/or increasing of the spring discharge has not been recorded in the hydrograph thru 1960 to 1985

(Refer to clause 5 in Appendix (I)-B). During that period from 1960 to 1985, groundwater has been mostly exploited by private wells for the purpose of irrigation in the middle to upper parts of the Wala basin.

The steady state calibration was made by comparing the computed piezometric heads with observed heads by using the water level map of 1984. The computed residual of the piezometric head at major control points in the basin are in the range between 1 to 5 m, that is; +5.1 m at Qastal, +0.8 m at Siwaqa, +3.4 m at Qatrana and +3.4 m at Sultani. Spring discharge of the Heidan springs was computed by solving the finite-element equation at each node with image specified-head, which is located along the Wadi Heidan at elevation between 324 and 330 m, for the flux across the node, then summing all of these fluxes to get the total. The computed spring discharge is 14.4 MCM/y in total, which is 96.3 % of the observed discharge of 15.0 MCM/y, that indicates a good precision of the computed total discharge. In general, the model matches observed conditions fairly well. Original groundwater level is presented in Fig. C-1 and the calibrated piezometric head as of the year 1986 is shown in Fig. C-9.

3.3.2 Non-steady state model calibration

The second step of the model calibration for the non-steady state condition was performed by assuming the two dimensional non-steady partial equation with additional parameter of strativity. Successive aquifer drawdown has been observed in the WAJ's monitoring wells at Siwaqa and Qatrana as shown in Fig. C-10. Hydraulic head in the aquifer is computed by the Galerkin finite element procedure with fixed boundary conditions, aquifer parameters of permeability and strativity and given present pumping rate as described in Clause 2.4. Identification of the aquifer parameters of strativity was performed by comparing the computed head with observed monitoring data at Siwaqa and Qatrana. Two years (1984 to 1986) of monitoring records was used to calibrate the computed head. From the pumping test at T-1 and T-3, following equation was preliminarily installed by correlating the estimated values of transmissivities and coefficients of storage as shown in Table C-9;

$$S = So * T^{1.0103} \quad \cdots\cdots\cdots\cdots \quad (4)$$
$$(So = 0.000028)$$

where, S = Storage coefficient (-)

So = Coefficient to strativity (-)

T = Transmissivity (m^2/d)

Sensitivity analysis on "S" was performed by changing "So" by 4 steps from 0.000012 to 0.000076. Fitted "So" is calibrated to be 0.000017, which matches observed conditions fairly well. Fig. C-16 shows a comparison of model-computed water level with measured 1985 and 1886 water levels in a monitoring well in Siwaqa well field. During this period from 1984 to 1986, existing pumping rate is assumed to be 32.5 MCM/y in total, which includes the intensive pumping rate of 10.1 MCM/y during 1986-87 from Siwaqa well field.

3.4 Model Prediction

After examining the hydrogeology and WAJ's water pipeline program in the Study Area, four potential well fields were selected, taking into account the water quality for future drinking use. They are "Rumeil", "Siwaqa-Qatrana," "Sultani" and "Lajjun". Among them, Lajjun well field is scheduled to be reserved for the future development of oil shale mining. "Siwaqa-Qatrana" and "Sultani" well fields are located in the central part of the Mujib basin along the zone of Desert highway, where groundwater table is located at a depth of about 100 m in an average, with salinity (T.D.S) of about 750 ppm. "Rumeil" well field is located at middle to lower reaches of Wadi Wala, where groundwater table is located at a depth of about 120 m in average, with salinity (T.D.S) of about 1,000 ppm. Safe water level which is the basis of the sustained yield is assumed to be 100 m of drawdown, which will be a maximum drawdown from a view point of water economy and aquifer reservation. In the Wala basin, the safe water level is assumed to be 100 m of drawdown, with condition that the pumping from the proposed well field will not give any adverse effect on flowing springs in Wadi Heidan. Rumeil well field has been proposed in the middle reaches of Wadi Wala with distance more than 10 km from Heidan springs, in order to avoid the influences. Validity of the non-steady model prediction is mostly dependent on the length of the monitoring period. In the model study predicting period may have a meaning within a range in time less than 10 times of the monitoring period. The period of monitoring, which is used for the non-steady model calibration was 2 years only from 1984 thru 1986. From the limited period of the monitoring of 2 years, the validity of the period of predicting piezometric head in the aquifer by this model study will not exceed more than year 2005. Predicted water levels in the year 2005 can be used with less reliability, and be interpreted to indicate the general hydrostatic conditions in the developing aquifer. From the model simulation analysis (Mode-23) by predicting piezometric head in the aquifer , sustained yield of each well field is estimated to be; (1) 7.0 MCM/y from "Rumeil" well field, (2) 9.6 MCM/y from "Siwaqa - Qatrana" well field and (3) 6.3 MCM/y from "Sultani" well field. The sustained yield from those three well fields is estimated to be 22.9 MCM/y in total, on top of 28.4 MCM/y of present pumping. In this prediction of using Mode-23, pumping rate at Siwaqa existing well field after 1986, taking into account the excessive drawdown caused by heavy pumping is assumed to be 6.0 MCM/y, which is 60% of peak pumping rate of 10.1 MCM/y during 1984 and 1986. The details of the number of well, location and well design of these proposed three well fields are shown in the Clause F3 of Appendix (II). Pumping rates of the other existing well fields are assumed to be the same as before 1986; 2.0 MCM/y from Qastal (WAJ), 3.0 MCM/y from Qatrana (WAJ), 1.4 MCM/y from Sultani (WAJ), 2.0 MCM/y from Ghureil (WAJ), 2.9 MCM/y from Abyad (Phosphate Mining) and other 11.1 MCM/y (Irrigation).

From the model analysis, piezometric head in the aquifer is estimated to be lowered by 20 to 90 m by the year 2004. Estimated drawdown at control points in the proposed three well fields by the year 2005 is 38 m in Rumeil, 46 m in Siwaqa-Qatrana and 74 m in Sultani. Predicted drawdown by the year 2145 at the major control points in the basin is presented in Fig. C-17. Computed drawdown is mapped on the basin mesh including year after 10, 20, 40 and 160.

Influence of 7.0 MCM/y withdrawal from the Rumeil proposed well field on the spring discharge at the Wadi Heidan is estimated by the model. The spring discharge in the Wadi Heidan is computed by solving the finite-element equation at each specified-head node for the flux across the node, then summing all of these fluxes to get the total. Predicted flow discharge of the Heidan springs is shown as follows;

Year	1986	1995	2005	2025	2065	2145
Discharge (MCM/y)	14.4	13.9	13.5	12.9	12.4	12.2

Decreasing of the spring discharge is estimated to be 1 MCM/y which is 7% of the present spring discharge at the Heidan.

3.5 Prediction of Change in Quality of Groundwater

Change in quality of groundwater is preliminarily predicted by using the results of measurement of hydro-chemistry and model simulation. Water in the B2/A7 Formation increases in dissolves solids (and/or electrical conductivity) from less than 500 ppm near outcrop areas to greater than 1,500 ppm in downflow areas. Both existing and proposed well fields are located in the areas with good to fair water quality in the range between T.D.S of 750 and 1,250 ppm. Whilst water in the aquifer in the proposed well fields generally increases in dissolved solids from 750 ppm in shallow part to greater than 2,250 ppm in deep part as shown in conductivity logs in Figs. C-5 to C-8. Quality of pumped waters from proposed well fields may be changed by lowering piezometric head by the long term pumping. Three dimensional distribution of the chemical constituents is needed to predict the quality of groundwater in each well field. Both horizontal and vertical changes in quality of groundwater have been measured in well fields at Sultani, Qatrana-Siwaqa and Rumeil as shown in Figs. C-5 to C-8 and C-11. The changes in T.D.S were predicted to couple with the results of hydrochemistry and model simulation (Mode-23). The T.D.S will be increased to correspond with lowering piezometric head in the aquifer, 4 to 60% in the proposed well field at Sultani and Qatrana-Siwaqa. Whilst the T.D.S in Rumeil well field is predicted to be constant as shown in Fig. C-20.

3.6 Groundwater Management Plan

In arid to semi-arid region, where potential of groundwater resources is limited, artificial recharge of groundwater is one of the most important study item to accomplish the groundwater management plan either by increasing the aquifer potential; or maintaining the long term pumping. In Mujib basin, no field experiment has been carried out for the groundwater recharge, however, preliminary estimate of the effects of the artificial recharge by coupling the flood storage dam schemes was made by using the simulation model. Wala recharge dam was selected for this purpose because the site is located between Rumeil well field and Heidan springs, and it was expected that the groundwater recharge by the Wala scheme give a good influence on not only enhancing the aquifer potential but also increasing the spring discharge. Analysis was made by assuming the injection rate of 5.4 MCM/y in total by using 11 injection wells which are penetrated in the A7 Formation. From the model simulation analysis, piezometric head in both well field of "Heidan" and "Rumeil" will be recovered by 3 to 14 m. Spring discharge at Heidan will also be increased by 1.4 MCM/y. Computed changes in the piezometric head in the well fields are shown in Fig. C-20. Other example of artificial recharge Qatrana and Rumeil recharge dam schemes was also examined by using the simulation model. The scheme assumes the injection rate of 3.2 MCM/y at Qatrana and 0.6 MCM/y at Sultani on top of proposed pumping program as described in Clause 3.4. The computed recovery will be 10 to 35 m as shown in Fig. C-20. A series of further hydrogeological investigation will be needed to examine the feasibility of Wala recharge dam scheme, including test drilling, pumping and pump-in test, tracer test, measurement of flood flow, suspended load and water quality between the area of damsite and Heidan springs.

Table C-1 ESTIMATED GROUNDWATER RECHARGE

Source	Volume (MCM/y)	Remarks
Outcrop/Boundary	52.2	Direct recharge through outcrops at boundary in recharge mounds.
Filtration	14.2	Indirect infiltration through overlying soil layer.**
Wadi Channel	2.3	Direct infiltration through outcrops in the wadi bed during flush floods.**
Total	68.7	

Remarks : * Recharge from the boundary of groundwater mounds was computed by using simulation model, which solves the finite-element equation at each specified-head node for the flux across the node, then summing all of these fluxes to get the total

** Tank model was used to estimate the volume of recharge (See Appendix-(I) B)

Table C-2 SUMMARY OF WELL INVENTORY (1/6)

No	Well Name	Coordinate (East)	Coordinate (North)	Ground Level (m)	Well Depth (m)	Water Depth (m)	G.W.L (m)	Yield (m3/h)	Draw-Down (m)	SC (m2/h)	Transmi-ssivity (m2/d)	EC (ms/cm)	TDS (ppm)	Aquifer
1	PVT - 1	242.560	131.720	734.2	363.0	151.8	582.4	108.0	2.8	39.3	1099	725	464	B2/A7
2	PVT - 2	242.955	131.710	734.2	200.0	158.0	576.2	60.0	0.2	400.0	8294	697	446	B2/A7
3	PVT - 3	242.870	132.070	733.9	310.0	157.9	576.0	108.0	2.8	39.3	1099	725	464	B2/A7
4	PVT - 4	239.420	135.230	785.7	310.0	213.0	572.7	60.0	17.3	3.5	106	630	403	B2/A7
5	PVT - 5	242.750	131.700	733.7	200.0	158.0	575.7	60.0	0.2	400.0	8294	697	446	B2/A7
6	PVT - 6	244.115	128.820	737.0	300.0	162.6	574.4	33.0	60.0	0.6	18	969	620	B2/A7
7	PVT - 7	244.765	130.250	745.8	350.0	172.6	573.2	20.0	69.6	0.3	9	—	—	B2/A7
8	PVT - 8	242.450	141.860	830.2	365.0	162.8	667.4	20.0	64.3	0.3	10	650	416	B2/A7
9	PVT - 9	241.770	144.150	865.7	235.0	135.0	730.7	18.0	0.0	—	—	747	478	B2/A7
10	PVT - 10	247.170	100.090	719.6	260.0	147.6	572.0	60.0	2.3	26.1	689	1289	825	B2/A7
11	PVT - 11	246.365	97.735	741.2	320.0	189.4	551.8	52.0	11.8	4.4	130	—	—	B2/A7
12	PVT - 12	243.900	98.260	740.6	262.0	169.2	571.4	70.0	0.8	87.5	2148	1739	1113	B2/A7
13	PVT - 13	241.755	100.350	719.7	304.0	156.5	563.2	65.0	0.0	—	—	1719	1100	B2/A7
14	PVT - 14	241.020	102.010	736.1	350.0	175.3	560.8	71.0	0.6	110.9	2675	2422	1550	B2/A7
15	PVT - 15	240.150	100.550	751.8	316.0	188.0	563.8	88.0	12.0	7.3	224	1619	1036	B2/A7
16	PVT - 16	243.270	116.250	676.4	300.0	124.2	552.2	18.0	128.0	0.1	5	—	—	B2/A7
17	PVT - 17	236.700	113.210	682.3	255.0	141.6	540.7	60.0	31.0	1.9	61	925	592	B2/A7
18	PVT - 18	241.450	116.745	709.9	265.0	151.6	558.3	57.0	0.5	114.0	2639	811	519	B2/A7
19	PVT - 19	239.916	117.649	690.2	270.0	136.5	553.7	60.0	54.5	1.1	36	841	538	B2/A7
20	PVT - 20	239.985	112.965	693.3	304.0	143.9	549.4	70.0	0.1	1400.0	26232	920	589	B2/A7
21	PVT - 21	235.565	135.670	799.2	263.0	146.0	653.2	35.0	96.0	0.4	12	639	409	B2/A7
22	PVT - 22	235.260	136.830	788.7	230.0	119.4	669.3	30.0	69.1	0.4	14	914	585	B2/A7
23	PVT - 23	237.160	138.150	807.8	180.0	152.4	655.4	50.0	10.9	4.6	134	555	355	B2/A7
24	PVT - 24	237.310	137.110	793.3	202.0	145.6	647.7	53.0	4.3	12.4	340	536	343	B2/A7
25	PVT - 25	236.100	136.365	786.1	303.0	144.3	641.8	35.0	49.6	0.7	22	613	392	B2/A7
26	PVT - 26	235.600	139.500	812.8	180.0	72.8	740.0	63.0	30.8	2.0	65	500	320	B2/A7
27	PVT - 27	234.550	139.860	819.5	201.0	91.3	728.2	20.0	22.5	0.9	26	475	304	B2/A7
28	PVT - 28	234.590	138.730	820.5	225.0	95.0	725.5	62.0	1.9	33.0	860	589	377	B2/A7
29	PVT - 29	234.135	138.499	843.0	213.0	109.6	733.4	58.0	17.6	3.3	101	—	—	B2/A7
30	PVT - 30	245.385	104.010	718.8	301.0	147.6	571.2	70.0	2.8	25.0	678	1439	921	B2/A7
31	PVT - 31	245.732	104.785	707.1	322.0	135.5	571.6	70.0	1.9	36.8	970	1709	1094	B2/A7
32	PVT - 32	246.485	104.560	718.5	228.0	147.0	571.5	55.0	24.7	2.2	69	1514	969	B2/A7
33	PVT - 33	247.105	105.410	722.3	565.0	146.2	576.1	34.0	66.1	0.5	17	1919	1228	B2/A7
34	PVT - 34	247.630	103.320	715.8	297.0	142.4	573.4	85.0	12.6	6.8	207	1380	883	B2/A7
35	PVT - 35	246.900	107.060	752.8	369.0	185.0	567.8	70.0	43.0	1.6	53	—	—	B2/A7
36	PVT - 36	247.520	109.075	700.8	340.0	133.6	567.2	20.0	70.0	0.3	9	1680	1075	B2/A7
37	PVT - 37	248.865	107.325	758.4	282.0	190.6	567.8	60.0	26.0	2.3	72	2156	1380	B2/A7
38	PVT - 38	244.140	103.000	694.4	255.0	123.7	570.7	62.0	1.3	48.8	1233	1458	933	B2/A7
39	PVT - 39	247.950	113.660	713.7			713.7			—	—	—	—	B2/A7
40	PVT - 40	252.650	110.400	746.1	350.0	199.3	546.8	60.0	22.0	2.7	85	1769	1132	B2/A7
41	PVT - 41	252.625	115.390	710.1	275.0	155.7	554.4	60.0	2.0	30.8	802	2250	1440	B2/A7
42	PVT - 42	252.520	116.070	703.8	300.0	149.7	554.1	75.0	0.3	250.0	5663	2230	1427	B2/A7
43	PVT - 43	259.530	106.490	790.7	297.0	210.4	580.4	50.0	17.8	2.8	85	2069	1324	B2/A7
44	PVT - 44	258.575	108.825	774.4	316.0	196.4	578.0	60.0	46.0	1.3	42	2609	1670	B2/A7
45	PVT - 45	254.315	106.805	779.1	330.0		779.1	32.0	46.8	0.7	21	2369	1516	B2/A7
46	PVT - 46	253.105	108.390	763.0	350.0	196.2	566.8	55.0	52.0	1.1	34	2609	1670	B2/A7
47	PVT - 47	254.520	111.130	751.4	204.0	206.7	544.7	40.0	31.8	1.3	39	3500	2240	B2/A7
48	PVT - 48	247.690	115.150	705.0	240.0	156.2	548.8	91.0	4.4	20.7	591	891	570	B2/A7
49	PVT - 49	257.608	111.260	801.7	285.0	232.3	569.5	40.0	28.3	1.4	43	2609	1670	B2/A7
50	PVT - 50	239.275	99.415	763.5	350.0	199.0	564.5	20.0	25.8	0.8	23	1528	978	B2/A7

Table C-3 SUMMARY OF WELL INVENTORY (2/6)

No	Well Name	Coordinate (East)	(North)	Ground Level (m)	Well Depth (m)	Water Depth (m)	G.W.L (m)	Yield (m3/h)	Draw-Down (m)	SC (m2/h)	Transmissivity (m2/d)	EC (ms/cm)	TDS (ppm)	Aquifer
51	PVT - 51	237.951	101.615	747.1	350.0	204.8	542.3	36.0	68.2	0.5	17	1739	1113	B2/A7
52	PVT - 52	238.115	104.500	695.3	303.0	138.9	556.4	50.0	59.2	0.8	28	1681	1076	B2/A7
53	PVT - 53	239.270	102.750	717.0	323.0	158.8	558.3	75.0	0.9	88.2	2190	1769	1132	B2/A7
54	PVT - 54	240.150	104.430	707.7	322.0	148.4	559.3	76.0	0.6	126.7	3055	1470	941	B2/A7
55	PVT - 55	235.220	105.540	695.5	300.0	210.0	485.5	35.0	42.0	0.8	26	1889	1209	B2/A7
56	PVT - 56	234.785	99.040	745.9	322.0	183.7	562.2	61.0	27.7	2.2	70	1859	1190	B2/A7
57	PVT - 57	236.255	98.345	768.0	325.0	206.1	561.9	50.0	41.3	1.2	39	1589	1017	B2/A7
58	PVT - 58	232.255	99.080	779.7	323.0	285.0	494.7	35.0	39.0	0.9	28	2055	1315	B2/A7
59	PVT - 59	232.120	96.915	755.4	401.0	218.6	536.8	19.0	35.4	0.5	16	1859	1190	B2/A7
60	PVT - 60	233.900	111.020	603.6	288.0	72.0	531.6	30.0	17.3	1.7	51	898	575	B2/A7
61	PVT - 61	232.830	111.060	590.0	255.0	89.7	500.3	45.0	8.0	5.6	160	---	---	B2/A7
62	PVT - 62	234.085	109.440	579.7			579.7	60.0	0.0	---	---	---	---	B2/A7
63	PVT - 63	232.575	109.700	569.4	152.0	82.6	486.8	50.0	44.7	1.1	36	934	598	B2/A7
64	PVT - 64	231.560	110.300	638.0	250.0	144.6	493.4	25.0	76.4	0.3	10	1230	787	B2/A7
65	PVT - 65	230.950	111.300	603.6	225.0	108.7	494.9	15.0	52.5	0.3	9	1164	745	B2/A7
66	PVT - 66	249.345	116.575	689.6	210.0	136.0	553.6	60.0	0.1	500.0	10132	969	620	B2/A7
67	PVT - 67	251.470	114.886	711.3	290.0	156.9	554.4	80.0	0.4	228.6	5282	1469	940	B2/A7
68	PVT - 68	251.690	115.815	702.7	273.0	148.3	554.4	60.0	28.8	2.1	66	1859	1190	B2/A7
69	PVT - 69	250.762	115.765	700.6	310.0	146.2	554.4	45.0	62.1	0.7	24	1641	1050	B2/A7
70	PVT - 70	251.072	116.640	698.0	225.0	143.3	554.7	80.0	2.3	35.2	951	1031	660	B2/A7
71	PVT - 71	246.365	114.000	701.7	323.0	152.9	548.8	50.0	22.1	2.3	69	784	502	B2/A7
72	PVT - 72	250.340	113.935	742.3	326.0	192.4	549.9	60.0	53.2	1.1	37	1395	893	B2/A7
73	PVT - 73	251.575	113.920	731.6	300.0	186.2	545.4	0.0	0.0	---	---	---	---	B2/A7
74	PVT - 74	257.030	114.310	728.0	358.0	168.6	559.4	30.0	92.8	0.3	11	2045	1309	B2/A7
75	PVT - 75	250.300	116.540	695.6	220.0	140.9	554.7	50.0	48.9	1.0	33	905	579	B2/A7
76	PVT - 76	250.175	115.075	710.2	304.0	155.0	555.2	71.0	0.8	87.7	2157	1228	786	B2/A7
77	PVT - 77	252.770	114.677	717.2	280.0	164.0	553.2	32.0	56.0	0.6	18	2386	1527	B2/A7
78	PVT - 78	245.255	118.285	688.5	267.0	130.5	558.0	70.0	3.6	19.4	538	---	---	B2/A7
79	PVT - 79	243.950	118.260	717.6	257.0	158.9	558.7	62.0	0.0	---	---	828	530	B2/A7
80	PVT - 80	246.770	116.975	687.1	210.0	128.8	558.4	75.0	19.5	3.8	120	930	595	B2/A7
81	PVT - 81	243.740	117.665	696.1	241.0	138.1	558.0	65.0	2.8	23.2	626	739	473	B2/A7
82	PVT - 82	256.600	121.800	768.2	280.0	211.6	556.6	72.4	33.0	2.2	71	1145	733	B2/A7
83	PVT - 83	256.285	120.180	743.5	205.0		743.5	40.0	0.0	---	---	---	---	B2/A7
84	PVT - 84	250.160	124.765	730.2	352.0	162.4	567.8	33.0	45.9	0.7	23	1391	890	B2/A7
85	PVT - 85	253.460	124.725	759.3	400.0	197.0	562.3	35.0	70.0	0.5	16	1255	803	B2/A7
86	PVT - 86	251.495	119.700	712.9	250.0	155.9	557.0	55.0	38.8	1.4	45	1230	787	B2/A7
87	PVT - 87	252.000	121.850	721.9	225.0	164.1	557.8	50.0	28.5	1.8	55	---	---	B2/A7
88	PVT - 88	250.780	122.960	724.1	338.0	162.6	561.5	40.0	62.5	0.6	21	1619	1036	B2/A7
89	PVT - 89	253.630	119.520	721.2	300.0	190.7	530.5	18.0	27.8	0.6	19	1650	1056	B2/A7
90	PVT - 90	253.795	117.365	716.0	275.0	159.5	556.5	70.0	60.0	1.2	39	1709	1094	B2/A7
91	PVT - 91	254.575	116.295	713.8	248.0	160.0	553.8	60.0	31.5	1.9	60	2330	1491	B2/A7
92	PVT - 92	249.720	117.530	698.7	245.0	142.8	555.9	65.0	32.0	2.0	65	889	569	B2/A7
93	PVT - 93	256.450	116.000	714.0	275.0	163.0	551.0	65.0	9.0	7.2	212	178	114	B2/A7
94	PVT - 94	247.880	122.450	705.9	345.0	144.7	561.2	38.0	56.0	0.7	22	1439	921	B2/A7
95	PVT - 95	246.960	120.050	694.8	250.0	133.8	561.0	28.0	23.5	1.2	35	906	580	B2/A7
96	PVT - 96	248.745	120.585	723.2	300.0	162.1	561.1	40.0	0.2	222.2	4503	900	576	B2/A7
97	PVT - 97	247.920	117.950	690.9	200.0	139.5	551.4	60.0	0.2	333.3	7039	900	576	B2/A7
98	PVT - 98	247.950	119.660	701.9	342.0	132.2	569.7	0.0	0.0	---	---	---	---	B2/A7
99	PVT - 99	247.325	118.920	705.9	297.0	150.8	555.1	76.0	16.4	4.6	143	819	524	B2/A7
100	PVT -100	248.265	118.875	695.6	305.0	139.6	556.0	72.0	18.6	3.9	120	---	---	B2/A7

Table C-4 SUMMARY OF WELL INVENTORY (3/6)

No	Well Name	Coordinate (East)	Coordinate (North)	Ground Level (m)	Well Depth (m)	Water Depth (m)	G.W.L (m)	Yield (m3/h)	Draw-Down (m)	SC (m2/h)	Transmissivity (m2/d)	EC (ms/cm)	TDS (ppm)	Aquifer
101	PVT -101	261.500	120.100	770.0	365.0	220.2	549.8	0.0	0.0	---	---	---	---	B2/A7
102	PVT -102	239.890	129.710	737.1	300.0	148.7	588.4	80.0	0.0	---	---	---	---	B2/A7
103	PVT -103	240.630	129.650	723.7	0.0	0.0	723.7	0.0	0.0	---	---	---	---	B2/A7
104	PVT -104	237.740	130.165	737.3	264.0	162.3	575.0	50.0	0.8	62.5	1491	655	419	B2/A7
105	PVT -105	240.500	133.970	753.7	215.0	175.1	578.6	50.0	0.3	166.7	3634	---	---	B2/A7
106	PVT -106	238.390	134.330	789.4	305.0	181.6	607.8	32.0	0.0	---	---	---	---	B2/A7
107	PVT -107	242.880	132.700	736.3	300.0	159.1	577.2	0.0	0.0	---	---	---	---	B2/A7
108	PVT -108	241.245	130.000	732.2			732.2	0.0	0.0	---	---	---	---	B2/A7
109	PVT -109	239.350	129.350	732.2	355.0	160.6	571.6	55.0	7.0	7.9	224	800	512	B2/A7
110	PVT -110	245.000	119.550	708.5	243.0	150.8	557.7	50.0	46.3	1.1	35	789	505	B2/A7
111	PVT -111	244.055	119.920	719.7	235.0	161.1	558.6	62.0	1.2	52.5	1319	769	492	B2/A7
112	PVT -112	243.135	120.450	714.0	400.0	163.3	550.8	20.0	67.0	0.3	9	1745	1117	B2/A7
113	PVT -113	248.878	121.020	723.2	250.0	165.4	557.8	40.0	23.5	1.7	52	734	470	B2/A7
114	PVT -114	241.955	121.175	716.7	283.0	159.7	557.0	65.0	17.5	3.7	114	719	460	B2/A7
115	PVT -115	237.940	123.285	705.9	350.0	140.8	565.1	70.0	1.4	50.0	1285	939	601	B2/A7
116	PVT -116	236.030	123.550	724.8	370.0	152.5	572.3	50.5	82.7	0.6	20	1770	1133	B2/A7
117	PVT -117	239.175	120.110	785.1	270.0	121.3	663.8	90.0	46.0	2.0	65	1605	1027	B2/A7
118	PVT -118	242.063	123.315	714.6	270.0	152.2	562.4	40.0	2.4	17.0	436	1141	730	B2/A7
119	PVT -119	243.900	123.770	708.9	280.0	143.5	565.4	45.0	75.7	0.6	20	1230	787	B2/A7
120	PVT -120	244.410	123.835	707.1	330.0	147.0	560.1	45.0	68.0	0.7	22	780	499	B2/A7
121	PVT -121	243.055	128.655	215.6	265.0	153.3	62.3	59.0	0.6	101.7	2393	1188	760	B2/A7
122	PVT -122	243.890	123.135	715.0	266.0	151.5	563.5	55.0	1.9	28.9	748	689	441	B2/A7
123	PVT -123	240.150	126.980	725.9	245.0	155.7	570.2	44.0	22.5	2.0	60	484	310	B2/A7
124	PVT -124	240.935	119.965	709.4	370.0	152.5	556.9	50.0	82.7	0.6	20	1770	1133	B2/A7
125	PVT -125	240.935	119.965	709.4	370.0	152.5	556.9	50.0	82.7	0.6	20	1770	1133	B2/A7
126	PVT -126	241.355	119.795	706.6	248.0	145.7	560.9	79.0	32.3	2.4	79	734	470	B2/A7
127	PVT -127	241.550	120.810	718.5	243.0	155.5	563.0	50.0	9.5	5.3	153	686	439	B2/A7
128	PVT -128	235.270	130.865	758.4	236.0	182.4	576.0	60.0	1.0	63.2	1553	530	339	B2/A7
129	PVT -129	238.000	130.925	737.4	260.0	161.9	575.5	45.0	0.2	300.0	6038	641	410	B2/A7
130	PVT -130	234.275	134.500	774.9	250.0	148.4	626.5	40.0	39.9	1.0	31	828	530	B2/A7
131	PVT -131	230.260	131.880	773.8	308.0	219.1	554.7	80.0	3.3	24.6	682	580	371	B2/A7
132	PVT -132	229.860	130.225	769.6	350.0	219.0	550.6	10.0	0.0	---	---	619	396	B2/A7
133	PVT -133	234.290	131.140	761.9	385.0	196.0	565.9	32.0	44.0	0.7	23	670	429	B2/A7
134	PVT -134	236.150	133.060	766.7	370.0	196.4	570.3	20.0	52.6	0.4	12	797	510	B2/A7
135	PVT -135	236.335	133.055	774.0	370.0	196.4	577.6	20.0	52.6	0.4	12	797	510	B2/A7
136	PVT -136	237.200	131.645	744.9	285.0	169.1	575.8	25.0	53.3	0.5	15	680	435	B2/A7
137	PVT -137	233.805	131.800	755.9	227.0	189.1	566.8	70.0	71.7	1.0	33	519	332	B2/A7
138	PVT -138	234.645	132.040	786.3	300.0	209.8	576.5	18.0	0.0	---	---	---	---	B2/A7
139	PVT -139	235.340	131.590	769.0	271.0	194.9	574.1	60.0	0.5	120.0	2790	520	333	B2/A7
140	PVT -140	236.640	132.270	760.1	395.0	191.0	569.1	25.0	89.0	0.3	9	781	500	B2/A7
141	PVT -141	235.300	124.710	741.2	316.0	177.2	564.0	0.0	0.0	---	---	---	---	B2/A7
142	PVT -142	232.830	125.810	756.3	232.0	181.5	574.8	40.0	42.0	1.0	30	1080	691	B2/A7
143	PVT -143	233.970	129.660	743.6	261.0	164.2	579.4	10.0	61.7	0.2	5	---	---	B2/A7
144	PVT -144	233.610	130.910	745.5	260.0	113.4	632.0	10.0	0.0	---	---	---	---	B2/A7
145	PVT -145	226.980	131.070	771.2	286.0	228.0	543.2	60.0	27.0	2.2	70	680	435	B2/A7
146	PVT -146	233.120	131.050	734.7	270.0	190.7	544.0	82.0	0.4	205.0	4805	589	377	B2/A7
147	PVT -147	231.915	130.480	763.2	345.0	206.3	556.9	0.0	0.0	---	---	---	---	B2/A7
148	PVT -148	232.190	131.605	757.4	305.0	192.5	564.9	60.0	0.7	85.7	2053	544	348	B2/A7
149	PVT -149	233.340	137.921	825.7	238.0	110.4	715.3	53.0	34.2	1.5	49	500	320	B2/A7
150	PVT -150	234.150	122.875	722.6	396.0	153.6	569.0	60.0	0.0	---	---	1056	676	B2/A7

Table C-5 SUMMARY OF WELL INVENTORY (4/6)

No	Well Name	Coordinate (East)	(North)	Ground Level (m)	Well Depth (m)	Water Depth (m)	G.W.L (m)	Yield (m3/h)	Draw-Down (m)	SC (m2/h)	Transmi-ssivity (m2/d)	EC (ms/cm)	TDS (ppm)	Aquifer
151	PVT -151	233.700	123.875	732.4	352.0	176.0	556.4	40.0	59.0	0.7	22	809	518	B2/A7
152	PVT -152	232.045	124.000	757.4	316.0	209.6	547.8	40.0	50.4	0.8	25	833	533	B2/A7
153	PVT -153	229.600	125.750	763.6	300.0	204.0	559.6	30.0	53.6	0.6	18	988	632	B2/A7
154	PVT -154	230.150	124.075	784.0	350.0	230.4	553.6	50.0	44.6	1.1	36	1300	832	B2/A7
155	PVT -155	231.700	122.390	763.3	334.0	205.0	558.3	35.0	68.0	0.5	17	1320	845	B2/A7
156	PVT -156	228.750	121.010	756.2	365.0	202.7	553.5	25.0	42.0	0.6	18	---	---	B2/A7
157	PVT -157	226.850	120.415	748.3	284.0	220.0	528.3	24.0	28.0	0.9	25	844	540	B2/A7
158	PVT -158	228.300	121.850	758.8	300.0	213.7	545.2	40.0	19.2	2.1	63	1559	998	B2/A7
159	PVT -159	230.100	119.550	755.0	364.0	208.0	547.0	36.0	65.0	0.6	18	1070	685	B2/A7
160	PVT -160	262.550	145.470	840.9	335.0		840.9	0.0	0.0	---	---	---	---	B2/A7
161	PVT -161	254.212	142.790	779.3	348.0	124.3	655.0	5.0	136.3	0.0	1	---	---	B2/A7
162	PVT -162	250.490	147.710	714.9	205.0	135.0	579.9	30.0	20.0	1.5	44	853	546	B2/A7
163	PVT -163	251.490	146.150	827.4	230.0	169.3	658.1	66.0	15.7	4.2	128	894	572	B2/A7
164	PVT -164	239.435	129.885	744.2	209.0	168.0	576.2	8.0	35.0	0.2	6	---	---	B2/A7
165	PVT -165	242.315	128.240	721.5	367.0	148.0	573.5	8.0	0.0	---	---	---	---	B2/A7
166	PVT -166	242.750	131.700	733.7	363.0	151.8	581.9	108.0	2.8	39.3	1099	725	464	B2/A7

Table C-6 SUMMARY OF WELL INVENTORY (5/6)

No	Well Name	Coordinate (East)	Coordinate (North)	Ground Level (m)	Well Depth (m)	Water Depth (m)	G.W.L (m)	Yield (m3/h)	Draw-Down (m)	SC (m2/h)	Transmi-ssivity (m2/d)	EC (ms/cm)	TDS (ppm)	Aquifer
1	SW - 1	251.860	86.900	719.6	74.0	57.7	662.0	65.0	8.5	7.6	224	552	353	B2/A7
2	SW - 2	254.120	82.020	735.4	170.0	69.8	665.7	119.0	0.2	517.4	11932	---	---	B2/A7
3	SW - 3	255.475	87.200	741.3	103.0	78.8	662.6	150.0	0.4	375.0	9259	950	608	B2/A7
4	SW - 4	253.030	89.180	764.6	400.0	100.6	664.0	32.0	45.1	0.7	22	---	---	B2/A7
5	SW - 5	253.500	86.870	727.5	170.0	62.1	665.4	148.0	42.1	3.5	120	1000	640	B2/A7
6	SW - 6	251.800	87.250	743.3	160.0	79.1	664.2	130.0	35.5	3.7	123	959	614	B2/A7
7	SW - 7	252.950	87.050	727.6	262.0	37.0	690.6	146.4	0.6	232.4	5944	880	563	B2/A7
8	SW - 8	254.800	86.940	743.6	260.0	82.0	661.7	0.0	0.0	---	---	---	---	B2/A7
9	SW - 9	251.100	87.280	714.2	163.0	50.0	664.2	0.0	0.0	---	---	---	---	B2/A7
10	SW - 10	250.840	87.830	710.2	273.0	47.3	662.9	146.0	24.3	6.0	199	969	620	B2/A7
11	SW - 11	250.200	88.250	712.1	254.0	0.0	712.1	0.0	0.0	---	---	---	---	B2/A7
12	SW - 12	249.820	89.700	752.3	192.0	87.2	665.1	109.0	14.9	7.3	230	900	576	B2/A7
13	SW - 13	253.050	85.150	767.3	283.0		767.3	0.0	0.0	---	---	---	---	B2/A7
14	SW - 14	252.110	85.850	745.3	206.0	84.6	660.7	89.3	3.5	25.5	717	---	---	B2/A7
15	SW - 15	251.670	85.760	750.9	200.0	0.0	750.9	66.3	2.9	22.9	621	---	---	B2/A7
16	SW - 16	249.550	86.300	752.0	186.0	73.6	678.5	101.0	1.3	77.7	2044	---	---	B2/A7
17	SW - 17	253.200	84.500	798.1	227.0		798.1	0.0	0.0	---	---	---	---	B2/A7
18	SW - 18	252.100	92.150	786.3	400.0		786.3	0.0	0.0	---	---	---	---	B2/A7
19	SW - 19	250.700	100.650	736.1	146.0		736.1	0.0	0.0	---	---	---	---	B2/A7
20	WALA - 1	224.090	106.650	458.8	77.0	8.9	449.9	7.0	14.6	0.5	12	903	578	B2/A7
21	WALA - 2	223.000	107.250	445.8	200.0	20.0	425.8	0.0	0.0	---	---	---	---	B2/A7
22	WALA - 3	224.450	106.750	472.6	167.0	21.4	451.2	44.0	53.3	0.8	27	1027	657	B2/A7
23	WALA - 4	221.750	107.100	423.2	204.0	23.4	399.8	120.0	43.4	2.8	94	1730	1107	B2/A7
24	WALA - 5	220.810	107.700	425.9	237.0	44.0	381.9	95.7	15.1	6.3	198	1344	860	B2/A7
25	WALA - 6	223.380	107.350	455.0	217.0	25.7	429.3	140.0	15.0	9.3	298	1439	921	B2/A7
26	WALA - 7	223.090	107.175	446.7	430.0	155.0	291.7	0.0	0.0	---	---	1869	1196	B2/A7
27	WALA - 8	222.380	107.400	438.3	339.0		438.3	0.0	0.0	---	---	---	---	B2/A7
28	WALA - 9	219.375	108.100	350.3	106.0	10.5	339.8	134.0	0.6	231.0	5828	889	569	B2/A7
29	WALA - 10	219.000	104.350	260.8	225.0		260.8	0.0	0.0	---	---	---	---	B2/A7
30	WALA - 11	219.900	107.525	344.2	200.0	9.2	335.0	0.0	0.0	---	---	---	---	B2/A7
31	WALA - 12	222.240	106.640	451.3	225.0	36.0	415.3	38.0	66.0	0.6	19	1169	748	B2/A7
32	WALA - 13	224.930	106.990	496.9	166.0	36.8	460.1	124.5	3.6	34.6	997	906	580	B2/A7
33	WALA - 14	223.900	107.050	476.5	240.0	26.2	450.3	77.0	73.4	1.0	36	1350	864	B2/A7
34	WALA - 15	220.500	108.250	413.2	305.0	53.6	359.5	61.6	71.5	0.9	29	1080	691	B2/A7
35	QTRN - 1	249.340	72.400	780.0	140.0	95.0	685.0	0.0	0.0	---	---	1769	1132	B2/A7
36	QTRN - 2	255.450	78.100	805.0	163.0	135.0	670.0	0.0	0.0	---	---	2730	1747	B2/A7
37	QTRN - 3	248.160	72.320	783.9	266.0	98.0	685.9	63.0	2.6	32.1	842	1289	825	B2/A7
38	QTRN - 4	249.590	73.770	782.6	219.0	98.1	684.5	82.0	3.3	21.6	607	1150	736	B2/A7
39	QTRN - 5	248.630	73.595	780.8	255.0	95.3	685.5	150.0	7.8	19.2	592	1559	998	B2/A7
40	QTRN - 6	249.500	72.820	738.0	203.0	95.0	643.0	55.0	2.0	27.5	713	---	---	B2/A7
41	QTRN - 7	247.260	70.760	---	314.0	98.0	---	62.0	7.0	8.9	255	0	0	B2/A7
42	QTRN - 8	248.890	74.940	785.0	230.0	103.3	681.7	115.0	27.3	4.2	138	---	---	B2/A7
43	QTRN - 9	249.440	76.120	780.0	223.0	102.6	677.4	123.0	3.8	32.5	938	---	---	B2/A7
44	QTRN - 10	0.000	77.440	247.9	226.0	113.6	134.4	50.0	13.3	3.8	111	989	633	B2/A7
45	QTRN - 11	247.500	76.100	780.0	263.0	103.5	676.5	60.0	70.9	0.8	28	1080	691	B2/A7
46	QTRN - 12	249.300	75.100	778.0	251.0	101.2	676.8	111.5	10.3	10.8	333	1309	838	B2/A7
47	QTRN - 13	248.680	74.950	778.0	215.0	95.0	683.0	120.0	9.3	12.9	396	1300	832	B2/A7
48	QTRN - 14	249.500	75.750	765.0	232.0	97.6	667.5	120.5	3.6	33.7	368	1203	770	B2/A7
49	QTRN - 15	248.950	75.900	781.9	233.0	98.6	683.3	114.3	2.9	38.9	1098	1309	838	B2/A7
50	QTRN - 16	249.650	76.510	775.0	241.0	100.1	674.9	126.0	1.9	65.6	1809	1200	768	B2/A7

Table C-7 SUMMARY OF WELL INVENTORY (6/6)

No	Well Name	Coordinate (East)	Coordinate (North)	Ground Level (m)	Well Depth (m)	Water Depth (m)	G.W.L (m)	Yield (m3/h)	Draw-Down (m)	SC (m2/h)	Transmi-ssivity (m2/d)	EC (ms/cm)	TDS (ppm)	Aquifer
51	BRNB - 1	244.255	118.265	688.3	292.0	144.5	543.8	81.0	1.1	75.7	1927	---	---	B2/A7
52	BRNB - 2	243.950	118.260	718.6	326.0	167.0	551.6	0.0	0.0	---	---	---	---	B2/A7
53	BRNB - 3	246.770	116.975	687.1	350.0	167.0	520.1	0.0	0.0	---	---	---	---	B2/A7
54	BRNB - 4	246.825	116.735	683.1	305.0		683.1	0.0	0.0	---	---	---	---	B2/A7
55	BRNB - 5	243.740	117.065	696.1	373.0		696.1	0.0	0.0	---	---	---	---	B2/A7
56	AB - 1	247.000	45.000	880.0	161.0	111.0	769.0	91.0	0.3	364.0	8254	---	---	B2/A7
57	AB - 2	250.000	45.000	855.0	161.0	113.8	741.2	130.0	2.5	52.0	1465	---	---	B2/A7
58	AB - 3	248.800	46.000	855.0	232.0	95.8	759.2	61.5	7.1	8.7	249	1139	729	B2/A7
59	AB - 4	243.300	47.800	850.0	180.0	98.5	751.5	57.0	10.1	5.6	166	---	---	B2/A7
60	AB - 5	249.700	49.300	945.0	180.4	103.1	741.9	80.0	1.2	69.0	1765	---	---	B2/A7
61	AB - 6	248.612	44.770	850.0	250.0	110.9	739.1	0.0	0.0	---	---	---	---	B2/A7
62	AB - 7	251.439	47.660	850.0	180.0	108.6	741.4	90.0	15.0	6.0	186	884	566	B2/A7
63	AB - 8	251.901	46.070	860.0	180.0	113.8	746.2	55.0	15.0	3.7	110	990	576	B2/A7
64	AB - 9	247.100	44.000	860.0	165.0	117.9	742.2	40.0	24.6	1.6	49	553	354	B2/A7
65	JICA-- 1	233.910	104.560	663.9	304.4	137.2	526.7	29.8	4.1	7.2	189	1740	1131	B2/A7
66	JICA-- 2	251.450	96.690	750.5	261.0	167.8	582.7	17.8	21.3	0.8	24	1260	806	B2/A7
67	JICA-- 3	248.550	83.350	789.6	291.0	125.5	664.1	51.6	14.0	3.7	110	1110	710	B2/A7
68	JICA-- 4	248.990	68.570	884.8	274.0	128.4	756.4	16.1	15.0	1.1	30	960	614	B2/A7

Table C-8 QUALITY OF GROUNDWATER IN TEST WELL (T1 - T4)

No	E.C ms/cm	T.D.S mg/l	pH (-)	Ca^{++} me/l	Mg^{++} me/l	Na^{+} me/l	K^{+} me/l	Cl^{-} me/l	SO_4^{--} me/l	CO_3^{--} me/l	HCO_3^{-} me/l	NO_3^{--} me/l
T-1	1,740	1,113	7.33	6.92	5.42	5.40	0.09	7.20	2.98	0.0	7.56	9.52
T-2	1,260	806	7.15	5.60	3.18	3.40	0.09	3.50	1.01	0.0	7.89	0.26
T-3	1,110	710	7.44	4.23	3.68	3.20	0.08	3.58	2.27	0.0	5.31	0.31
T-4	960	614	7.81	2.96	3.18	2.80	0.08	3.18	1.46	0.0	4.41	0.00

Table C-9 ANALYSIS OF PUMPING TEST (T1 - T4)

Well No.	Steady State	Non Steady	
	Modified Equilibrium Eq.	Jacob Method	
	Transmissivity (m^2/d)	Transmissivity (m^2/d)	Storage coefficient (-)
T-1	189	556	0.0265
T-2	24	-	-
T-3	110	35	0.0009
T-4	30	-	-

Remarks: 1) Tests are based on 48 to 72 hours of continuous pumping.
2) Observation holes are installed beside test wells of T-1 and T-3.

Table C-10 ESTIMATED REGIONAL TRANSMISSIVITIES

Locality	Number of well	Average Transmissivity
Qastal - Jiza	20	1,975
Jiza - Dabba	41	1,603
Wadi Heidan	10	754
Wala drainage area	104	1,369
Siwaqa	12	2,620
Qatrana	14	630
Abyad	8	1,530

Table C-11 T.D.S OF BASEFLOW AND FLOOD FLOW

Unit : T.D.S (mg/1)

(year)	Wadi Mujib D/S Confluence	Wadi Mujib U/S Confluence	Wadi Heidan U/S Confluence	Wadi Heidan U/S Spring	Qatrana Dam
1965	1,344	-	-	-	-
1966	-	-	-	602	-
1972	-	-	-	774	-
1973	979	-	-	-	-
1977	1,056	1,250 - 1,280	909 - 947	480	-
1986	-	-	-	-	365

Source of data: MMP (1965, 1966, 1973) and NRA/WAJ files

Remark : Full measurement was performed in June 1977.
D/S = Downstream
U/S = Upstream

Table C-12 DIRECT COST OF INJECTION WELLS

Dam	Recharge Well (JD)	Filter Unit (JD)	Intake Facility (JD)	Total (JD)	O&M (JD/y)	Injection Water (MCM)	Remarks
Qatrana Exist.	289,000	2,200	20,000	311,200	6,400	3.2	By 7 wells with a total depth of 1,925 m
Sultani Exist.	75,000	1,700	4,000	80,700	1,200	0.6	By 2 wells with a total depth of 500 m
Siwaqa C	60,000	1,700	4,000	65,700	1,200	0.6	By 2 wells with a total depth of 400 m
Wala	330,000	-	8,300	338,300	5,000	5.0	By 11 wells with a total depth of 3,200 m

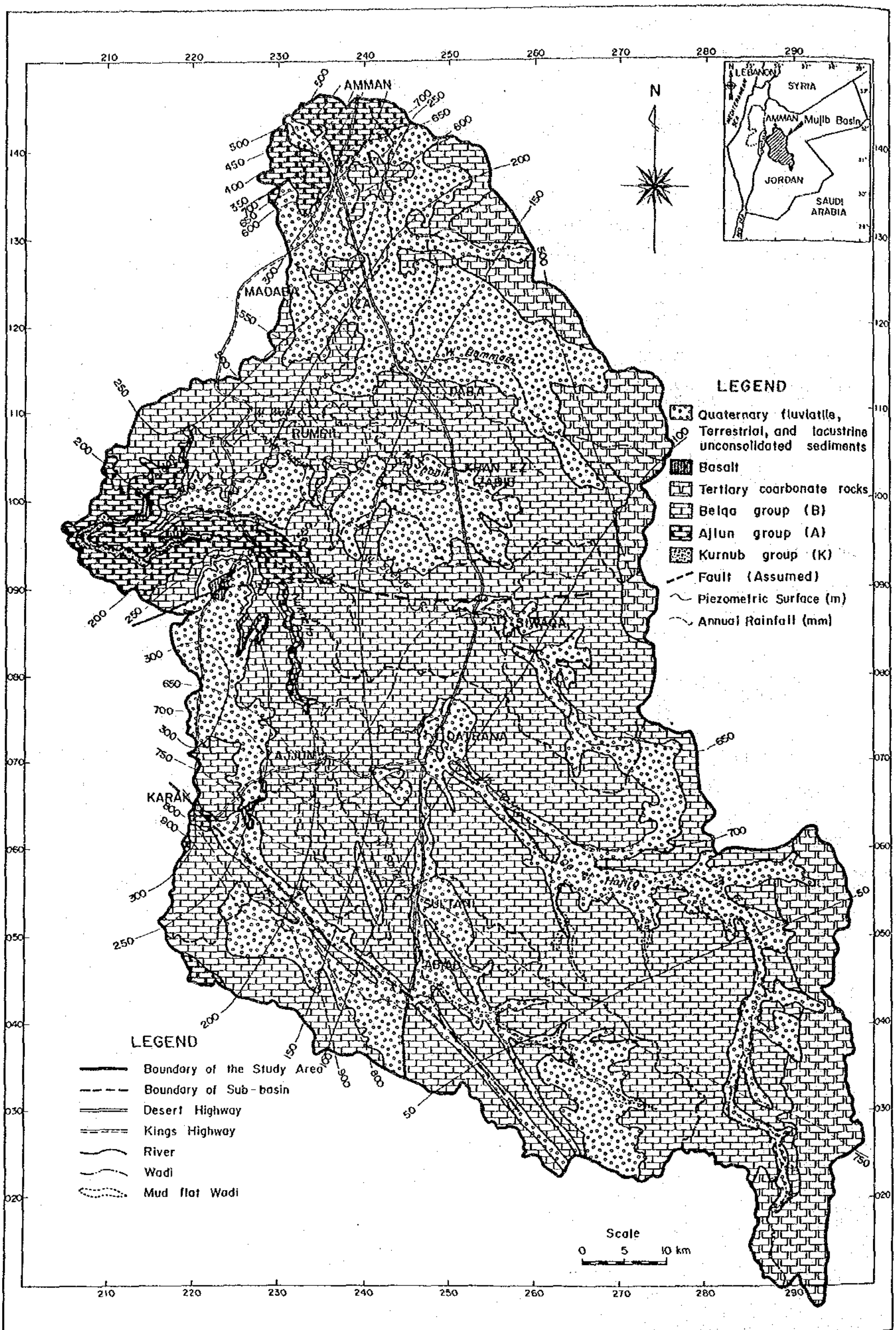

Fig.C-1 Hydrogeological Map

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
JAPAN INTERNATIONAL COOPERATION AGENCY

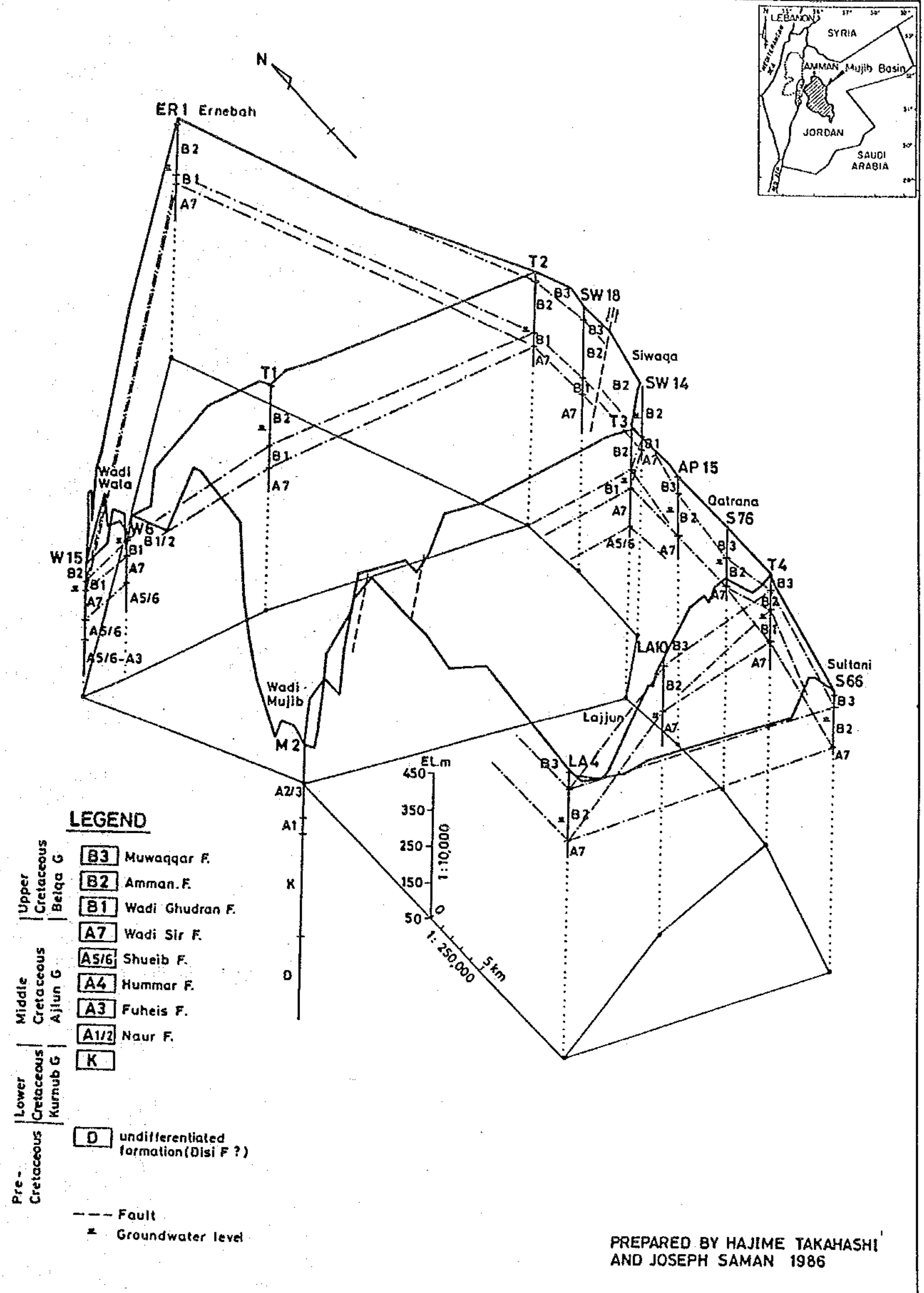

Fig.C-2 Fence Diagram of Geology in the Mujib Basin

THE HASHEMITE KINGDOM OF JORDAN
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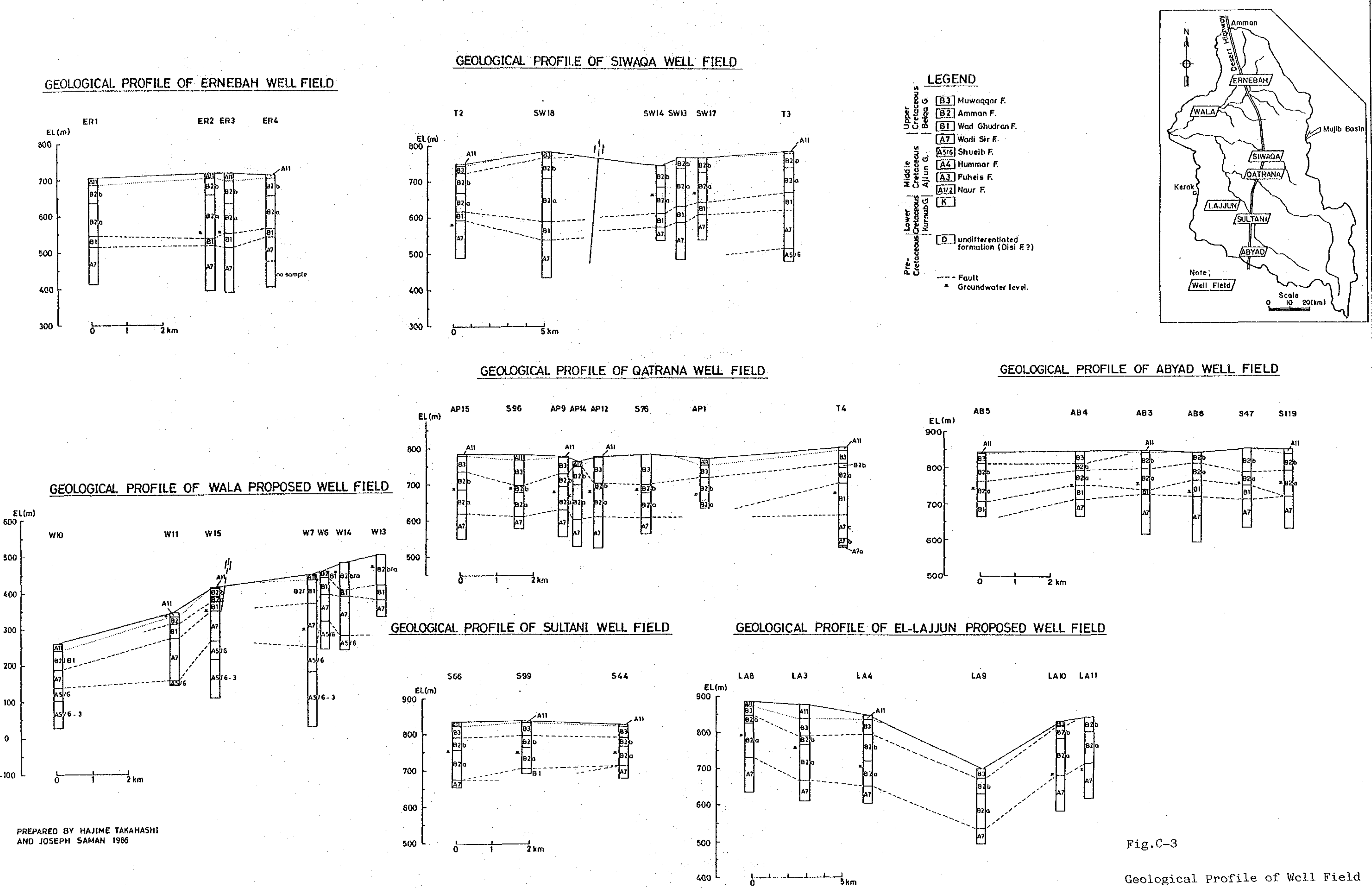

Fig.C-3

Geological Profile of Well Field

THE HASHEMITE KINGDOM OF JORDAN
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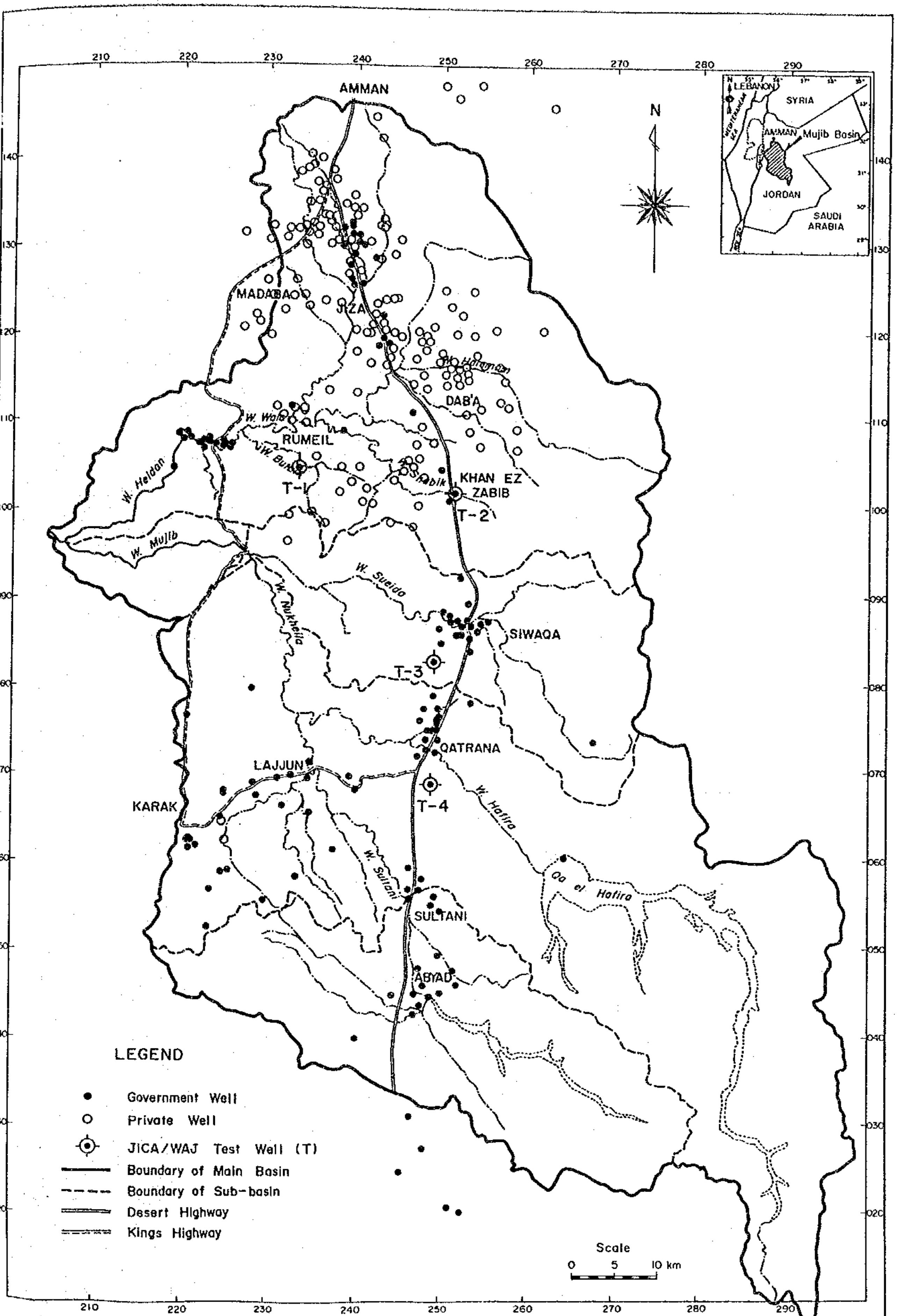

Fig.C-4 Location Map of Groundwater Wells

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
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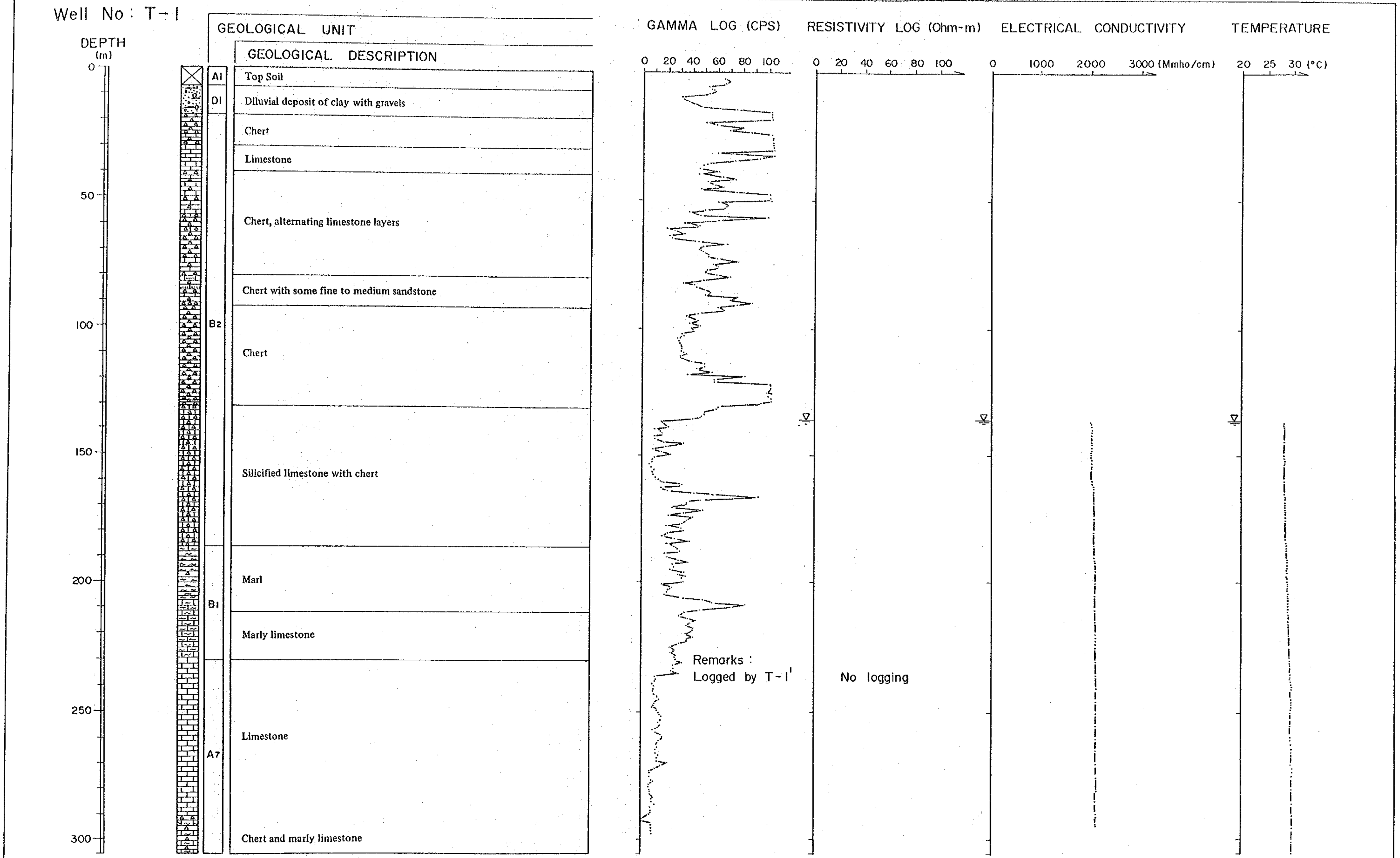

Fig.C-5

Summary of Well Log (T-1)

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
JAPAN INTERNATIONAL COOPERATION AGENCY

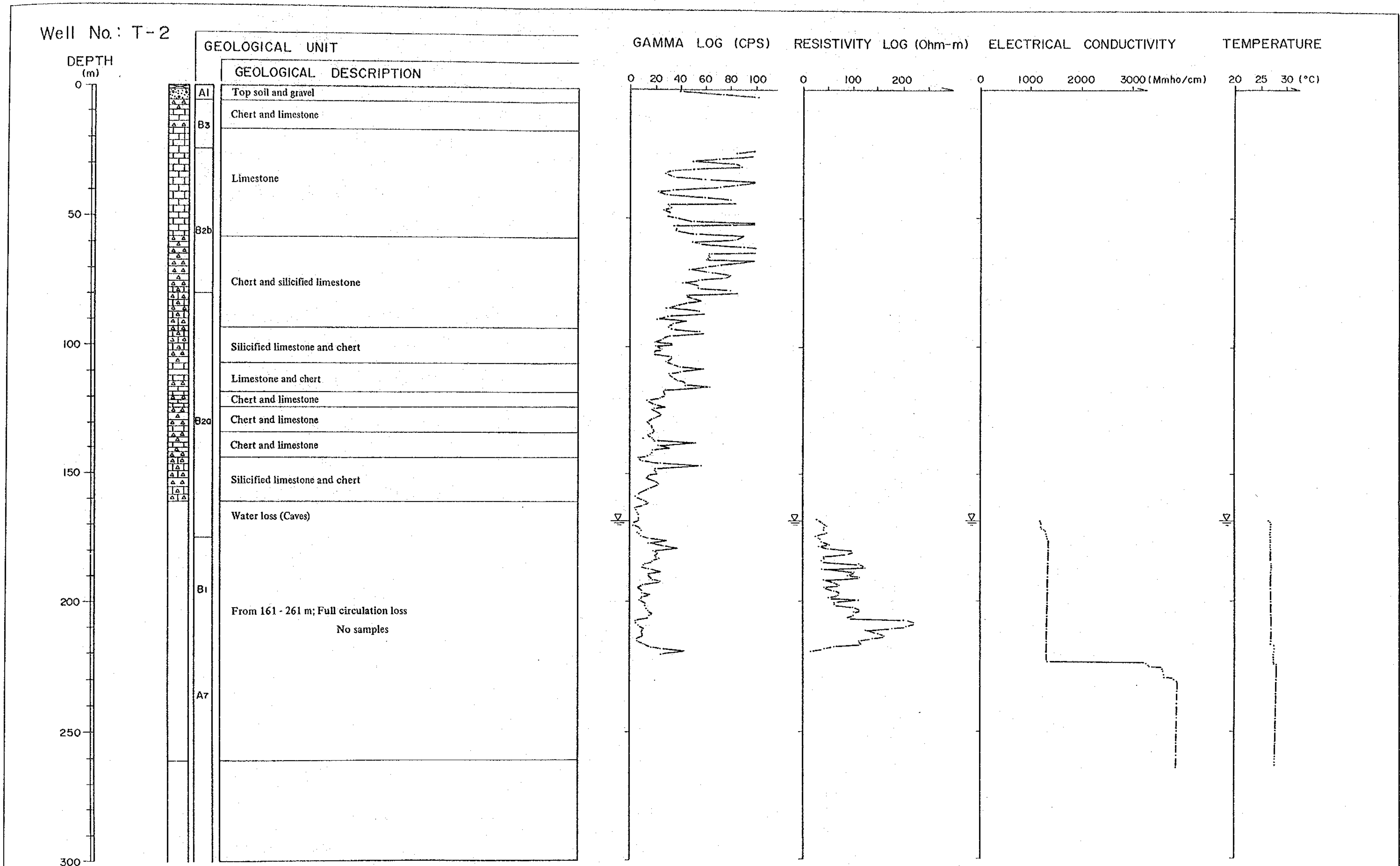

Fig.C-6

Summary of Well Log (T-2)

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
JAPAN INTERNATIONAL COOPERATION AGENCY

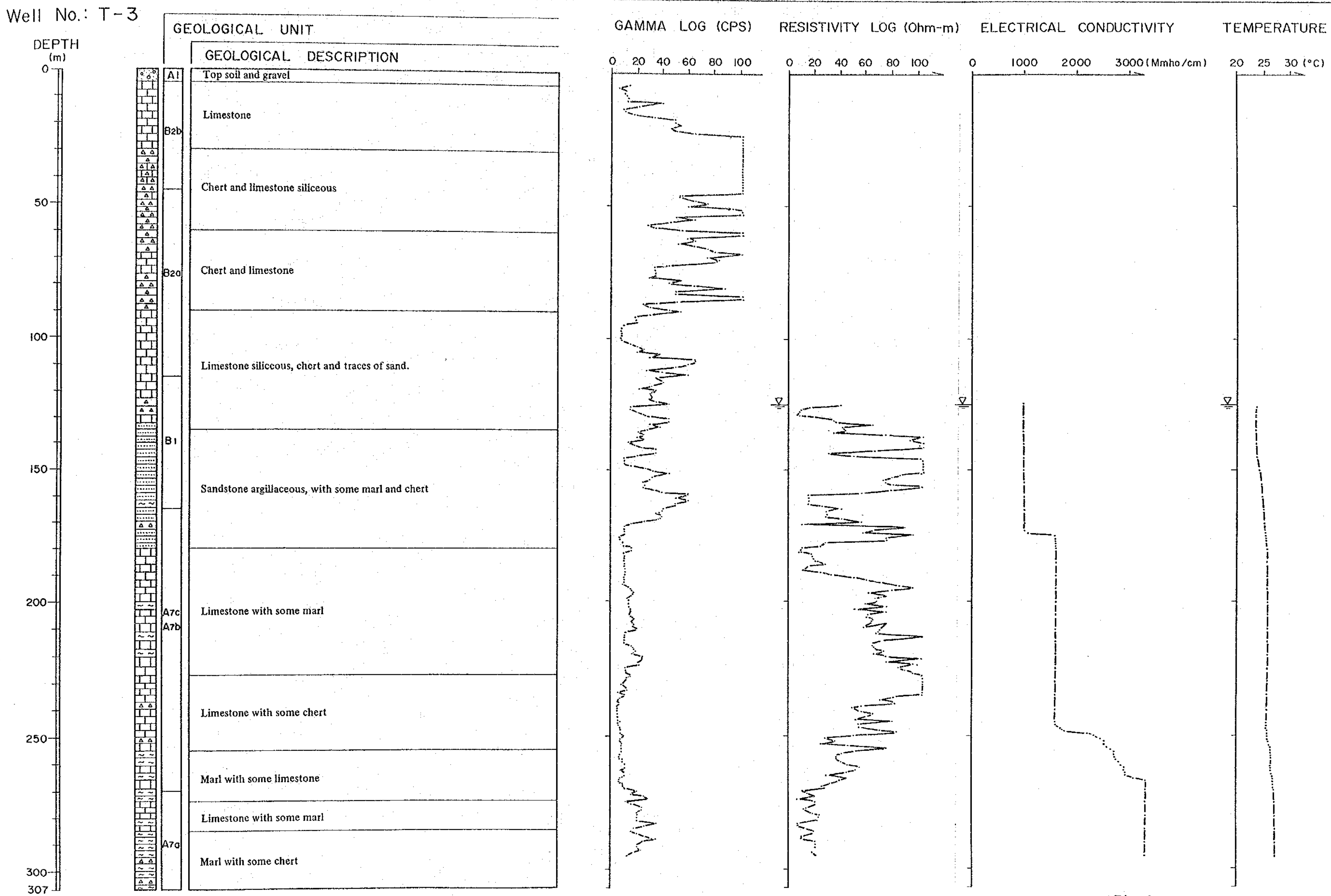

Fig.C-7

Summary of Well Log (T-3)

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
JAPAN INTERNATIONAL COOPERATION AGENCY

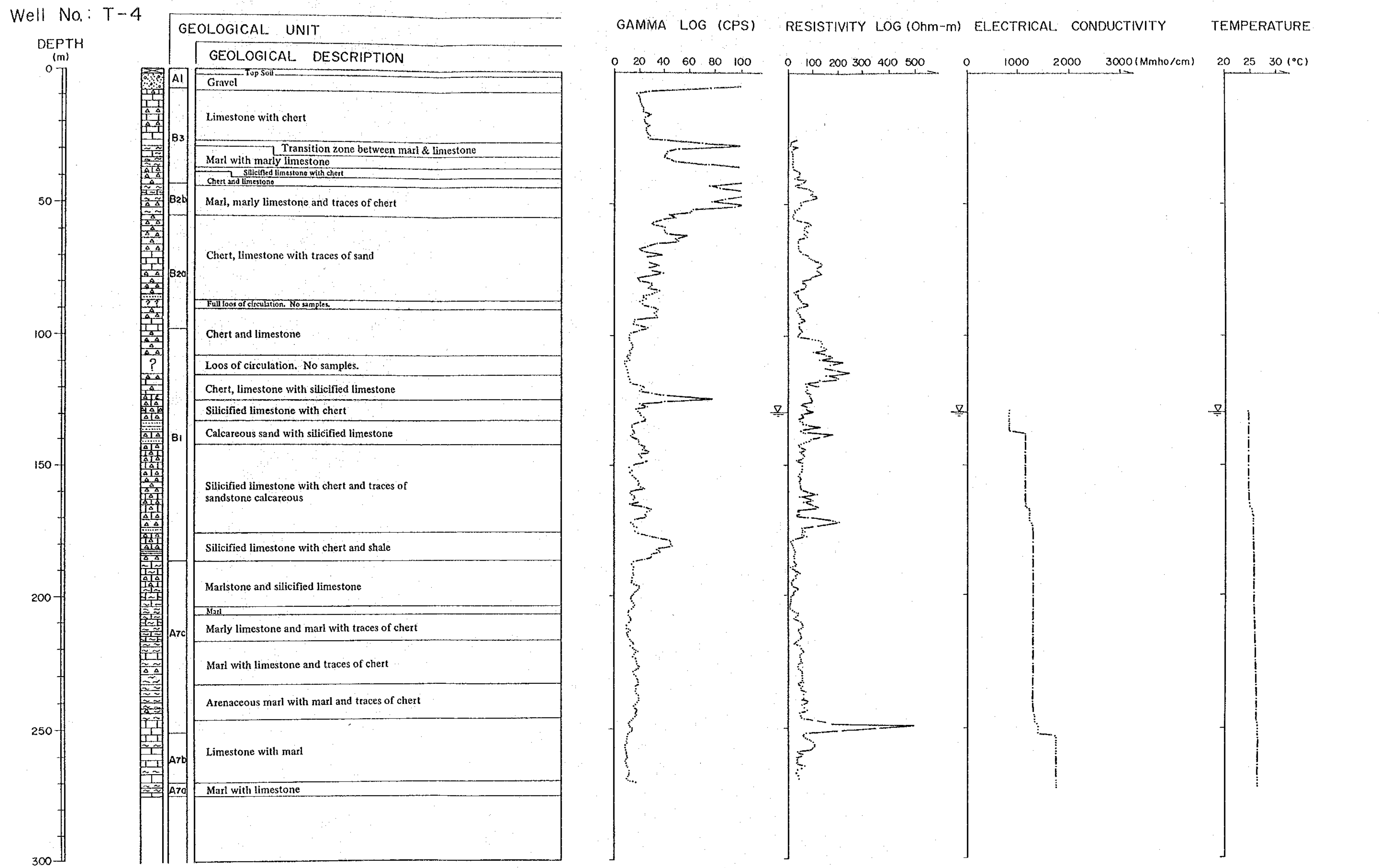

Fig.C-8

Summary of Well Log (T-4)

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
JAPAN INTERNATIONAL COOPERATION AGENCY

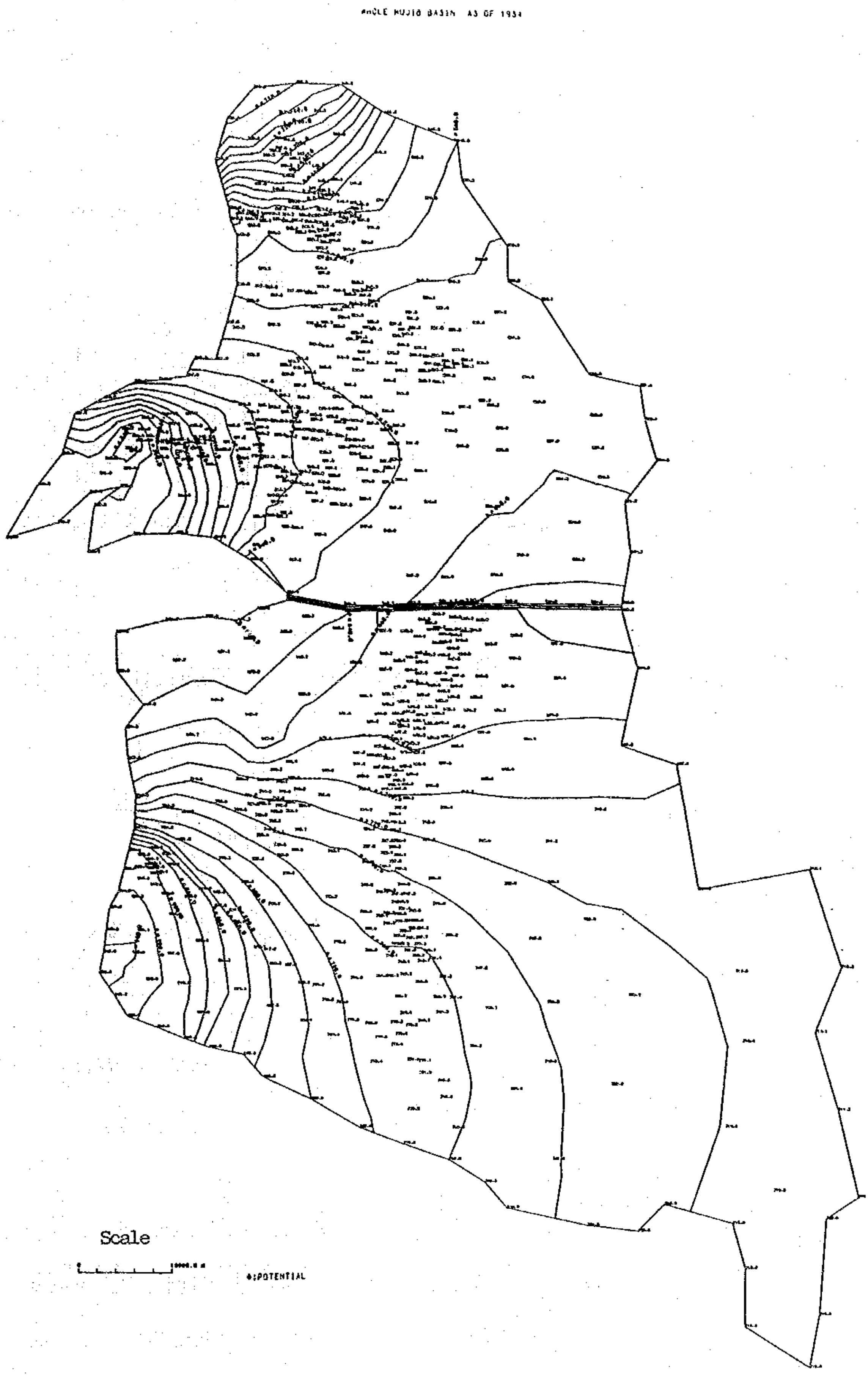

Fig.C-9 Piezomertic Surface in the B2/A7 Aquifer

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
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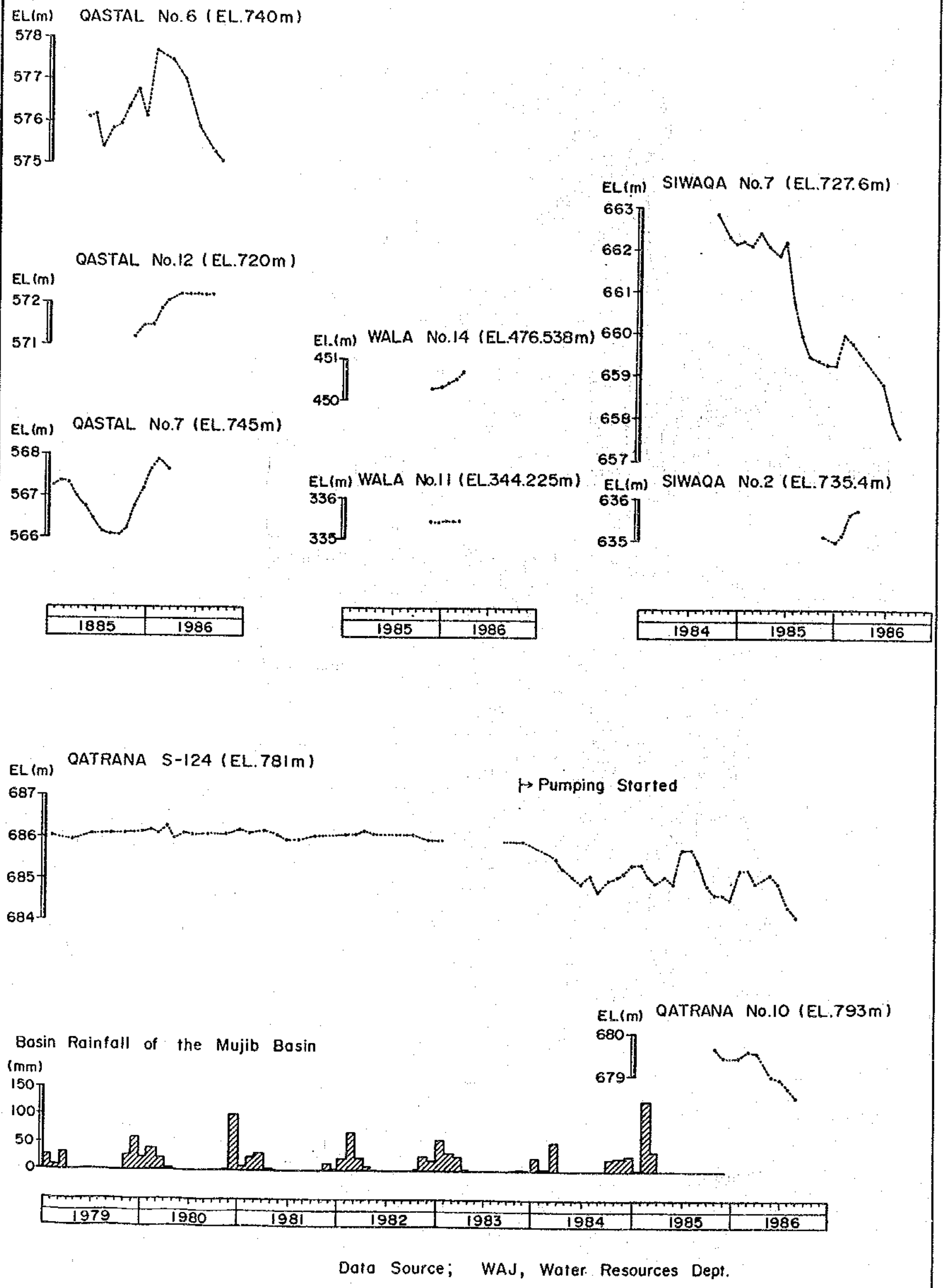

Fig.C-10 Groundwater Monitoring

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
JAPAN INTERNATIONAL COOPERATION AGENCY

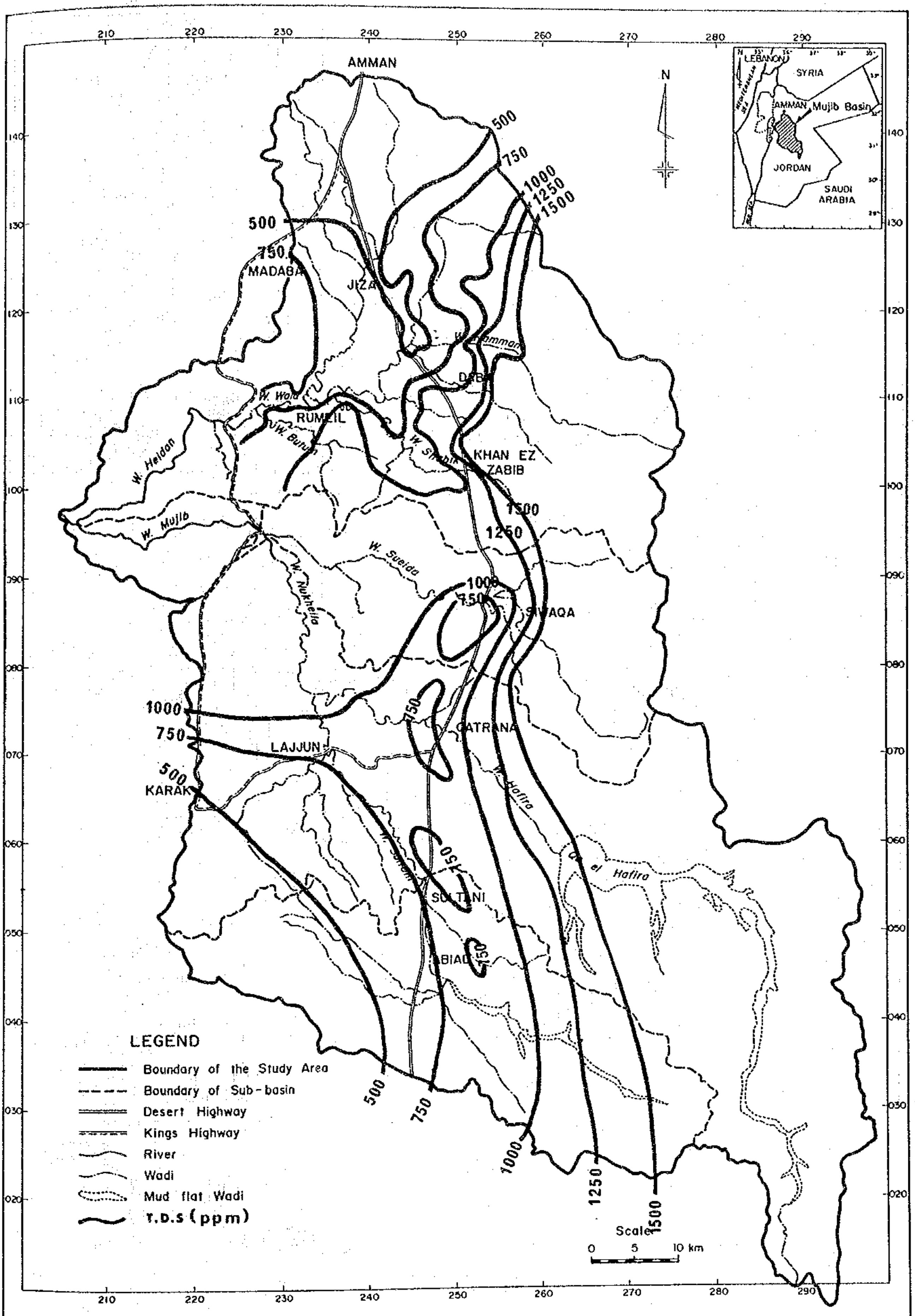

Fig.C-11 T.D.S in the B2/A7 Aquifer

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
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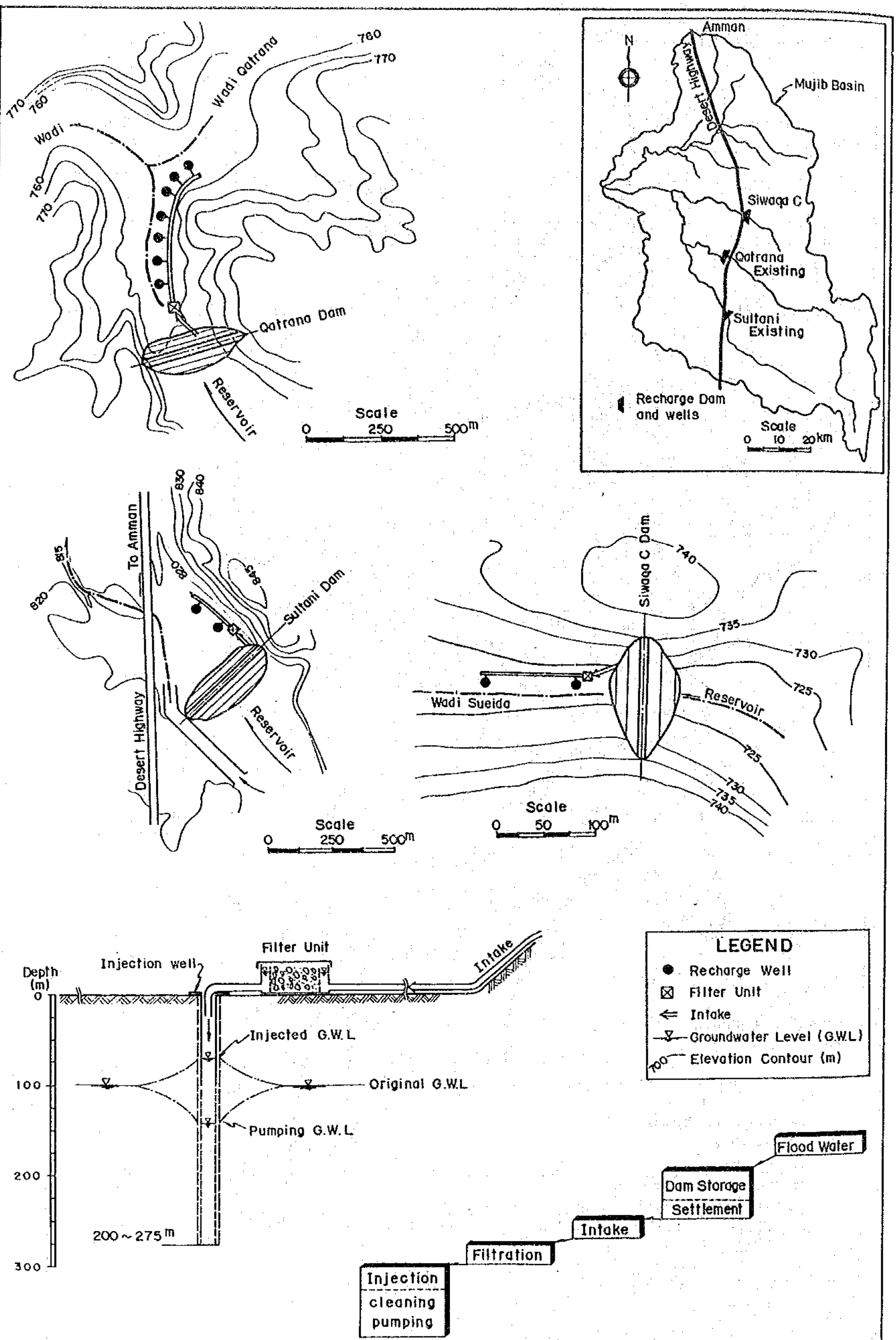

Fig.C-12 Groundwater Recharge and Dams

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
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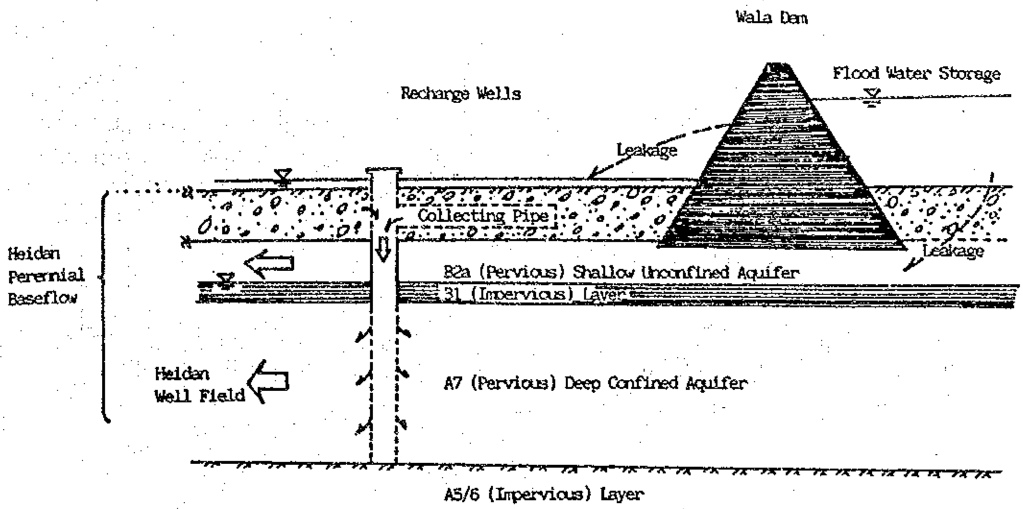

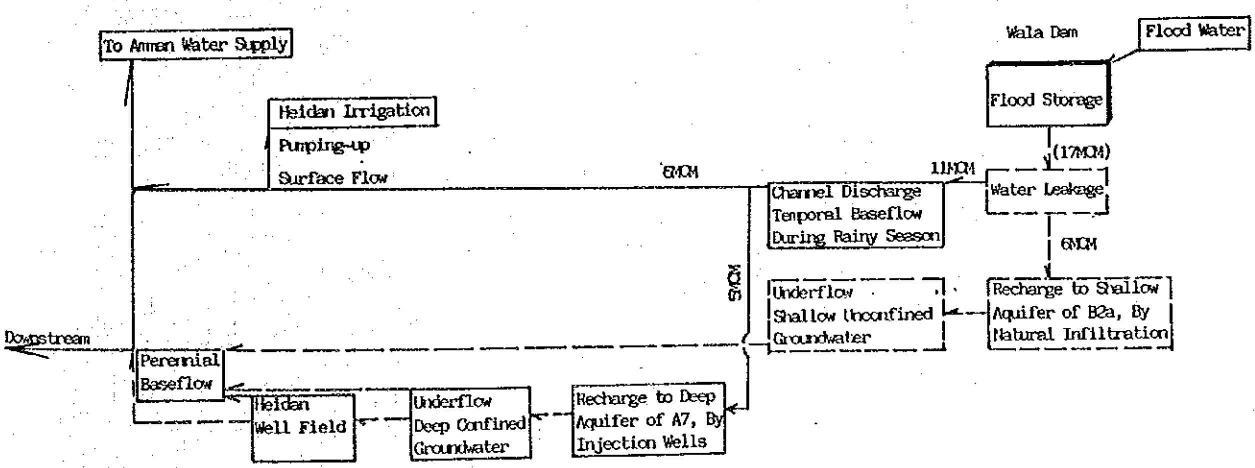

Fig.C-13 Schematics of Wala Artificial Recharge Dam Scheme

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
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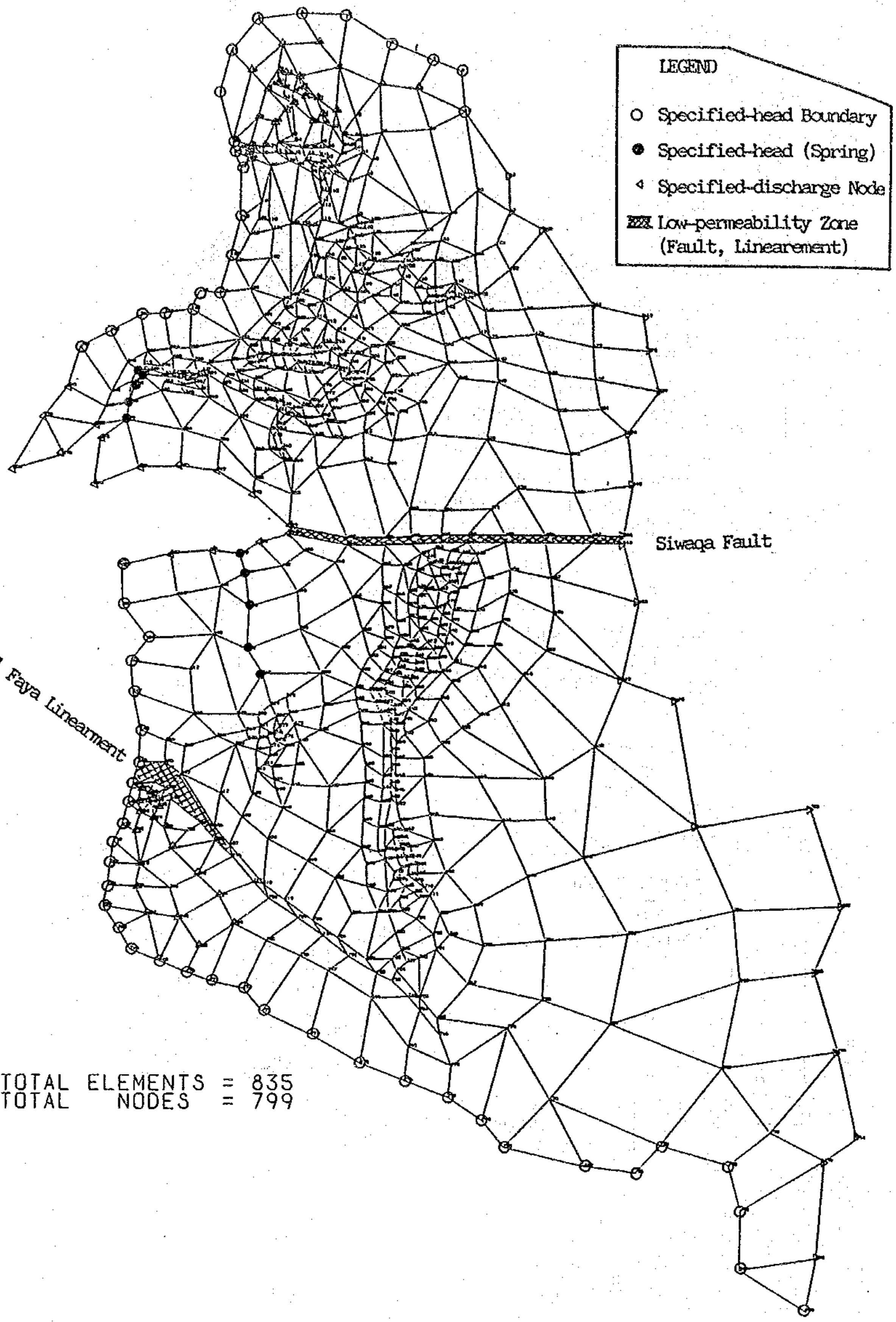

Fig.C-14 Finite-Element Grid Showing Boundary Conditions

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
JAPAN INTERNATIONAL COOPERATION AGENCY

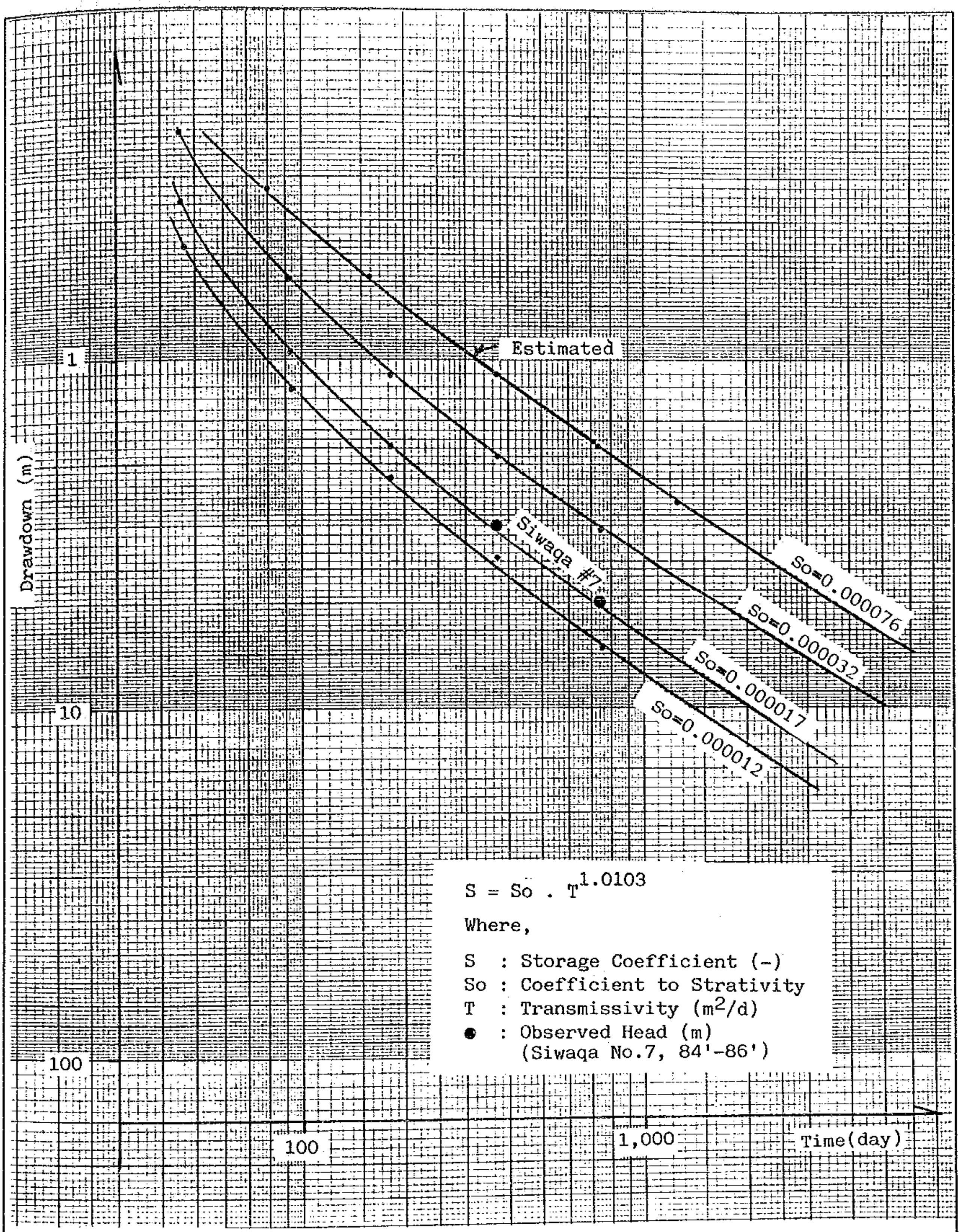

Fig.C-15
Calibration of Model Parameters

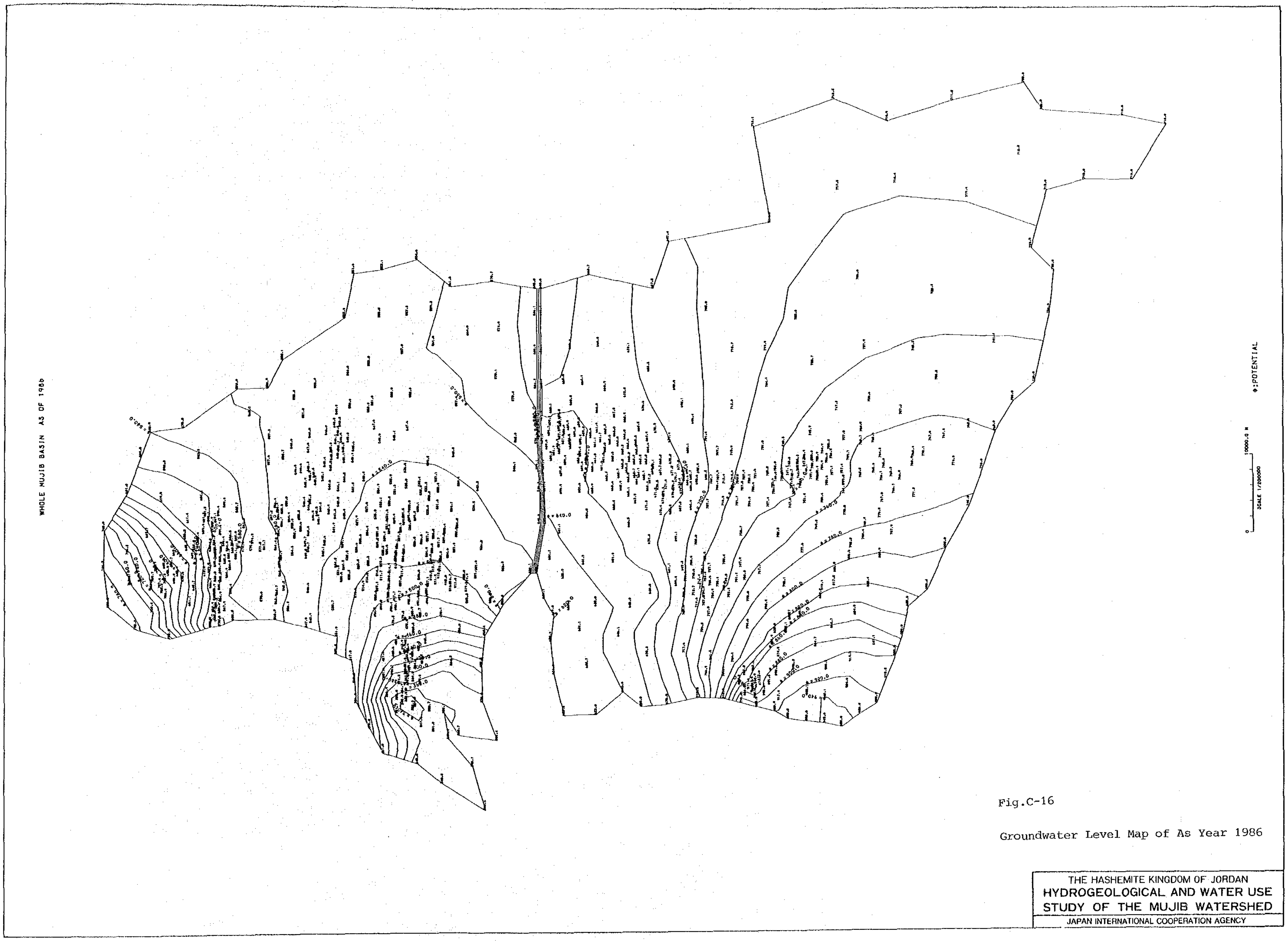

Fig.C-16

Groundwater Level Map of As Year 1986

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
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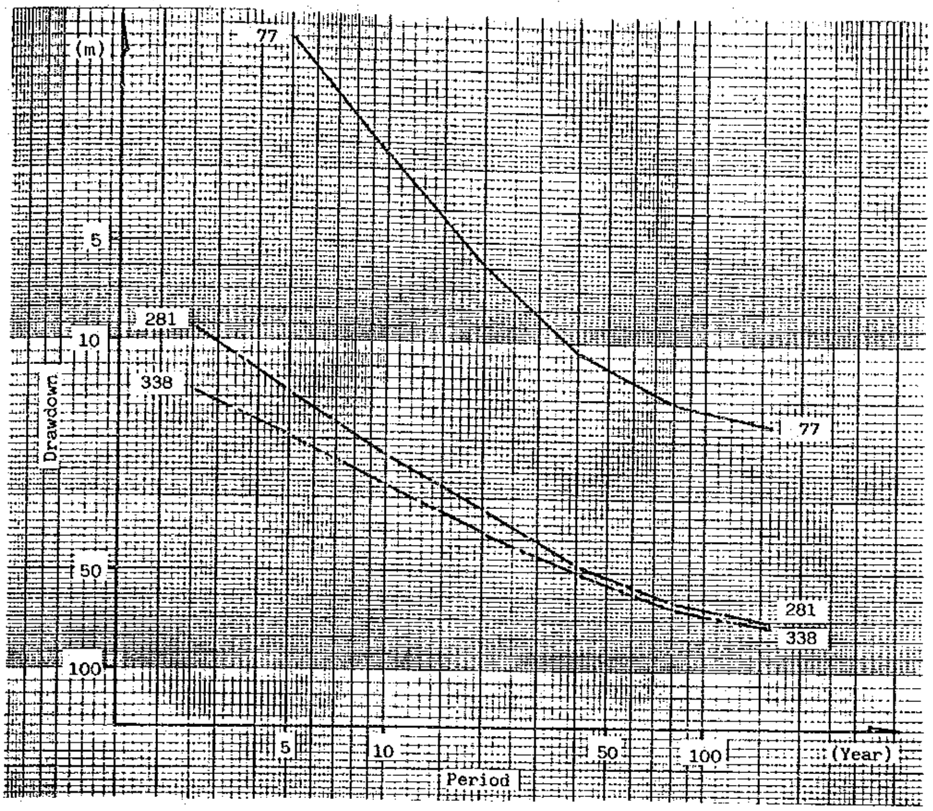

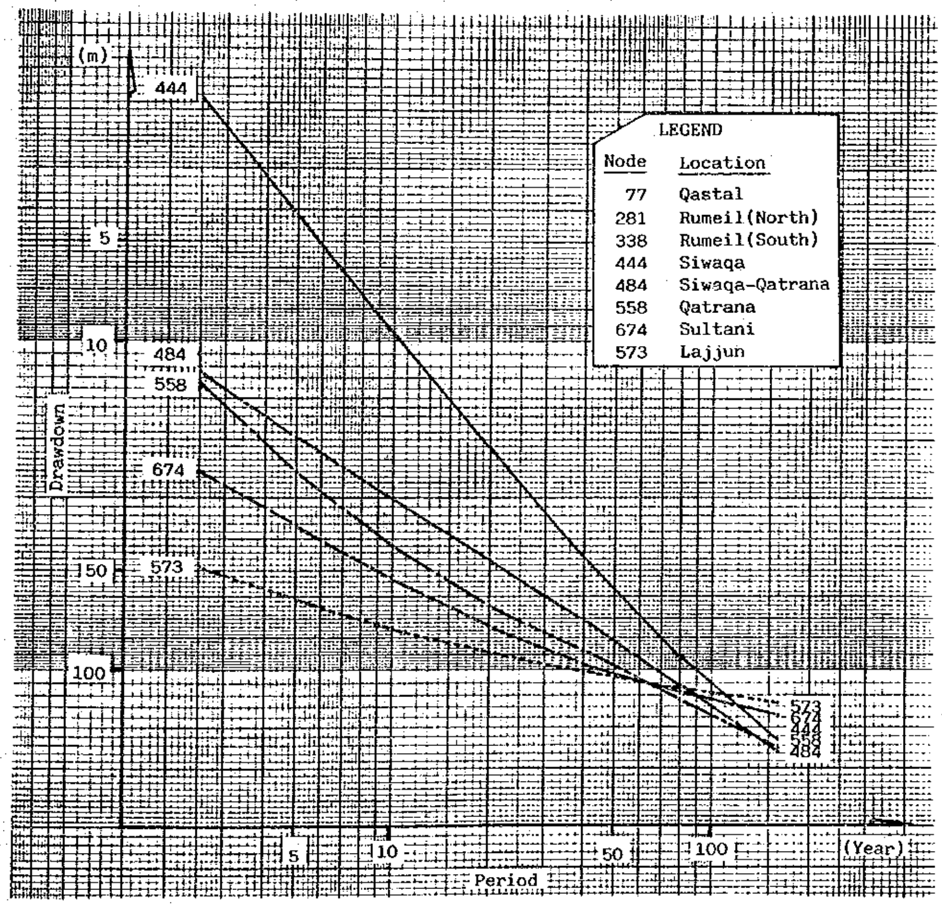

Fig.C-17

Estimated Drawdown in Representative Wellfield

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
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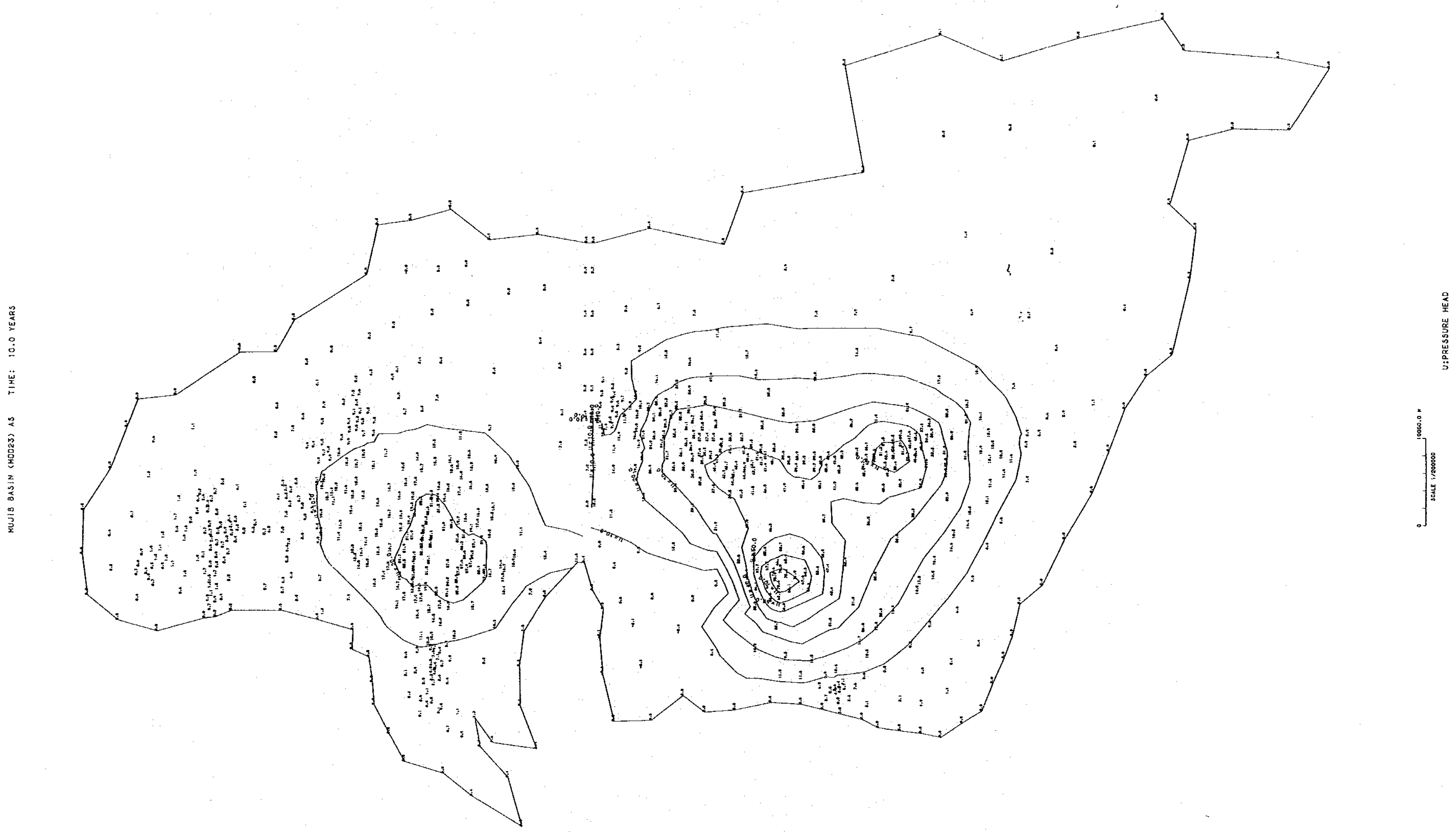

Fig.C-18

Drawdown Map after 10 Years

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE
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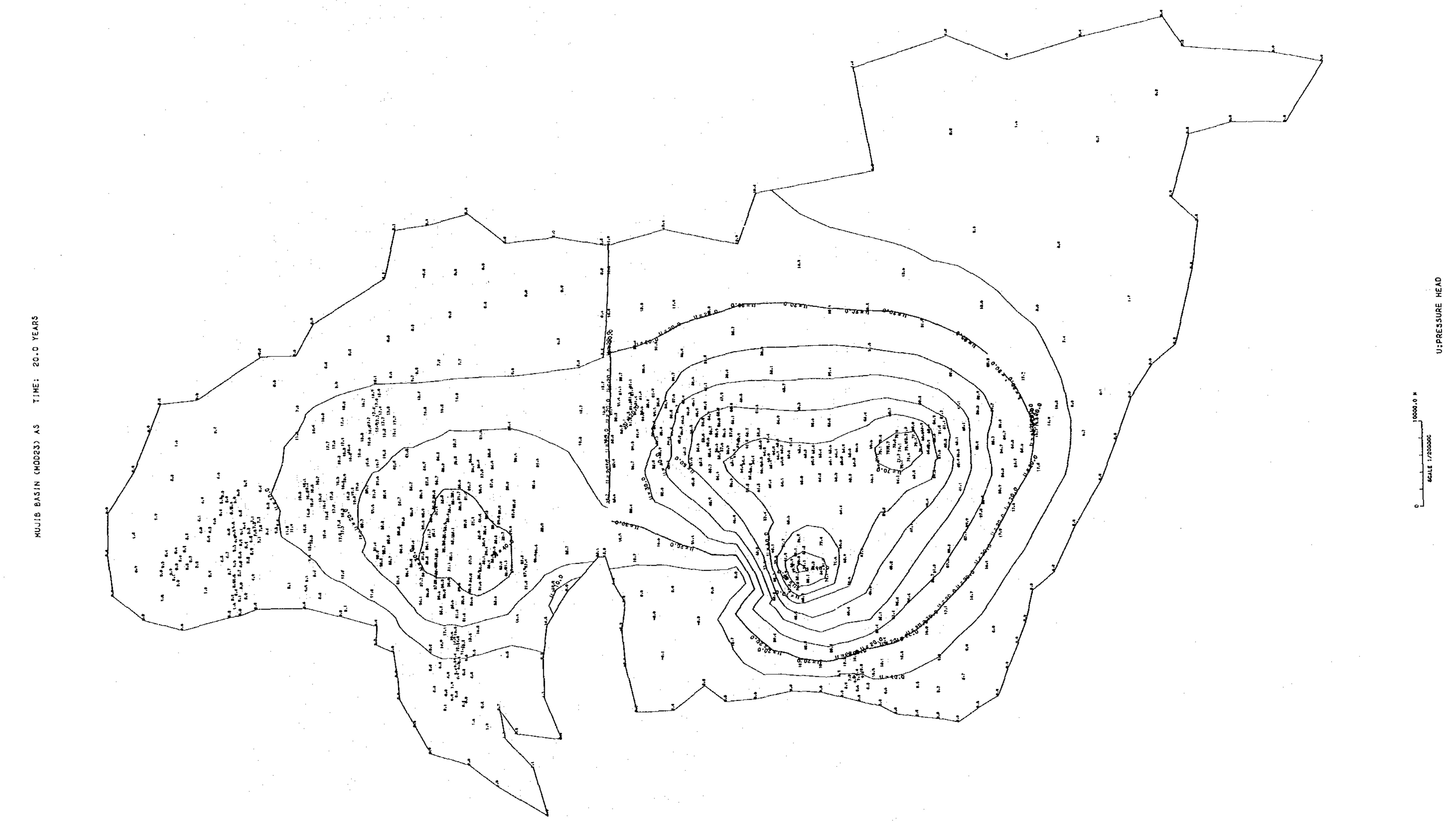

Fig.C-19

Drawdown Map after 20 Years

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
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Fig.C-20

Drawdown Map after 40 Years

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE
STUDY OF THE MUJIB WATERSHED
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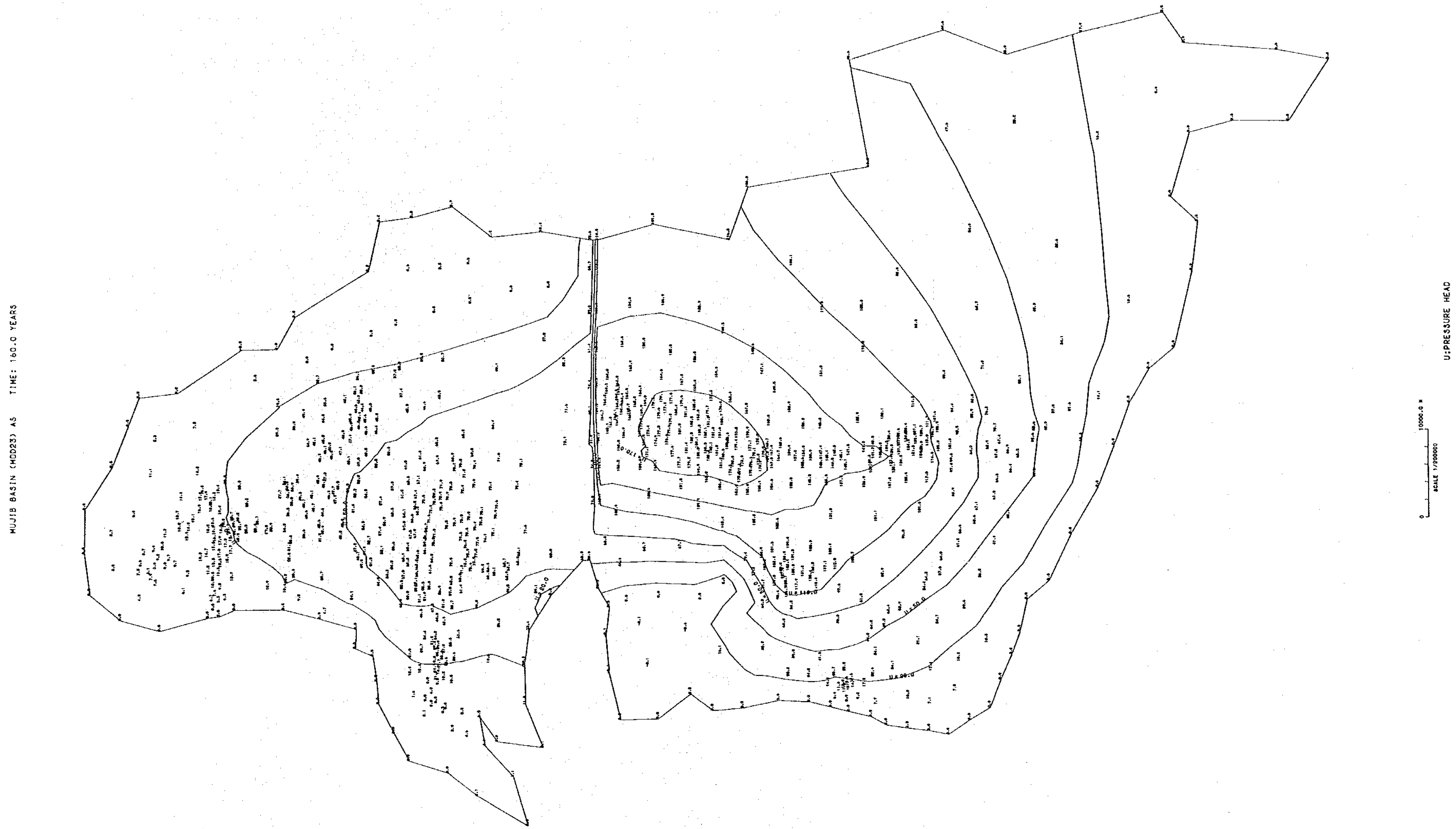

Fig.C-21

Drawdown Map after 160 Years

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
JAPAN INTERNATIONAL COOPERATION AGENCY

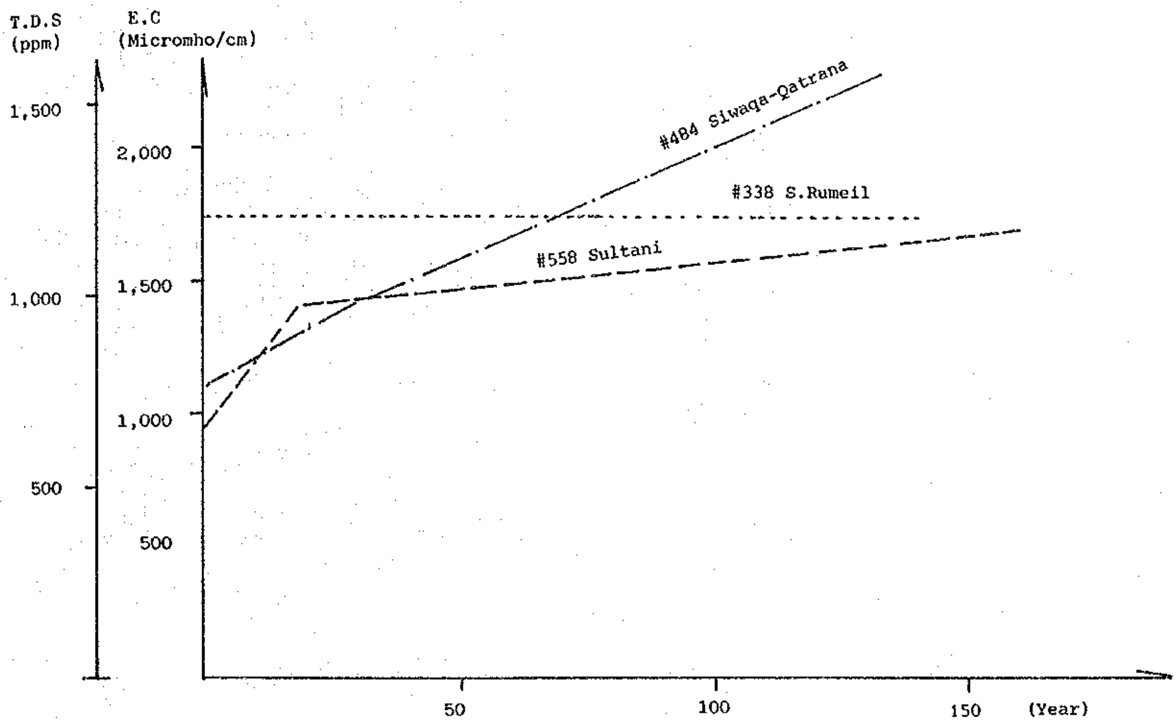

Fig.C-22

Estimated Change in Quality of Groundwater

THE HASHEMITE KINGDOM OF JORDAN
HYDROGEOLOGICAL AND WATER USE STUDY OF THE MUJIB WATERSHED
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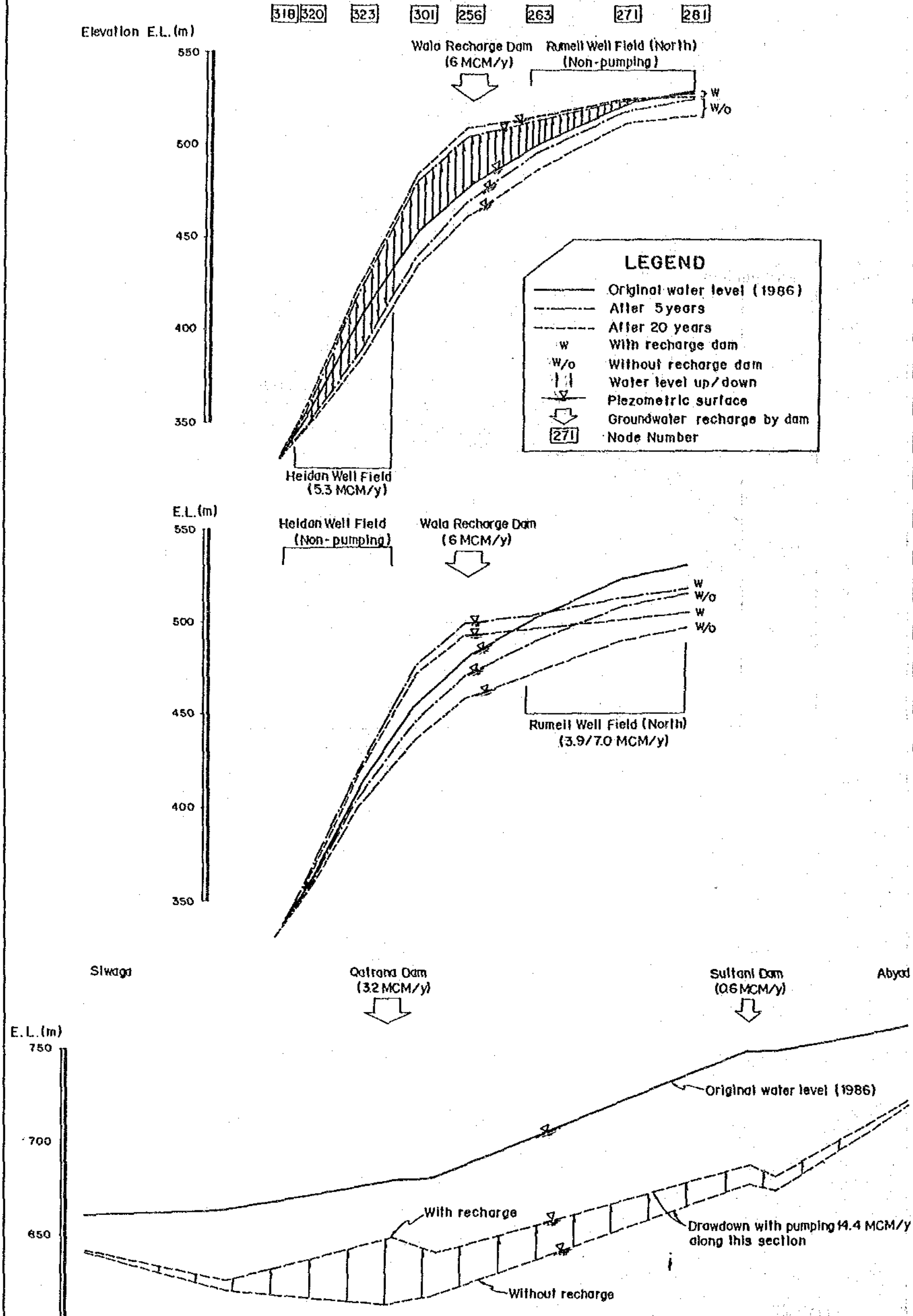

Fig.C-23

Estimated Change in Piezometric Head by Artificial Recharge

THE HASHEMITE KINGDOM OF JORDAN
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APPENDIX D

MUNICIPAL WATER SUPPLY PLANNING

TABLE OF CONTENTS

LIST OF TABLES

1. PRESENT CONDITION

1.1 Consumption of Water in the Whole Nation of Jordan

The consumption of water as of 1982 is shown as below:

Item	Water Volume
Municipal water	59 MCM/y
Industrial water	15
Agricultural water	416
(Total)	490

(Source: World Bank Report 1984)

Water for the agricultural water use occupies 85% of the total volume and municipal and industrial use amount to only 15% of the total. The agricultural water is supplied mainly by surface water and for highland agriculture, water is supplied by groundwater.

1.2 Area and Population

(1) Area and Population of the Study Area

The Study Area consists of Mujib basin and the Greater Amman area which is located within a radius of 30 km centered around Amman city.

The estimated area and population as of 1985 for each area is as follows:

Section	Area (km^2)	%	Population	%
Mujib basin	6,600	6.9	77,000	2.9
Greater Amman area	2,827	2.9	1,616,000	60.8
Whole Jordan	96,200	100.0	2,658,000	100.0

The population of the Study Area occupies 63.7%, nonetheless, the area accounts for only 9.8% of whole nation of Jordan. Especially in the Greater Amman area, the population occupies 60.8%, although the area accounts for only 2.9% of whole Jordan. It shows that the Greater Amman area is very narrow, but has large potential in the planning of water supply aspect.

(2) The Population of the Greater Amman Area for Each Governorate.

The Greater Amman area span over four governorates. The estimated population of the Greater Amman in 1985 was as follows:

Governorate		Population	%
Amman and Zarqa		1,471,000	91.0
Irbid		5,000	0.3
Barqa		140,000	8.7
	(Total)	1,616,000	100.0

(3) Distribution of Population in Jordan

The estimated distribution of population in Jordan as of 1985, are shown as follows:

Governorate	Population	%
Amman and Zarqa	1,517,000	57.1
Irbid	730,000	27.5
Balqa	176,000	6.6
Karak	146,000	5.5
Ma'a	89,000	3.3
(Total)	2,658,000	100.0

Amman Governorate and Zarqa Governorate occupy 57% of total population.

1.3 Utilization of Past Records of Water Supply Volume

The amount of water consumption is approximately proportionate to population so the past records of water supply is utilized as follows:

For the supply volume of the Greater Amman area, the data for Amman and Zarqa Governorates are used since the population of the both areas is nearly same as shown below.

the Greater Amman area	1,616,000
Amman and Zarqa Governorated	1,517,000

2. WATER SUPPLY VOLUME

2.1 Water Supply Volume of the Whole Nation of Jordan

Water supply volume as of 1985, is shown in Table D2.1. The total supply volume is 92.5 MCM/y, the largest supply volume is 52.3 MCM/y for Amman Governorate and second is 16.1 MCM/y for Irbid Governorate.

2.2 Water Supply Volume for the Greater Amman area

Water supply volume for the Greater Amman area is considered nearly same as the total value of Amman and Zarqa Governorate (refer to Para. 1.3), which is shown in Table D2.2. Water supply volume for the Greater Amman area as of 1985, is estimated as 61.5 MCM/y.

3. WATER SOURCE AND SUPPLY SYSTEM SYSTEM

3.1 Exisitng Water Sources and Supply System

The following is the current situation concerning the water sources and supply systems for the Greater Amman area.

(1) Amman bore holes and Zarqa bore holes:

Both of these wells are located to Amman and Zarqa where the water from these wells is consumed. Therefore, water is sent directly to the distribution reservoirs built in and around the city.

Based on the records of 1985 the water supply volume is estimeated to be 20.1 MCM/y from Amman bore holes and 9.2 MCM/y from Zarqa bore holes. The large figure for the Amman bore holes is supposedly due to over extraction. A safe yield is estimated to be 15 MCM/y for the Amman bore holes and 9 MCM/y for the Zarqa bore holes.

(2) Azraq Water Conveyance System

Fifteen wells were bored an and around the Azraq area, which is a famous desert oasis located in the northeast side of Amman. The water pumped from these wells is stored in a collecting reservoir and then sent to the Ain Ghazal reservoir in Amman city by a discharging pump station.

One water pipe of Ø600 mm and 100 km in length has been built. Since the distance is very long, a booster pump station (pump capacity of 2,700 m^3/hr) with a reservoir was built at Khaw, a suburb of Zarqa which is 70 km from Azraq. This facility was completed in 1980.

The actual records of the water supply volume discharged from Azraq to Amman since 1982 are shown in Annex M4319 in the Report.

The actual discharge volume in 1985 was 15.6 MCM/y. A sustained yield from the Azraq well field is considered to be 15 MCM/y.

(3) Qatrana-Siwaqa-Qastal Water Conveyance System:

The Qatrana-Siwaqa-Qastal water conveyance system conducts water from the well fields in Qatrana, Siwaqa and Qastal (located along the Desert Highway extending south of Amman) to Amman.

The water from each well field is eventually sent to the Qastal Pump Station, pump capacity of 2000 m^3/hr and then pumped to the Quweisima reservoir located in the southern suburb of Amman.

The actual records of the discharged water volume at the Qastal pump station since 1985 are shown in Annex M4319.

The annual discahrge volume has reached 15.1 MCM/y in 1985. A sustained yield from these well fields, as mentioned later, is considered to be 3 MCM/y from Qatrana, 6 MCM/y from Siwaqa and 2 MCM/y from Qastal or a total of 11 MCM/y. It is realized that these sustained yields have been exceeded in order to deal with the water shortage in Amman.

Outline of pipeline of this system is as below.

Qatrana-Siwaqa;	pipe diameter	400 mm
	length	18 km
Siwaqa-Qastal;	pipe diameter	600 mm
	length	45 km
Qastal-Quweisima;	pipe diameter	600 mm
	length	20 km

This system was completed in 1983.

*Note: A part of water is sentd to Jiza and Queen Alia Airport.

3.2 Sustained Yield of Water Sources

Sustained yield of the existing water sources are estimated as follows:

Azraq well field	15 MCM/y
Qatrana well field	3
Siwaqa well field	6
Qastal well field	2
Amman bore holes	15
Zarqa bore holes	9
(Total)	(50 MCM/y)

4. PREVIOUS STUDY

4.1 Previous Study for Water Supply Projects

Water supply projects for the Greater Amman area have been studied about big projects, such as Maqarin Dam Project on the Yarmuk River and Water Conveyance Project from the Euphrates River. However, these projects have many problems to execute construction. The reason of these problems are caused by international river of these projects. In the Five Year Development Plan 1986-1990, only Mukhebah Project is taken up in the Plan. The outline of this project in the Five Year Plan is as follows.

Project Name: Delivering Al-Mukhebah Water to Middle Region and Amman.

Purpose of the Project: This project aims at conveying water from Al-Mukhebah wells using pipes to the middle region and Amman, for 26 MCM/y totally.

Project Components:

- Intake installations and treatment
- Pump stations along the pipeline
- Pipeline with a suitable diameter
- Primary and secondary reservoirs.

Project Cost: The estimated cost of this project is JD44 million.

5. ON-GOING PROJECT

5.1 On-going Project Around Amman

To meet the growing water demand in the Greater Amman, water is supplied to Amman by over extraction from wells. To relieve the water shortage in Amman the following five water supply projects were decided to be constructed.

Wala Water Conveyance Project

Mukhebah Water Conveyance Project, which is described in said Para.4.1.

New Siwaqa Water Conveyance Project

Ring Pipeline, Madaba-Yadudah-Suweilih Pipeline

Ring Pipeline, Yadudah-Abu Alanda-Pipeline from Azraq, Pipieline.

The outline of these projects are described in Para. F1104 and routes are shown in Annex M4321.

6. PROPOSED WATER SUPPLY PROJECTS

6.1 Outline of Proposed Water Supply Project

Water supply projects are described in the Chapter of "F1. The Projects" in the Report. The water sources of these projects are Sultani, Siwaqa-Qatrana and Rumeil well fields. The conveyance water volume of the pipelines are equal to the sustained yield of the well fields. The pipelines to be proposed are as below considering the using of on-going projects of WAJ.

Sultani-Siwaqa pipeline
From Sultani wellfield to Siwaqa pump Station planned by WAJ.

Intake quantity:	
from Sultani wellfield	6.3 MCM/y
from Siwaqa-Qatrana wellfield	9.6
total	15.9 MCM/y
Design flow of pipeline	1.3 x intake quantity
Pipe diameter	500 - 800 mm
Length	40.7 km

Rumeil-Madaba pipeline
From Rumeil wellfield to Madaba point at Wala-Madaba-Yadudah pipeline planned by WAJ.

Intake quantity	
from Rumeil wellfield	7 MCM/y
Design flow of pipeline	1.3 x intake quantity
Pipe diameter	300 - 700 mm
Length	27.4 km

6.2 The Study Items

The following items are studied in the Report

(1) Route Selection
(2) Water Supply System: Alternatives of arrangement of pump

station and reservoirs

(3) Optimum pipeline diameter.

Table D-1 MONTHLY WATER SUPPLY VOLLUME FOR EACH GOVERNORATE
(1985)

Unit: (m^3)

Month	Amman	Zarqa	Irbid	Balqa	Karak	Ma'an
Jan	3,878,596	600,204	1,242,418	176,961	309,225	527,881
Feb	3,551,604	552,344	1,088,500	186,616	248,808	543,500
Mar	4,162,618	548,179	1,283,090	239,103	289,509	611,072
Ap	4,235,400	713,736	1,307,400	241,680	305,550	628,800
May	4,696,407	888,057	1,448,909	259,996	382,881	726,144
Jun	4,710,840	885,240	1,420,830	238,800	420,360	763,440
July	4,765,816	905,789	1,459,356	232,779	428,110	800,575
Aug	4,405,534	918,313	1,504,430	213,152	469,712	722,245
Sep	4,697,760	851,490	1,420,170	211,620	436,685	683,220
Oct	4,622,224	841,805	1,423,582	218,302	400,148	742,171
Nov	4,280,580	739,800	1,280,940	202,110	360,720	609,000
Dec	4,336,621	710,241	1,191,547	200,570	320,912	611,227
Total	52,344,000	9,155,198	16,071,172	2,624,659	4,372,620	7,968,175

Total (92,536,824)