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WATER MASTER
PLAN

A HYDROGEOLOGICAL EVALUATION OF THE ENVIRONS OF LAKE NASSER

March, 1981

MINISTRY OF IRRIGATION

UNDP IBRD

FOREWORD

This report is one of a series of technical reports prepared to document the work done by or for the first phase of the Master Plan for Water Resources Development and Use EGY 73/024. A complete list of the reports prepared in this series is given below.

Number	Title
1.	Water Planning : Methods and Three Alternative Plans.
2.	Water Demands.
3.	Water Supply.
4.	Groundwater.
5.	Regulation Studies.
6.	Project Information System.
7.	Water Quality.
8.	The Organization, Administration and Legal Framework for Water Planning.
9.	Water and Wastewater Studies Municipal and Industrial Sectors.
10.	Industrial Water Use and Wastewater Production.
11.	Water Management Capabilities of the Alluvial Aquifer System of the Nile Valley, Egypt.

Number	Title
12.	Sediment Processes in the Nile River.
13.	Fisheries, Ecology, Health and Fish Farming.
14.	Hydrological Simulation of Lake Nasser.
15.	Mathematical Model for the Upper Nile.
16.	Agro Economic Model.
17.	Consumptive Use of Water by Major Field Crops in Egypt.
18.	Hydrogeological Evaluation of Environs of Lake Nasser.
19.	Economic Evaluation of Land Reclamation.
20.	The Irrigation System.

The first phase of the project was executed by the International Bank for Reconstruction and Development, financed by the United Nations Development Program, and the Ministry of Irrigation was the Co-operating Agency. Work began in October 1977 and the first phase concluded in March 1981. A bridging project document was signed in March 1980 to extend the work to December 1981 and to prepare for a second phase commencing January 1982.

Acknowledgement

This report was prepared by D.P. Carr and Ashraf A. Khafagi, of the Water Master Plan Project staff.
The typing was done by Mrs. V. Rizkallah.

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I INTRODUCTION AND SUMMARY OF CONCLUSIONS

1.01 For years to come the High Dam reservoir - Lake Nasser - will be the most important element governing the supply of water to Egypt. Therefor, the Master Plan Project devoted a substantial effort into investigations of the best way of using this unique facility. Technical Report 14 of the Project describes the development of a hydrological simulation model of the reservoir and its calibration using monthly data from the period January 1968 through December 1977. Technical Report 5 discusses the results of regulation studies performed with this model to balance alternative future national water demand and supply scenarios. The present report describes a desk study undertaken by Project staff to both assess the hydrogeological impacts resulting from the creation of Lake Nasser and evaluate the potential for groundwater development that have arisen in consequence.

1.02 Of the many facets of the High Dam that have attracted both national and international attention, the question of losses to groundwater from the impounded waters is probably the topic which has been the subject of the most debate. It has been asserted by some that their magnitude would prevent the efficient functioning of the reservoir. Exaggerated predictions have been made of the long-term consequences of reservoir filling on the groundwater dynamics of both the Nile valley and the Kharga-Dakhla Oasis complex. Proposals have been made for extensive development of groundwater for irrigation in the environs of Lake Nasser. From the standpoint of national water planning a definitive assessment of these factors based on a rational synthesis of data collected since impoundment was required.

Objectives and Scope of the Study

1.03 In view of the above remarks the objective of the present study may be summarized as :

- to provide a sound hydrogeological evaluation of the impact of Lake Nasser on the regional groundwater system which, in so far as it is possible, should enable an independent check to be made on the estimates of losses to groundwater derived from calibration of the hydrological simulation model.

1.04 The scope of the work was limited to a study of data that had been supplied to the Water Master Plan Project by various government agencies as of March 1980. A digital model of the hydrogeological conditions on a typical cross-section was developed as part of the study. This model was implemented on the Project's HP 9845 desk-top computer facility.

Conclusions

1.05 Part II of this report reviews the available data and discusses the hydrogeological environment of the study area. It is concluded that the groundwater system affected by filling of the reservoir is contained in a more-or-less flask shaped basin having a single sub-surface flow exit. Previous studies adopted a vertical sub-division of the sandstone aquifer around Lake Nasser into confined and unconfined portions. This assumption was not accepted in the present study which treats the formation as a single hydrogeological unit which is characterized by an anisotropic permeability distribution. It is demonstrated in Section III that the vertical head differences observed in the system can be explained in terms of vertical gradients associated with recharge and that they do not imply classical confined conditions at depth. Though pump test data for the aquifer in the environs of Lake Nasser are admitedly limited, the interpretation given herein suggests that its basic parameters are inkeeping with the known hydraulic characteristics of the Nubian formation elsewhere in the Western Desert.

1.06 The creation of Lake Nasser has resulted in the division of the original groundwater body into three more or less distinct sub-systems of which two are effectively closed. The observed piezometric response to impoundment is explained with the help of a digital model of a typical cross- section in Section III. This model is used to provide forecasts of future response of the system. It will be a very long time before significant water level changes are experienced either within the newly established closed groundwater sub-systems to the east and west of the reservoir or downstream of the sub-surface outflow front.

1.07 It is estimated that prior to construction of the High Dam, of the order of $5 \times 10^6 m^3$/year were 'lost' to groundwater in this area. Studies reported herein corroborate the estimates of annual loss to groundwater derived from calibration of the hydrological simulation model of Lake Nasser described in Technical Report 14 of the Project. Forecasts of future loss are given in Section III of the present report. It is foreseen that these will reduce from their current level of about $1.6 \times 10^9 m^3$ per year to around $0.7 \times 10^9 m^3$ by the year 2065 - ie 100 years after impoundment.

II. HYDROGEOLOGICAL ENVIRONMENT OF THE HIGH DAM RESERVOIR

2.01 For practical purposes the site of the Dal rapids in the natural river is considered as the southern limit of the lake formed by the High Dam. The morphological features of the pre-dam river channel from Dal to Aswan have been described by Geoistrazivanja (Reference 1), Hurst (Reference 5) and Abu El-Izz (Reference 6). About eighty per cent of the land area flooded by the reservoir is underlain by sandstones of the Nubian formation which outcrop to the north of the second cataract at Wadi Halfa. To the south of Halfa the inundated area is comprised for the most part of essentially impermeable crystalline rocks of the basement complex. Hence from the hydrogeological standpoint the area of primary interest is limited to the environs of Lake Nasser north of the second cataract.

Available Data

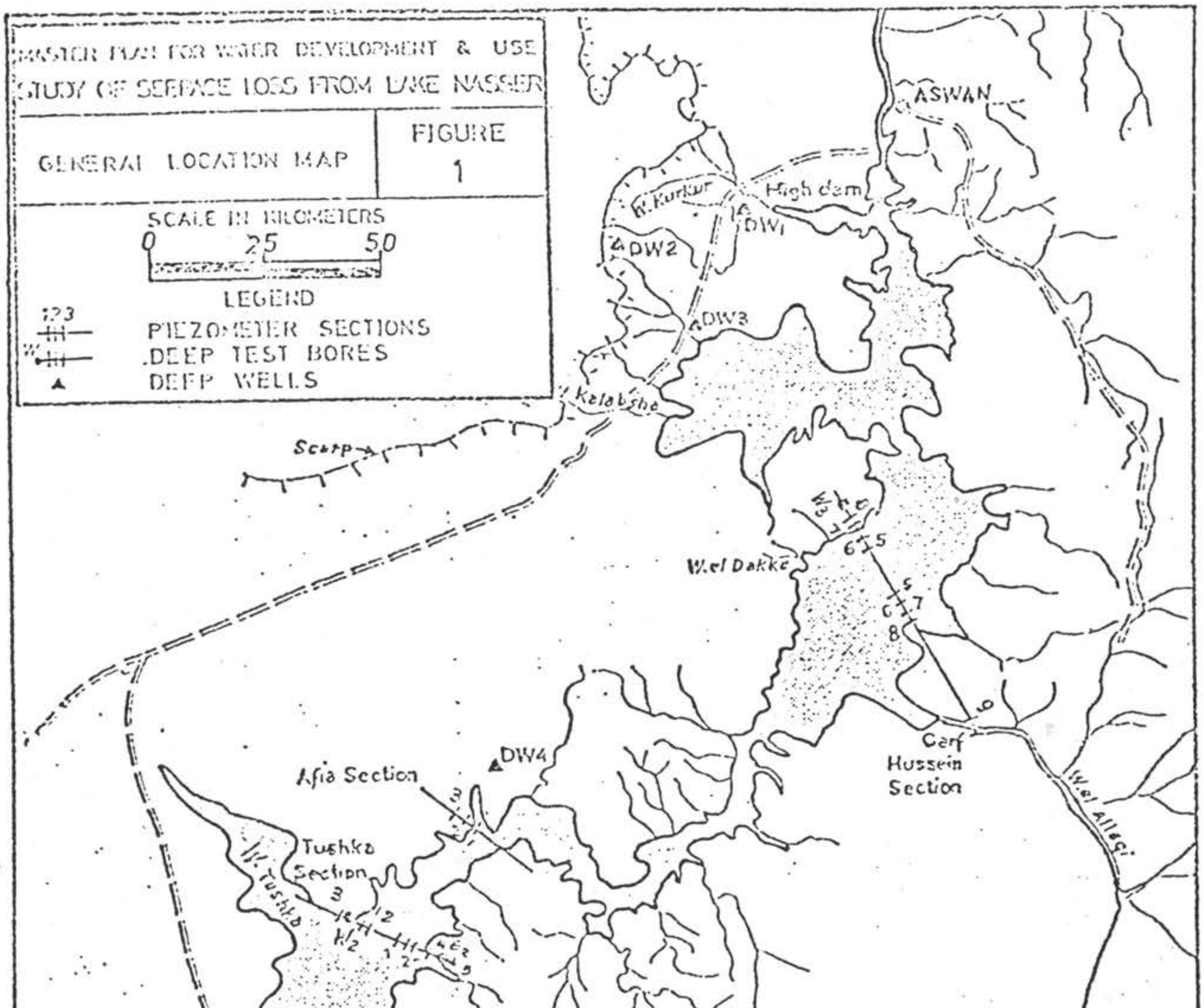
2.02 Maps. Various maps of the reservoir area were available for use in this study. The most important ones used being :

- General location maps of the Lake Nasser area at a scale of 1:1 million from 'Operational Navigation Chart' series, US Department of Defence.
- Well location maps at a scale of 1:½ million prepared by Geoistrazivanja, (Reference 1).
- Surface geology map derived from interpretation of LANDSAT I imagery presented in a study by the Remote Sensing Center of EASRT (Reference 2) at a scale of 1:1 million.

2.03 Boreholes & Piezometers. A series of boreholes were drilled on the northern flanks of the reservoir area prior to the construction of the High Dam. Reference 1 gives details of the results obtained from this drilling program which was designed to provide information on the likely magnitude of the losses to groundwater after impounding. The boreholes were layed out along four section lines which traverse the reservoir area. For the most part they were drilled to a depth corresponding to a bottom-of-hole elevation of around SSL + 90, that is to slightly below the water level in the river prior to filling of the reservoir. However, deep holes which penetrated the sedimentary sequence down to its contact with the basement complex were drilled on some of the remote ends of these cross-sections. All holes were completed as 3 inch piezometers. Fully penetrating bores had their screens placed near the bottom of the hole and were sealed higher up with cement plugs. They thus enable piezometric levels at depth to be observed.

2.04 Figure 1 shows the location of piezometers and their cross-sections. The configuration of each is summarized below:

- Garf Hussein cross section has four and five shallow piezometers to the west and east of the river channel respectively; one deep piezometer is located near the end of its western extension;
- Afia cross section has three shallow piezometers all located to the west of the river channel;
- Toshka cross section has three and five shallow piezometers to the west and east of the river channel respectively, a deep piezometer is located near to both its ends;
- Adindan cross section has four shallow and one deep piezometer located on each side of the river channel.


MASTER PLAN FOR WATER DEVELOPMENT & USE
STUDY OF SEEPAGE LOSS FROM LAKE NASSER
GENERAL LOCATION MAP
FIGURE 1
SCALE IN KILOMETERS
0 25 50
LEGEND
PIEZOMETER SECTIONS
DEEP TEST BORES
DEEP WELLS
ASWAN
High dam
W. Kurkur
DW1
DW2
DW3
DW4
Kalabshe
Scarp
W.el Dakka
Garf Hussein Section
W.el Allaqi
Afia Section
Tushka Section
W. Tushka
Abu Simbil
Adindan Section
Wadi Halfa

In addition, a further four deep wells (numbered DW1 to DW4) were drilled for the E.G.D.D.O. to the west of the area to be inundated. All borehole locations have been surveyed and their reference elevations are known.

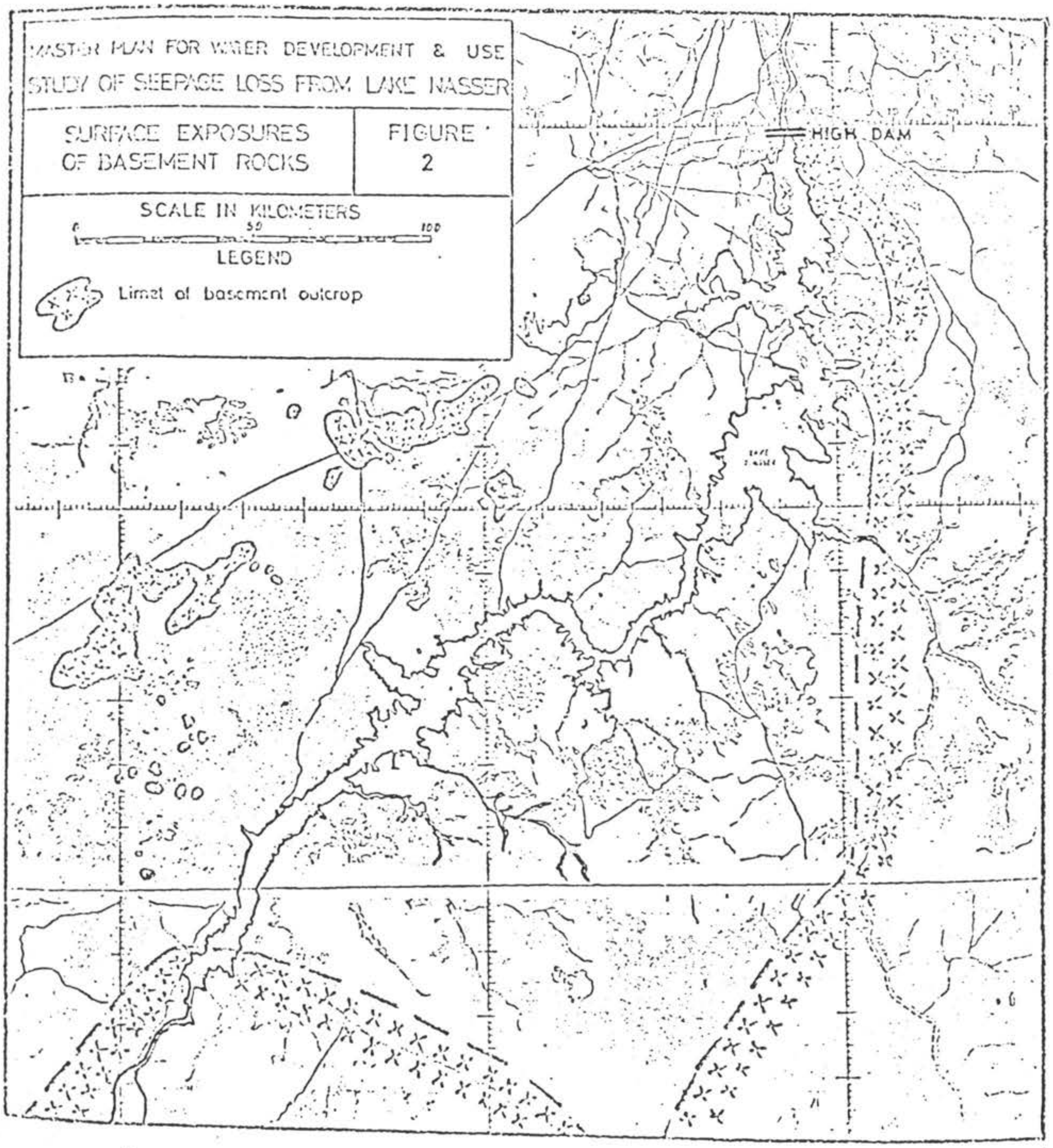
2.05 Water Levels. Observations were made in both shallow and deep piezometers at monthly intervals in the early years of reservoir filling. In later years, when level changes became more gradual, the frequency of observation was reduced to two or three readings per year. Many of the shallow piezometers became submerged by the rising waters of Lake Nasser but observations continue in holes at the extremes of the piezometer cross sections beyond the lateral limits of the lake at top water level. Hydrographs developed using this data are given in Section III of this report.

2.06 Daily records have been maintained of levels in Lake Nasser upstream of the High Dam. The lake level hydrograph is also shown on these figures.

2.07 Hydrogeological Characteristics. Descriptions of the petrological characteristics of the environs of the reservoir are given in References 1, 2 and 3. The results of pressure tests on the boreholes of the cross sections described in Para. 2.03 are discussed in References 1 and 3. A pump test on a borehole located near Abu Simbel is described in Reference 1. Much general information is available on the regional characteristics of the aquifers of the Western Desert. Data given in Reference 4 on the hydrogeology of the Kharga-Dakhla salient is of particular pertinence to this study.

Geology of the Area

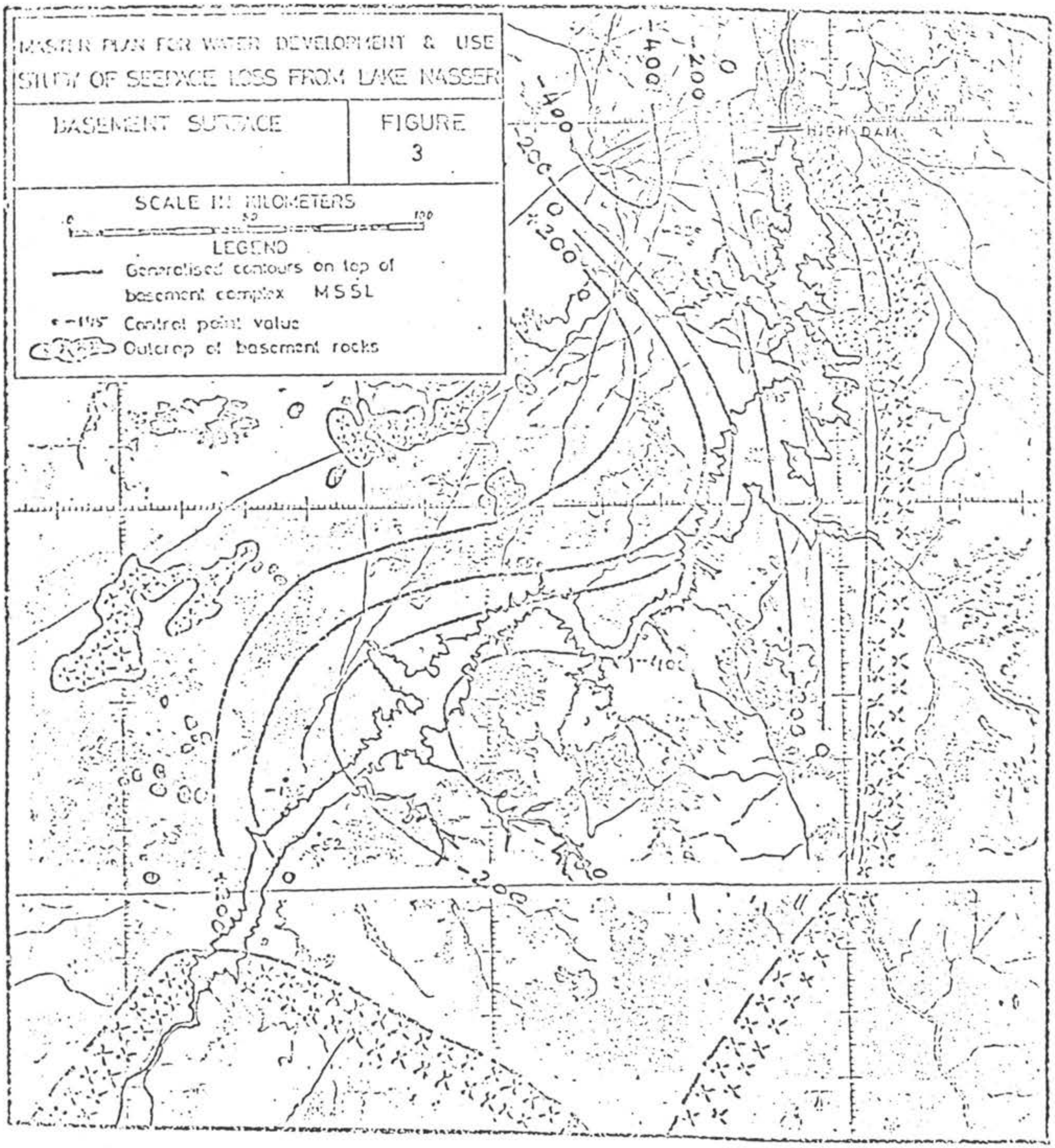
2.08 Figure 2 shows a simplified map of the surface geology


MASTER PLAN FOR WATER DEVELOPMENT & USE
STUDY OF SEEPAGE LOSS FROM LAKE NASSER
SURFACE EXPOSURES OF BASEMENT ROCKS
FIGURE 2
SCALE IN KILOMETERS
0
50
100
LEGEND
Limit of basement outcrop
HIGH DAM

of the study area based on the [illegible] interpretation of LANDSAT imagery given in Reference 2. On the regional scale the environs of Lake Nasser are dominated to the north by a sedimentary succession of cretaceous and quaternary age with some exposures of the underlaying crystalline basement complex. South ofthe latitude of the second cataract - ie at the Sudan/Egypt boundary - the reservoir is flanked by basement rocks. The characteristics of these geological units are summarized below.

2.09 Basement Complex exposures are composed of igneous and metamorphic rocks belonging to the late Precambrian and early Paleozoic. For the most part these consist of granite and granodiorities with some basic regoliths. The surface of these crystalline exposures is very irregular. Boreholes have been drilled to basement at nine locations in the study area where the crystallines are overlain by the sedimentary sequence. Figure 3 shows inferred contours on the surface of the basement using this data. It is accepted that these contours define a much more subdued surface than that which in all probability exists but it is believed that this smoothed surface is hydrogeologically more meaningful than the complex interpretation given in Reference 1.

2.10 The interpretation of the shape of the top of the basement given in Figure 3 indicates that its predominant feature in the study area is a saddle structure having an elongated north-south corridor some 80 kms in length with a floor elevation of around SSL-200 m. To the north this runs down to a depression in the vicinity of Wadi Kurkur where elevations fall below SSL-400 m. In the south this saddle opens out into another large depression in the basement about which little is known. At the eastern end of the Toshka cross section the basement contact in this depression is at about SSL-400 m.


MASTER PLAN FOR WATER DEVELOPMENT & USE
STUDY OF SEEPAGE LOSS FROM LAKE NASSER
BASEMENT SURFACE
FIGURE 3
SCALE IN KILOMETERS
0
50
100
LEGEND
Generalised contours on top of basement complex MSSL
Control point value
Outcrop of basement rocks
HIGH DAM
-400
-200
0
200

2.11 Cretaceous Sequence. The Basement is unconformably overlain by predominantly sandstone rocks of Cretaceous age. These rocks are part of a vast clastic sequence underlaying much of North Africa which in the Western Desert is known as the Nubian formation. In the vicinity of the reservoir the Nubian is composed of sand and sandstone interbedded with clay and shale. Reference 4 observed that the intercolations of clays and shales in the Nubian in the Kharga-Dakhla region are laterally discontinuous and of varying thickness and lateral extent. As such it was concluded that these beds did not constitute a significant hydrogeological subdivision of the formation in the vertical when viewed on the regional scale. Logs from the Lake Nasser area manifest similar characteristics to those of the Kharga-Dakhla and it is rational to extrapolate the above conclusion to that area. Hence, in this study the Nubian formation will be treated as a single hydro-geological unit. This is a significant departure from the interpretation of the hydrogeology of the Nubian succession in the environs of Lake Nasser given in Reference 1.

2.12 Examination of the borehole logs given in Reference 1 suggests that the proportion of clay/shale material decreases with height above the basement contact. Although the data are admitedly limited, the proportion of sand within the first 200-300 meters above the base of the formation is about 40% and increases to a mean maximum of about 75% in the upper portions of the local section. In this regard it is noteworthy that Reference 4 reports the average section sand proportion in the Kharga-Dakhla salient of the formation to be 70 percent in the drilled sections which are for the most part at least 300 meters above the basement contact. In the environs of Lake Nasser there is no evidence of any preferential lateral variability in the pattern of distribution of sand percentages. The sandstones found in the section range from fine to coarse grained and both friable and well cemented material is encounted.

2.13 Combination of land surface topography and the surface structure of the basement contact described in Paragraph 2.10 result in the Nubian formation having its maximum local thickness of 570 m on the Toshka cross section. From there it decreases both to the south west and north east. At Garf Hussein its thickness is about 250 m from whence it pinches out to the north and basement rocks become exposed at surface about 45 km south of Aswan. To the southwest of Toshka the Nubian thins to about 330 meters at Adindan and then runs out to a feather edge south of the second cataract. The Sudanese portion of the lake is thus to all intents and purposes not in hydraulic contact with the main body of the Nubian formation.

2.14 Quaternary Deposits. The surface of the Nubian has been much altered by weathering and is covered by recent windblown sand, sand dunes and alluvial deposits. The latter are for the most part composed of clayey, limy, silty sand materials found on the near-flat plans that flank the reservoir and along the bottoms of the main Wadi courses. On the regional hydrogeological scale these deposits are of little significance.

Hydrogeology

2.15 Definition of the Aquifer System. The Nubian formation is the only unit of hydrogeological significance in the environs of the reservoir. As noted in Paragraph 2.11 this formation will be treated as a single hydrogeological unit.

Previous studies have attempted the vertical subdivision of the Nubian around Lake Nasser into confined and unconfined portions on the basis of clay-shale breaks which were regarded as being regionally extensive. The observance of head differences between deep and shallow piezometers was advanced as further evidence in support of this zonation. The present study recognizes that these clay-shale breaks are more likely to be lenticular in shape and irregular in both their lateral and vertical distribution. Moreover it will be demonstrated that the observed piezometric response of both deep and shallow boreholes to the filling of the reservoir can be explained in terms of the phenomena of three dimensional flow through a markedly anisotropic aquifer system which has a unit-section horizontal permeability that decreases with depth.

2.16 Crystalline basement rocks which underlay the Nubian formation constitute an essentially impermeable base to the aquifer system. To the northeast the outcrops of these rocks form an evident lateral no-flow boundary from Aswan to about the latitude of Garf Hussein. The Nubian then opens out to the southwest to form a large lobe which reflects the southern basement depression described in Paragraph 2.10. The lateral boundary formed by the crystalline contact encircling this lobe is not well defined by the available data, but it does turn back west to cross the Nile again at Wadi Halfa.

2.17 There is much confusion in the available literature about the effective hydrogeological boundary conditions to the west of the reservoir. Indeed some studies regard the Nubian aquifer in the environs of Lake Nasser as a primary source of the groundwater system which discharges in the Kharga depression. However, any credible interpretation of the nature of this western hydrogeological boundary must reconcile the following information :

- the shape of the basement contact inferred in Figure 3 coupled with a predominance of the locally oldest stratta of the Nubian at surface with many 'windows' of basement to the west of the lake suggest that a regional basement high develops in this direction with the consequent pinching-out of the sandstones;

- west, and remote from the lake, piezometric gradients are relatively flat and a regional basement high must result in marked reductions in the thickness of saturated Nubian in a westerly direction. This is evidenced by the decrease in observed saturated thickness in the fully penetrating wells of the study area. Along the line of the main flow axis these range from 300 to 400 meters falling to 55 meters at well DW4;

- the string of basement outcrops marking the Abu Bayan uplift to the south of the Kharga depression are known to be associated with an extensive area where the saturated thickness of the Nubian feathers-out into insignificance. A major fault line to the east of this depression acts as an impermeable flow barrier which extends southwards to the locality of Abu Bayan. Thus, the Kharga depression is effectively closed to inflow both from the east and southeast, see Reference 4. Piezometric heads on the southern inflow face feeding the depression have been established through simulation to be in the range of SSL + 200 m.;

- it is reported that geophysical investigations have been conducted on the plains adjacent to Lake Nasser, however, the results of these surveys were not available for use in this study. No doubt they could shed some light on the important topic of the nature of the western hydrological boundary. Drilling investigations are understood to have been started in the Toshka depression which lies between the more or less parallel basement swells of Umm Shaghir and Abu Bayan. From first reports it would seem that only very limited thicknesses of sandstone material have been encounted in these boreholes.

In the light of the above it is rational to conclude that the saturated section of the Nubian is pinched out by basement rocks along much of the western margin of the study area. It would thus seem that these rocks form a no-flow lateral boundary which encircles the aquifer from Wadi Halfa running west then north round to the Wadi Kurkur whence it again swings in a westerly direction.

2.18 The inferred locations of the lateral boundaries of the aquifer are shown on Figure 4. It is noteworthy that this interpretation implies that the groundwater system affected by filling of the reservoir is contained in a more-or-less flask shaped basin having a single subsurface flow exit to the north.

2.19 Aquifer Characteristics. As noted in Paragraph 2.11 the lithology of the Nubian is characterised by intercalations of clay-shale lenses in a sandstone matrix. Although the saturated portions of this formation are herein regarded as a single aquifer unit on the regional scale, the evident tendency for the relative proportions of clay-shale material to increase with the age of the sub-stratta of the formation - ie as the basement contact is approached - will have a dominating influence on the permeability characteristics of the system. To a first approximation it can be assumed that horizontal flow predominates in the sandstone material with little or no lateral movement taking place in the clay-shale portions of the section. Thus, at any level in the saturated section the effective local transmissivity will be determined by the relative proportions of sandstones by thickness and their unit horizontal permeability.

2.20 Significant vertical hydraulic gradients inevitably develop in the vicinity of extensive recharge features such as that associated with the filling of Lake Nasser. It is, therefore, important that the vertical permeability characteristics of the aquifer complex be taken into account in describing the flow dynamics of this system. Although the vertical permeability of a 'clean' sand or sandstone deposit is normally at least an order of magnitude less than their horizontal permeability, it is nevertheless several orders of magnitude greater than that of clay or shale. Hence the mean vertical permeability of deposits containing extensive clay-shale intercalations will be essentially determined by the proportion of clay in the section and will decrease rapidly as this proportion increases.

2.21 Geoistrazivanja (Reference 1) has reported permeability estimates derived from injection pressure tests on the boreholes described in Paragraph 2.03. These estimates are between one and two orders of magnitude smaller than the range of horizontal permeability generally accepted as representative of the Nubian and display no rational pattern. In addition to the limitations of these tests discussed in Section 6.1.1 of the Geoistrazivanja report (op.cit) the practice of testing short lengths of cut section results in something approaching spherical flow conditions in the vicinity of the test section. The results are thus greatly influenced by the controlling effect of vertical permeabilities on this local flow field. It is concluded that these data can not be used to derive reliable permeability estimates.

2.22 Horizontal Permeabilities. There is much evidence to indicate that the conditions of sedimentation of the Nubian sandstone produced an essentially consistent type of deposit from the hydrogeological standpoint over a vast area. An analysis of pump-test data from some 86 wells tapping this formation in the Khufra Oases in Libya about 1000 kms to the west of Lake Nasser, yielded a mean permeability for their screen sections - which varied from around 30 to 300 meters - of 3.9 m/day. Values ranged from 1.6 to 17.7 m/day with a standard deviation of 56 per cent. (Source of data, Reference 8). Similarly, Barber and Carr, (Reference 4)analysed data from 80 wells in the Kharga-Dakhla region with screened lengths varying from 40 to 600 meters. Mean permeabilities for these screened sections ranged from 0.2 to 13.1 m/day with an average of 3.6 m/day. The standard deviation was found to be 2.6 m/day giving a coefficient of variation of 72 per cent.

2.23 The overall proportion of sand material encounted in the Nubian in the environs of Lake Nasser is less than that observed in the Kharga-Dakhla region. Few data are to hand but it would seem that the sand proportion in the screen sections in Khufra is about the same as that in these two oases. However, whereas there is no evidence of any preferential distribution of sand stratta through the section of the Nubian tapped in these depressions, data from deep boreholes

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on

in the vicinity of Lake Nasser indicate that the proportion of sand in the formation reduces as the basement contact is approached in this locality. Accepting the concept that horizontal flow for the most part takes place through the sand beds, Barber and Carr (op.cit) demonstrated that a reliable estimate of regional mean horizontal permeability for a section of the Nubian can be derived by factoring their estimate of the average regional permeability of sand beds of 5.0 m/day by the proportion, by thickness, of sand strata in the section . Extension of this approach to the aquifer in the environs of Lake Nasser should enable realistic estimates of the distribution of horizontal permeability in the vertical to be developed.

2.24 Accepting the vertical distribution of sand material described in Paragraph 2.12 implies that upwards of the first 100 meters of Nubian above the basement contact has a mean horizontal permeability of less than 1 m/day which increases over the next few hundred meters to stabilize at around 3.5 m/d for those parts of the formation laying above, say, the 400 meter isopach line. Reference 2 reports the permeability obtained from pump-testing a borehole in the Abu-Simbel area as 1.9 m/day; Reference 1 also reports the results of pump tests near Abu Simbel as giving permeabilities in the range of 3.0 m/day to 0.7 m/day. Little information is available on these tests and in particular the setting and lengths of the screens is not known. Nevertheless, given that the thickness of saturated Nubian in this area is estimated to be around 250 meters, and making some allowance for the likelyhood of a preference for screening the better developed sand beds during well construction, these results do support the general thrust of the reasoning described above.

2.25 <u>Vertical Permeability</u>. In paragraph 2.19 it was noted that whereas the permeability of sand beds in the section governs horizontal flow in the Nubian, it is the characteristics of the intercalated clays and shales that control the movement of water in the vertical. In practice, at the regional scale, it makes no difference whether the head loss associated with vertical flow is considered to result from overcoming resistance to flow directly through a clay-shale bed or by energy losses incurred on a tortuous flow path which meanders round these lenticular deposits. Both these phenomena can be composited in an effective vertical leakage parameter which can be defined conceptually as the ratio of mean vertical permeability to the thickness of the aquifer section being considered.

2.26 Barber and Carr, (Reference 4), derived an estimate of the effective vertical permeability in the Kharga-Dakhla area of 2.5×10^{-3} m/day through calibration of a digital simulation model of the aquifer. A vertical permeability of 2×10^{-3} m/day has been reported as representative of conditions in the Kufra area, Reference 8. These estimates apply to sections of the Nubian which have relatively smaller proportions of clay and shale strata than is encountered in the environs of Aswan - see Paragraph 2.12 - and it is therefore rational to take this into account when estimating representative vertical permeabilities for this area. Accepting this approach implies that the vertical permeability of the first 100 meters or so above the basement is probably less than 1×10^{-3} m/day and that it improves with the increases in proportion of sand strata in the section to stabilize at around 2.5×10^{-3} m/day for those parts of the formation laying above, say, the 400 meter isopach line. Though on first sight these values may seem small, it should be appreciated that they can have a very significant effect on the flow domain when applied over a large area.

2.27 Storativity. Estimates of the apparent storage characteristics of the Nubian are available from observations of water level response to exploitation in the Khufra, Kharga, and Dakhla Oases. However in those areas the formation is for the most part under confined conditions and computed storage coefficients are influenced by water releases arising from a combination of expansion of the water itself, changes in the aquifer fabric, compaction of the formation , and leakage through or drainage from the confining beds. In the environs of Lake Nasser the aquifer is under water-table conditions and groundwater storage changes resulting from filling of the reservoir well be dominated by the specific yield of the formation.

2.28 None of the pump-test data from the Oases of the western desert provide direct estimates of specific yield for the Nubian, see References 4 and 8. Barber and Carr (op cit) discussed the interpretation of the storativity data from the Kharga-Dakhla region in some detail. And, after reviewing assessments by various authors, they adopted a value of 10% for the specific yield of the Nubian against long term dewatering conditions.

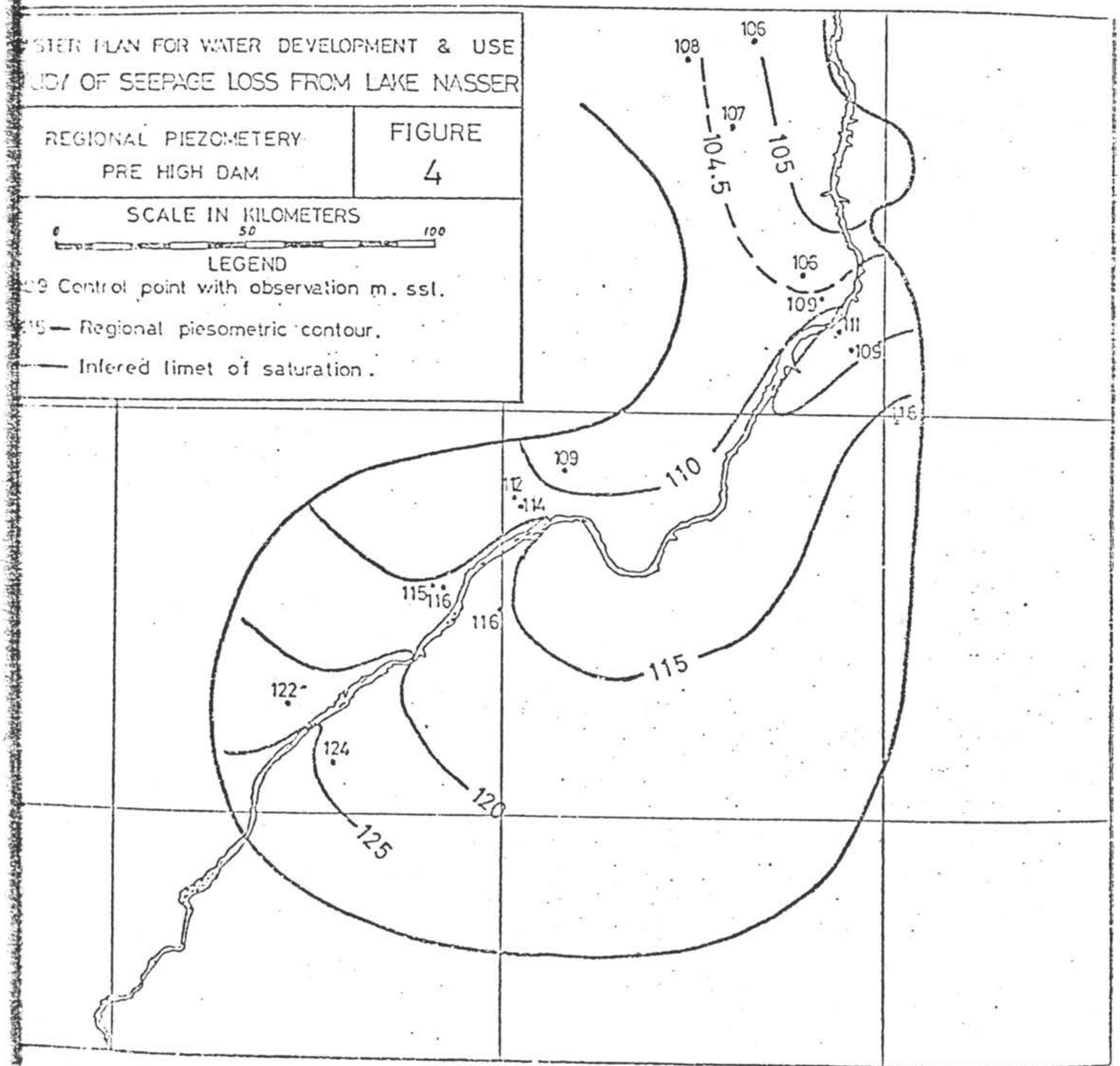
2.29 Medium grain sizes for the sand material in the aquifer range from 0.5 to 1.0 mm. and Geoistrazivanja (Reference 1) report that the total porosity, as determined by laboratory analysis, of samples from the environs of Lake Nasser range from 25 to 30 per cent. It is noteworthy that these porosity values are at the upper end of the range typically quoted for sandstone material. A number of standard charts are given in the hydrogeological literature which enable estimates of specific yield to be developed from co-axial relationships between grain size, porosity and permeability. These charts are for the most part only compiled for nonindurated sediments and thus give values somewhat higher than specific yields appropriate for hard rocks with similar grain size-porosity-permeability characteristics. Such charts indicate that a specific yield of 15% would be reasonable for non-indurated sediments with the properties quoted above. If allowance is made for the difference between such aquifers and the predominantly sandstone strata of the Nubian - and recognizing that the storativity parameter of interest must take account of the fillable storage in those parts of the aquifer which were above the water table prior to impounding of the reservoir - it would indeed seem reasonable to use a value around the 10% estimate of specific yield adopted by Barber and Carr (op cit.) for model studies in the Kharga-Dakhla area in evaluating groundwater storage changes in the environs of Lake Nasser.

Pre-High Dam Piezometry

2.30 Little is known about groundwater conditions in the study area prior to the beginning of the High Dam investigations in the 1960's. Measurements of water levels in a few wells were made by Ball before construction of the Aswan (low) dam in 1902; from these it has been concluded that under natural conditions the river functioned as a drain from, rather than a recharge source to, the groundwater body, see Reference 1. This interpretation is in-keeping with the results of more recent regional hydrogeological studies which show that the Nile does indeed act as a drain for the groundwater systems of the greater part of the Sudan.

2.31 Piezometric observations in the wells drilled to support engineering studies for the High Dam enable a reasonably reliable picture to be developed of the flow dynamics of the aquifer system before the start of reservoir filling. These data are given in Reference 1 and include observations on some of the piezometric cross sections (see Paragraph 2.03) for the 1963 through 1965 operation cycles of the reservoir which marked the period when outlet control passed from the Low to the High Dam. During this time the lake level fluctuated between 104 and 130 meters SSL. These data demonstrate that in the vicinity of the shore line a dynamic recharge mound developed and subsequently decayed in response to these surface water level fluctuations. It is also evident that under the operation cycle of the Low Dam, groundwater at a distance of, say, 3 km from the top-water shore line played no part in 'bank storage' interchanges with the reservoir. Hence, piezometric levels in the more remote boreholes of the cross sections can be taken to be representative of regional flow conditions. These do show that there was a net regional flow vector away from the low dam reservoir and that on balance it functioned as a recharge source to the aquifer.

2.32 Figure 4 has been constructed using data from boreholes at the remote ends of the cross sections which showed little or no response to changes in surface water levels along with observations in the outlaying 'Dw' series of wells. Although control is sparse it is believed that this map does give a reasonably reliable picture of conditions before the construction of the High Dam. The strength of the recharge ridges shown along the course of the river may be over emphasized at the regional scale. But this not withstanding, the following aspects of the inferred piezometry are noteworthy :



STER PLAN FOR WATER DEVELOPMENT & USE
UDY OF SEEPAGE LOSS FROM LAKE NASSER
REGIONAL PIEZOMETERY
PRE HIGH DAM
FIGURE
4
SCALE IN KILOMETERS
0
50
100
LEGEND
Control point with observation m. ssl.
Regional piesometric contour.
Infered limet of saturation.
104.5
105
110
115
120
125

- the general steepening of the hydraulic gradient in the vicinity of Garf Hussein is in agreement with the shape of the basement surface defined by Figure 3;

- the suggestion that the aquifer receives some lateral recharge across its easterly limit of saturation is in-keeping with the known features of the (westerly draining) eastern wadi systems which have large catchment areas relatively rich in desert vegetation with numerous 'water points' in weathered granitic rocks at altitudes in excess of SSL+300, see Reference 1;

- to the north, the groundwater system is dominated by a convergence of flow lines which appears to return all subsurface outflow to the Nile in the vicinity of Aswan.

III RESPONSE OF THE AQUIFER TO CREATION OF LAKE NASSER.

3.01 Construction work on the High Dam was essentially completed in mid 1964 and reservoir filling commenced with the impoundment of the flood of that year. Peak annual water levels in Lake Nasser rose from SSL+120 in late 1964 to stabilize at about SSL+176 in the latter 1970's. Figures 5 through 8 show hydrographs of the response observed in boreholes on the four piezometric cross sections described in Paragraph 2.03 to reservoir filling . End-of-year, ie peak, lake levels are also shown on each of these figures. Most of the shallow piezometers were submerged by the rising waters of the reservoir and observations are therefore only available from bore holes beyond the lateral limits of the lake at top-water level after 1976.

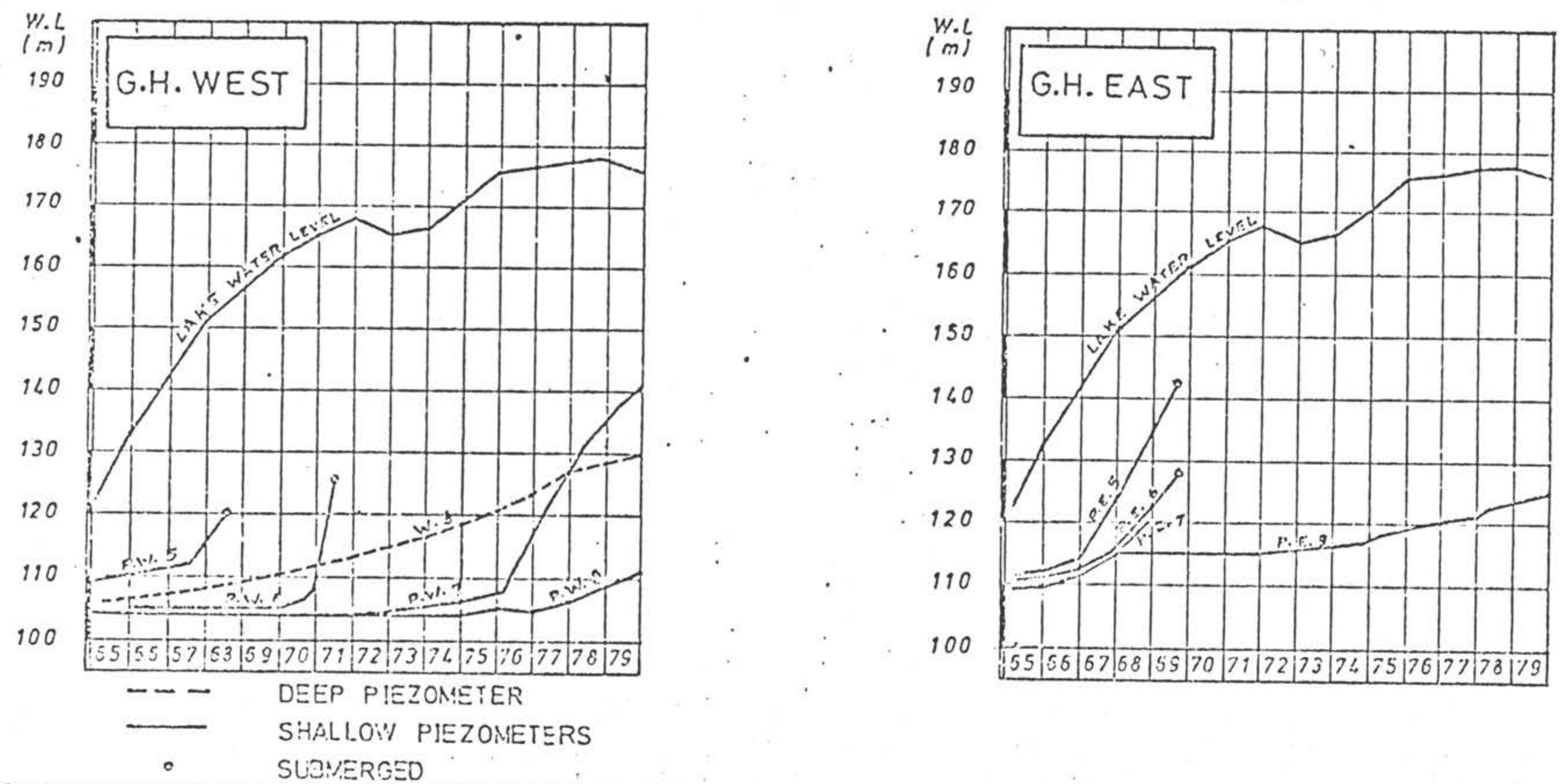
3.02 Figure 9 shows the inferred piezometry in the environs of Lake Nasser in the late 1970's - ie shortly after reservoir filling had been completed. On comparison with Figure 4, pre-High Dam piezometry, it is apparent that creation of Lake Nasser has resulted in the division of the original groundwater body into three more or less distinct sub-systems. These are :

- the south eastern basin, which is roughly triangular in shape with an area of around12,000 Km^2. The lake forms a head controlled hydraulic boundary to this sub-system and its eastern and southern limits are defined by the inferred location of the feather edge of saturated Nubian;

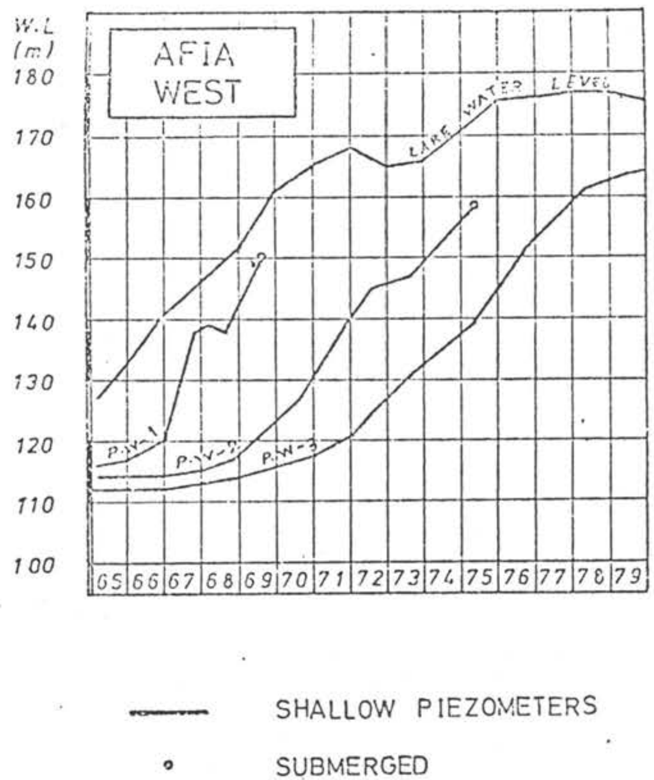
- the south-west - north-east elongated basin which is more or less rectangular with an average effective width of 50 Km and an area of upwards of 7,000 Km^2. This sub-system is defined by the lake to the east which functions as a hydraulic head controlled boundary and the inferred limit of saturation to the west;

- the north west trending Wadi Kurkur subsurface outflow system which has a front length of about 60 Km that now feeds the convergence zone that apparently returns all flow originating from this direction back to the Nile downstream of Aswan.

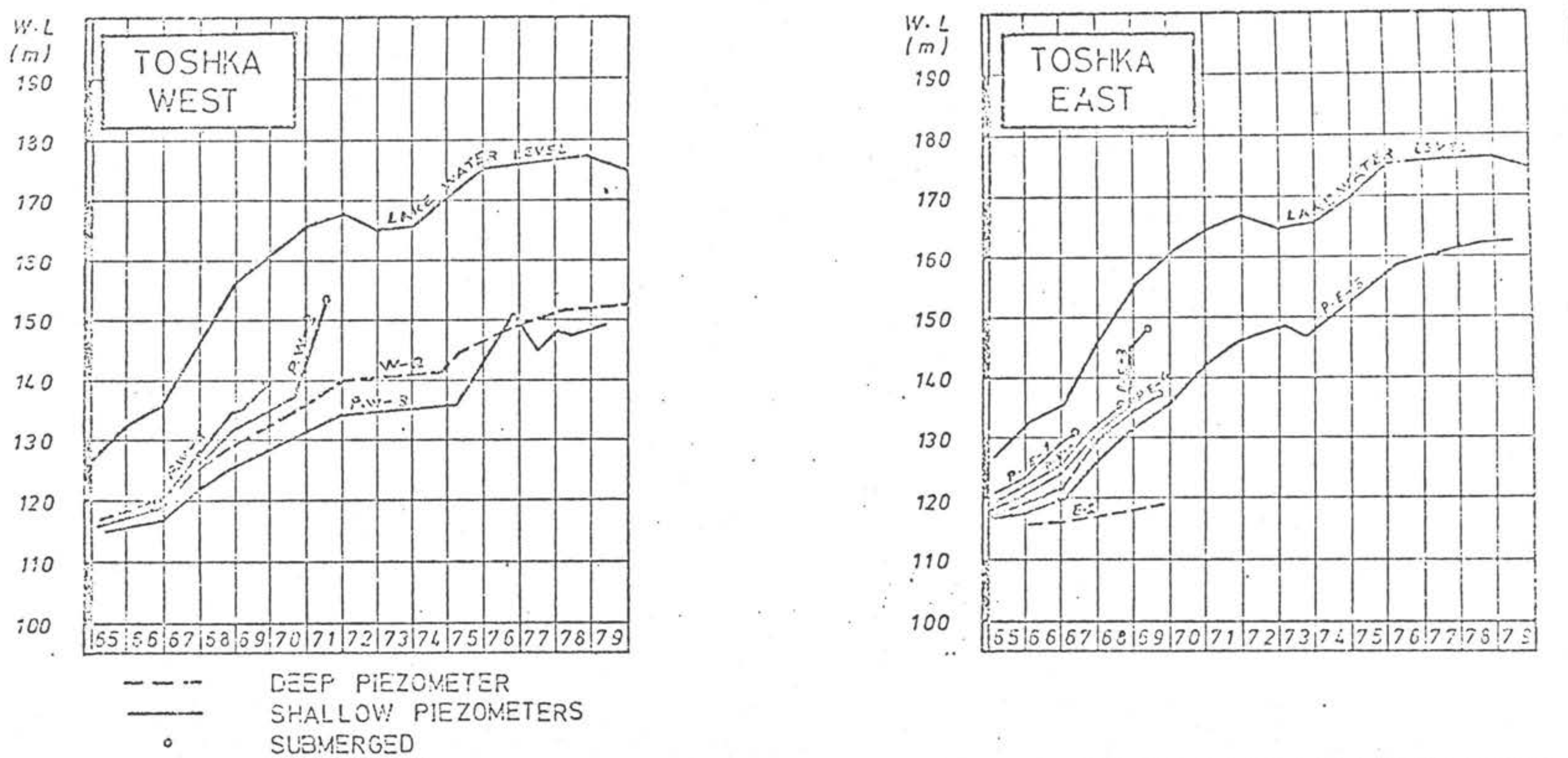
It is noteworthy that of the three groundwater sub-systems created as a result of the filling of Lake Nasser, two are closed basins which are primarily recharged by losses to groundwater from the reservoir. These losses are manifest as increases in the total volume of groundwater stored in



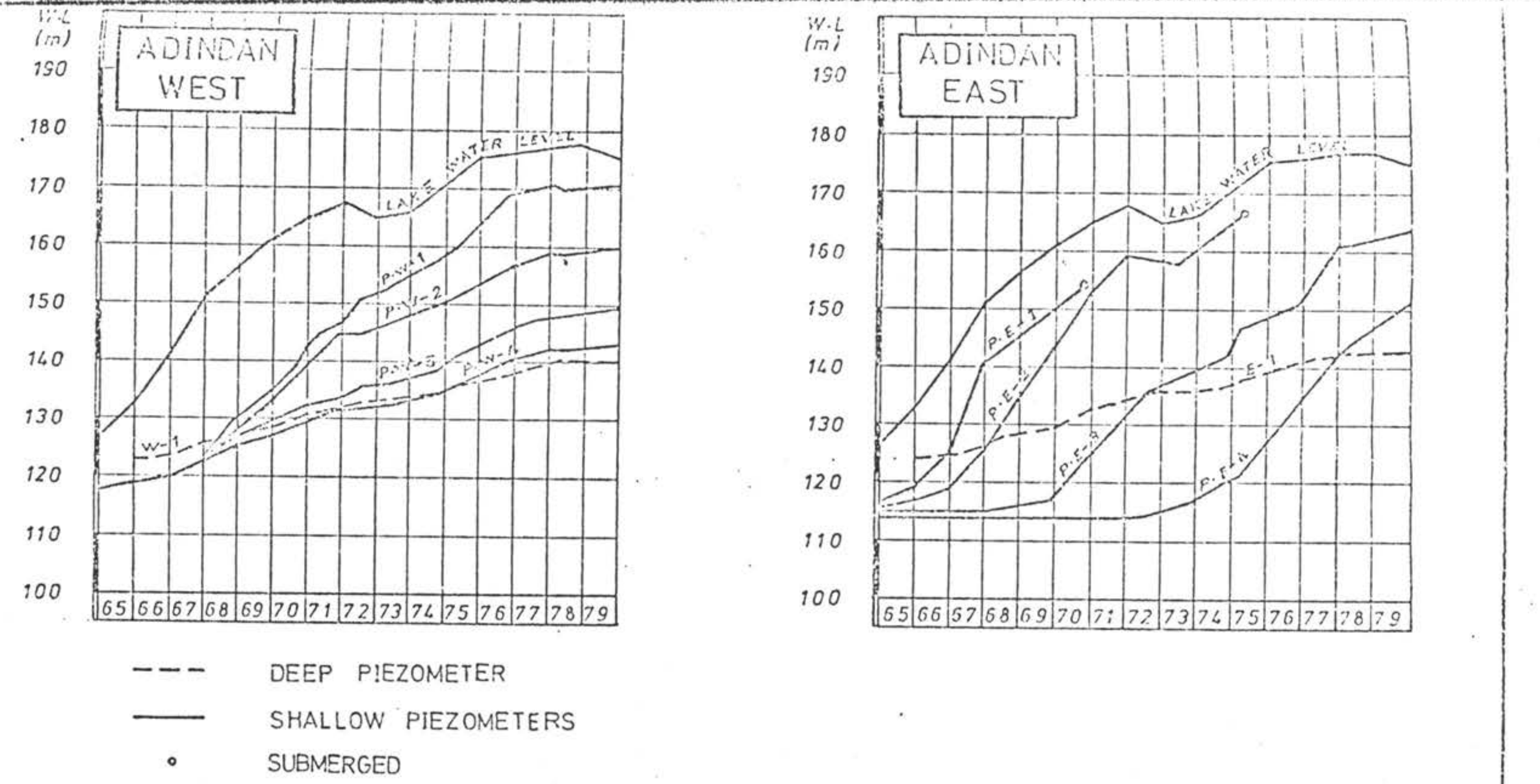
MASTER PLAN FOR WATER DEVELOPMENT & USE STUDY OF SEEPAGE LOSS FROM LAKE NASSER	HYDROGRAPHS OF WATER LEVELS	FIGURE 5



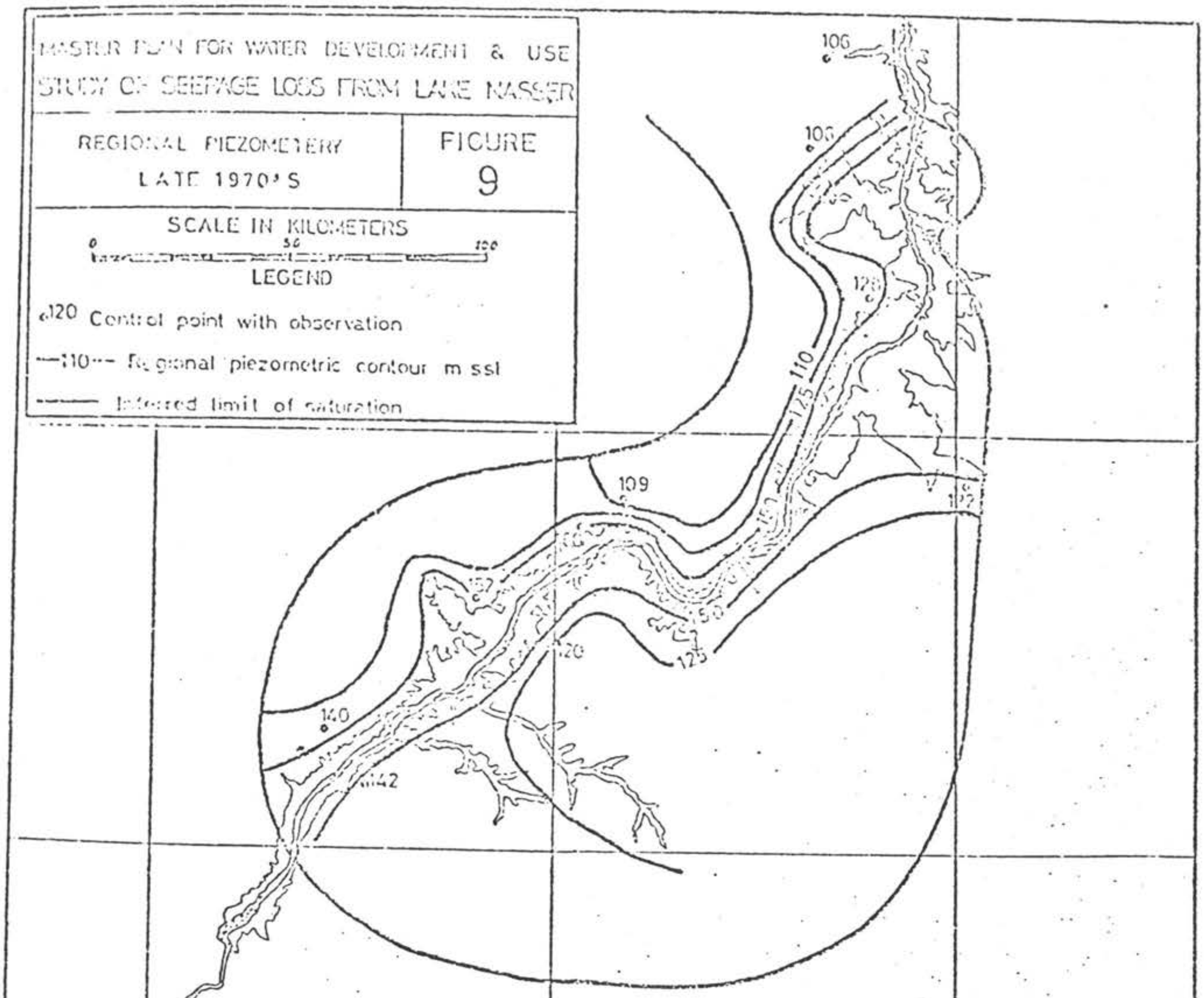
MASTER PLAN FOR WATER DEVELOPMENT & USE STUDY OF SEEPAGE LOSS FROM LAKE NASSER	HYDROGRAPHS OF WATER LEVELS	FIGURE 6



MASTER PLAN FOR WATER DEVELOPMENT & USE STUDY OF SEEPAGE LOSS FROM LAKE NASSER	HYDROGRAPHS OF WATER LEVELS	FIGURE 7



MASTER PLAN FOR WATER DEVELOPMENT & USE STUDY OF SEEPAGE LOSS FROM LAKE NASSER	HYDROGRAPHS OF WATER LEVELS	FIGURE 8


MASTER PLAN FOR WATER DEVELOPMENT & USE
STUDY OF SEEPAGE LOSS FROM LAKE NASSER
REGIONAL PIEZOMETERY
LATE 1970'S
FIGURE
9
SCALE IN KILOMETERS
0
50
100
LEGEND
120 Control point with observation
110 Regional piezometric contour m ssl
Inferred limit of saturation
106
109
110
125
150
120
140
142

the closed sub-systems and they may thus be viewed in the very long term as sub-surface extensions to storage capacity.

3.03 Accepting the above, it is important that both the time scale and volumes associated with future changes in the amount of water stored in these closed sub-systems is fully appreciated. Moreover, it is essential that a realistic evaluation is made of the magnitude of the changes that can be expected in return flows to the river as a result of the creation of the north western outflow front. The subsequent paragraphs of this section attempt to place these considerations in a national water planning context.

Piezometric Response to Reservoir Filling

3.04 Studies of the transient behaviour of deep unconfined aquifer systems subject to laterally extensive recharge have demonstrated that vertical head differences are developed which can have a controlling influence on the flow pattern, see Bouwer, Reference 9. Such head differences would develop even if the aquifer were perfectly homogeneous and, contrary to the conclusion of some other workers, (Reference 1 and 3), the observation of differential behaviour of water levels in deep and shallow boreholes in the vicinity of Lake Nasser, does not by itself suggest the existence of hydraulically separate upper and lower aquifers.

3.05 Response Observed Since Impoundment. When considering the hydrographs of borehole level response given in Figures 5 through 8 both the characteristics of the aquifer system as described in Section II, and the advance of the shore line with increasing reservoir elevation should be kept in mind.

The shallow boreholes subject to submergence all show a somewhat similar response and demonstrate the existence of relatively steep gradients away from the lake in the first few kilometers from the shore. These data indicate that a classical recharge mound with a sharp reversed 'S' type front, developed and advanced as the shoreline expanded with increasing lake levels.

3.06 Consideration of water level changes in the paired deep and shallow boreholes at the remote ends of the piezometric cross sections gives a major insight into the nature of recharge conditions after impoundment. The observed behaviour of these boreholes is summarized below and subsequent paragraphs show that it is indeed inkeeping with the response to be expected on theoretical grounds.

- Garf Hussein cross section has a pair of deep and shallow piezometers at its western end (DW3 and PW8 respectively of Figure 5). The location of the screen portion of the deep borehole is not known. These holes are about 3 km away from the lake shore at top-water level. Figure 5 shows that although the deep piezometer started to respond with the initiation of impoundment, water levels in the shallow zone did not begin to rise untill 10 years thereafter - that is untill the shore line had expanded to within 3½ kms of their location. In consequence, an <u>upwards</u> vertical gradient developed at this site and by the end of 1979 there was a 20 m head difference in the vertical.

- Toshka cross section has paired piezometers at both ends, To the west these boreholes are about 1 km away from the lake shore at top-water level; in the east the boreholes were submerged after about five years. The deep borehole to the west was screened below SSL-100 and that to the east below SSL-360. Figure 7 shows that at each end of this cross section both piezometers in the borehole pairs started to respond with the onset of impoundment. In the western pair an upwards gradient developed from the outset and reached a maximum vertical head difference of 8 m after about 10 years when the lake shore was about 3 kms from these holes. Since that time this difference has declined, and by the end of 1979 it was about 3 m. To the east the deep piezometer responded slower than the shallow one. At the time of its submergence (five years after the onset of impoundment) the resulting downwards vertical gradient had developed a head difference of 15 m.

- Adindan cross section has also piezometer pairs at both its ends. To the west these boreholes are about 5 kms from the lake shore at top-water level and to the east about 3.5 kms. The western deep hole is screened below SSL-30 whilst the eastern one is screened below SSL+30. Figure 8 shows that in the early years after impoundment upwards vertical gradients developed at both ends of this cross section. In the west the maximum head difference of about 5 m occured in the early years, this subsequently diminished over the next 10 years and by the end of 1979 a downwards gradient had developed with a vertical head difference of about 2 m. The shallow piezometer at the eastern end of this cross section did not start to rise until 7 years after the initiation of impoundment - that is until the shore line had expanded to within 4 kms of the boreholes. By then the response in the deep hole had resulted in an upwards vertical gradient showing a head difference of about 20 m. After the level in the shallow well started to rise this gradient gradually decreased untill by the end of 1977 - 14 years after the start of reservoir filling - it had been reduced to zero. In the intervening period the shallow piezometer has continued to respond faster than the deeper one and the gradient in the vertical has thus been reversed. By the end of 1979 a downwards net head difference of 10 m. had been established at this site.

3.07 Although data are limited for piezometers remote from the reservoir, it is apparent that there has been no marked change in water levels in areas that are more than, say, 15 kms from the maximum extent of the shore line of Lake Nasser at top-water level.

Simulation of Theoretical Response for a Typical Cross-Section

3.08 Analytical studies of the transient behaviour of groundwater systems subject to laterally extensive recharge have been described in some detail by Bouwer, Reference 9. In general, all such systems have the following similar characteristics :

- in the portion of the aquifer directly below the recharge area the piezometry is dominated at the start by the downwards vertical gradients which must be generated to move water from the recharge source into the aquifer;
- adjacent to the edge of the recharge area the piezometry develops the marked horizontal gradients required to drive water laterally into the main body of the aquifer;

- further out from the edge of the recharge source, upwards vertical gradients develop which serve to feed flow to the rising water table where increases in storage are taking place;
- remote from the recharge source the strength of this upwards vertical gradient gradually diminishes and flow in the aquifer becomes essentially horizontal.

The relative importance of vertical gradients in each of these regions changes through time. If the lateral dimensions of the recharge area are large in comparison to the thickness of the aquifer, then the vertical gradients below it will quickly stabilize. And, after the rapid initial water table rise phase in the aquifer adjacent to the recharge source is over, horizontal flow starts to dominate in this region. In more distant areas marked upwards vertical gradients persist for a longer period of time. Although the region near to the recharge source gives the appearance of adopting a new pseudo steady state piezometric configuration relatively quickly, it takes a very long time indeed for the whole flow domain to move to a new stability.

3.09 Description of the Model. The recharge mound resulting from the creation of the High Dam reservoir is clearly the response of a complex three dimensional groundwater flow system. Nevertheless it was apparent that useful insights into this phenomenon could be obtained by analysing the theoretical behaviour of a typical aquifer cross-section. To this end, a digital simulation model was developed on the Project's HP 45 'desktop' computer for a cross-section having the physical characteristics described below. The 'Integrated Finite Difference Method' (IFDM) of analysing fluid flow in porous media - see Narasimihan and Witherspoon, Reference 10 -

was used for this study. A copy of the BASIC language program code is deposited on the Project's files.

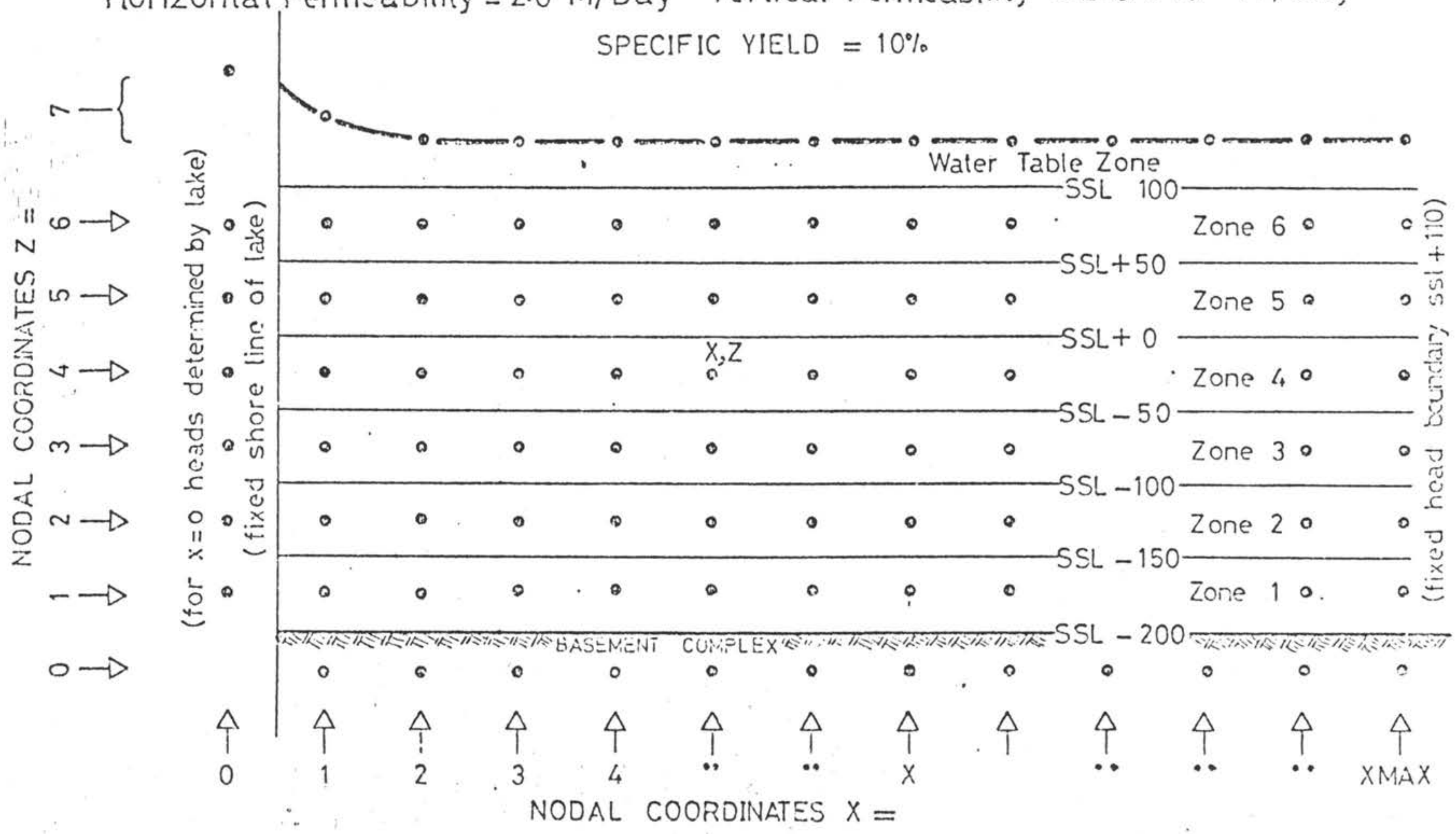
3.10 For modelling purposes, no attempt was made to simulate the advance through time of the lateral extent of the shore line as levels in the reservoir rise. This refinement could be added to the model, but it would substantially increase the Program's complexity. Moreover, the various portions of Lake Nasser are sufficiently different in this regard to preclude rational typicalization. The model, therefor, assumes a fixed location for the lateral limit of the recharge area, ie a fixed shore line for the lake. Given the relative width of the lake when compared to the thickness of the aquifer - which ranges from 30:1 to 100:1 - it is also reasonable to assume for the lake-ward boundary condition that head levels in the aquifer beneath the lake are constant in the vertical and equal to the standing water elevation in the reservoir. Trial calculations demonstrated that these, admitedly gross, simplifications of the lake-ward boundary condition have little influence on the simulated response in the longer term for locations which are two or more kilometers from the top-water shore line.

3.11 From consideration of the aquifer characteristics as described in Section II, the cross-section to be simulated was defined as shown by Figure 10. Though the developed computer program does allow the hydrogeological parameters of the model to be varied with depth, it was considered that the available information did not justify such a refinement and average values were adopted. The horizontal permeability was taken as 2 m/day; vertical permeability as 2.0×10^{-3} m/day; and specific yield as 10%, on the basis of the conclusions of Paragraphs 2.22 through 2.29.

DEFINITION OF IFDM NODAL NETWORK & BOUNDARY CONDITIONS

Horizontal Permeability = 2.0 M/Day Vertical Permeability = 2.0×10^{-3} M/Day

SPECIFIC YIELD = 10%



MASTER PLAN FOR WATER DEVELOPMENT & USE STUDY OF SEEPAGE LOSS FROM LAKE NASSER	MODEL OF TYPICAL CROSS SECTION	FIGURE 10

3.12 A rectangular elemental sub-division of the aquifer was used to construct the IFDM nodal network as indicated in Figure 10, with the vertical dimension being divided into seven horizontal zones. The developed code enables inter-nodal distances to be varied and this facility was employed to subdivide the horizontal dimension into fifteen 'delta x's' which increased with distance from the lake shore. Initial conditions - ie pre-High Dam - were obtained by running the model to steady state with a water level of SSL+120 impressed on the lake-ward boundary nodes and a fixed head boundary condition of SSL+110 200 kms away from the edge of the recharge source. The distribution of heads generated by this steady state run, as well as those for selected time - points in the transient simulation are given in Annex 1.

3.13 The transient simulation performed for this study consisted of impressing the recorded rise in Lake Nasser levels on the model using yearly time steps from end–1964 through end–1979. The future was projected on the assumption that average water levels in the reservoir would remain at SSL+175. Thus, if anything , this forecast will tend to over estimate the long term response of the regional groundwater system to losses from the reservoir. The projection was run out to the time point representing 100 years after impoundment using progressively increasing lengths of time step. Full details of the results obtained are given in the tabular printouts of Annex 1, while Figure 11 shows a hydrograph of the response of both the water table and the piezometry at depth, for various distances away from the edge of the laterally fixed shore line.

3.14 Comparison of Observed & Simulated Piezometric Response. When comparing the observed response of the paired deep and shallow piezometers discussed in Paragraph 3.06 and the simulated response shown in Figure 11 due allowance must, of course, be made for the influence on the former of the expansion in shore line with increasing contents of the reservoir. This phenomenon is responsible for the relative slowness in the response in early years of the shallow boreholes at the remote ends of the Garf Hussein and Adindan cross sections which exhibited little change untill the shore line approached within 3 to 4 kms. Examination of the observed and simulated piezometric fluctuations suggests the following observations :

- the model realistically simulates the response observed in the piezometer pair at the western end of the Garf Hussein cross-section. It confirms that vertical flow phenomenon can indeed explain the development of the 20 meter head difference between shallow and deep piezometers that has been observed at this site;
- when allowance is made for both the effects of lateral expansion of the shore line on the free water table and the relatively shallow setting of the screens in the deep borehole, the model results are in keeping with the response observed in the western piezometer pair of the Toshka cross-section;
- on first sight the observed response of the eastern piezometer pair on the Toshka cross-section might seem to be at variance with the model results. However prior to its submergence this deep borehole was clearly in the aquifer region where the piezometry is dominated by the downwards vertical gradients which must be generated to move water from the recharge source into the aquifer as discussed in Paragraph 3.08. As noted above, this region was not incorporated into the model. Nevertheless, trial calculations made with the program have demonstrated that downwards head differences of the order of

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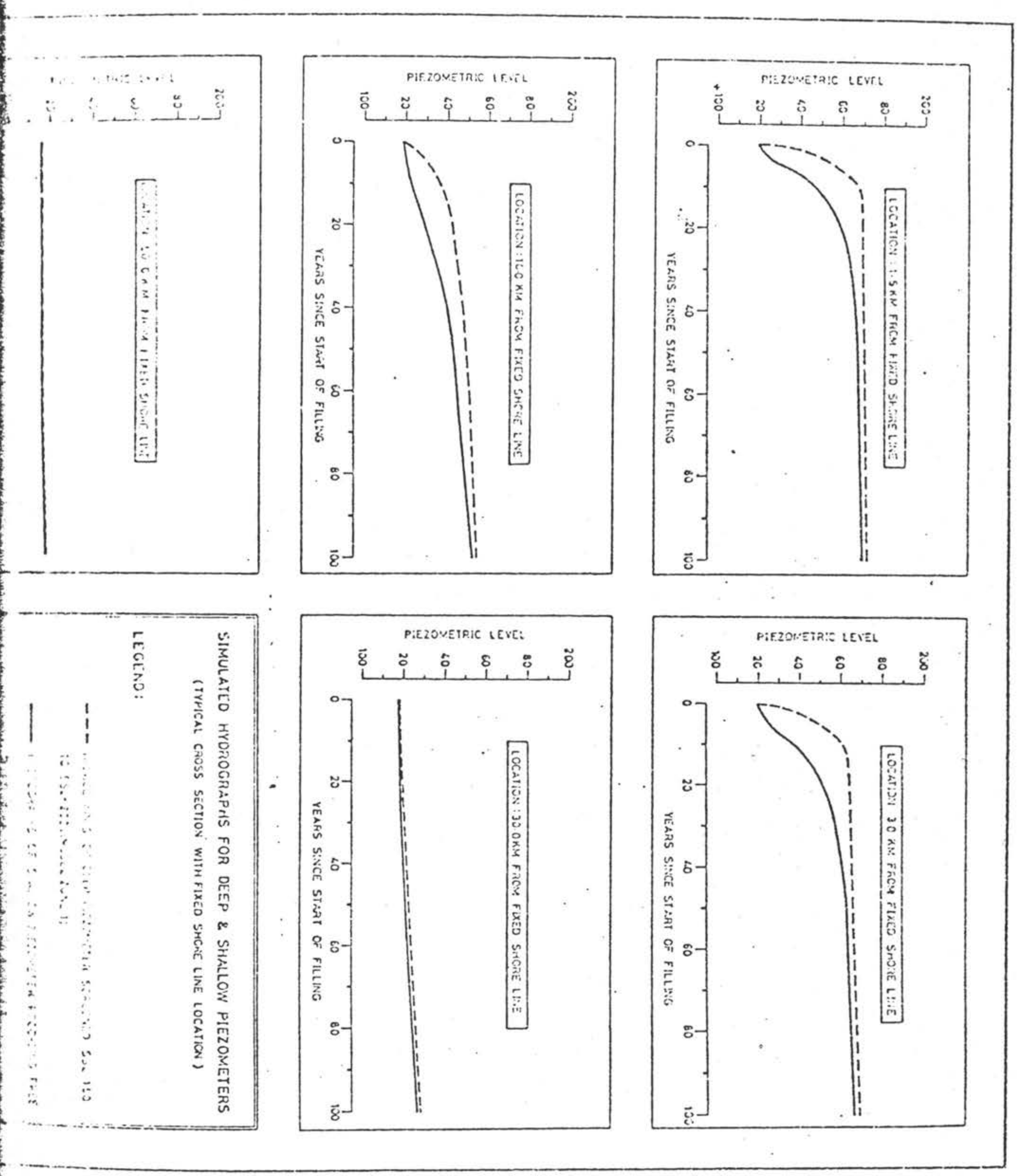

SIMULATED HYDROGRAPHS FOR DEEP & SHALLOW PIEZOMETERS
(TYPICAL CROSS SECTION WITH FIXED SHORE LINE LOCATION)

30 meters would develop beneath the reservoir in the early years after impoundment;

- the growth and then decay of the upwards vertical gradient observed in the response of the piezometer pairs at both ends of the Adindan cross-section are in accord with the model results. The marked reversal of this gradient in later years in the eastern pair no doubt arose from a combination of the effects of the relatively high proportion of clay in the originally saturated section (about 50%) and the shallowness of the basement rocks. Taken together these properties represent a significant departure from the characteristics of the typical cross-section adopted for the model;
- the simulation results are in accordance with the observation that sites remote from the shore line have, as yet, shown little or no response to reservoir filling.

In conclusion therefor, this simple model of a typical cross-section provides a rational explanation of the response of the groundwater system in the environs of Lake Nasser to impoundment of the reservoir.

3.15 Forecast of Long-term Water Level Changes. This conclusion suggests that the simulation model developed for a typical cross-section can be used to provide credible estimates of the likely magnitude of future water level changes in areas remote from the shore line of the reservoir. Paragraph 3.02 has described how the creation of Lake Nasser resulted in the division of the original regional groundwater body into three, more or less distinct, sub-systems as evidenced by the late 1970's piezometry of Figure 9.

Consideration of these subsystems and the simulated response hydrographs given in Figure 11 demonstrates that due account must be given to the very long time required for significant water level changes to be experienced either within the newly established closed groundwater sub-systems or downstream of the Wadi Kurkur subsurface outflow face. After 100 years the water table at the eastern limit of south-eastern triangular shaped closed basin will have changed by less than 1 meter. Whilst on the boundary of the south west-north east rectangular closed basin the change will be of the order of 4 meters. In the convergence zone to the west and north of Aswan, head changes of less than 10 meters are foreseen after 100 years.

3.16 Technical Report N° 2 of the FAO 'Lake Nasser Development Centre Project' (Reference 11) describes some preliminary regional groundwater model studies which were made to evaluate the effect of Lake Nasser on the surrounding groundwater reservoir. Very limited information were available for those trial studies which treated the aquifer system as a single layer with pure horizontal flow. Though the results reported therein are only of qualitative interest, they do support the above conclusion concerning the long time required for significant water level changes in locations that are remote from the reservoir.

Losses to Groundwater from Lake Nasser.

3.17 As noted in Paragraph 2.30, it is generally accepted that prior to the construction of the Low Aswan Dam in 1902 the River Nile functioned as a drain for the regional groundwater body to the south of Aswan. Geoistrazivanja, Reference 1 estimated the loss to groundwater from the Low Dam reservoir in the early 1960's to be about $5x10^6 m^3$/year. Results obtained from the simulation of steady state pre-High Dam situation using the model of a typical cross-section as described above indicates an average loss condition of 20,000 m^3 per line kilometer of shore line in contact with the aquifer for a mean water level of SSL+120. Estimating the contact shore line at 210 kms in the west and 230 kms in the east, yields an annual loss to groundwater from the Low Dam reservoir under steady state conditions of about $9 \times 10^6 m^3$/year. It is likely that the loss to groundwater in the years prior to the construction of the High Dam was somewhere between the above two estimates.

3.18 <u>Losses Since Impoundment</u>. Two approaches have been employed to estimate losses to groundwater from Lake Nasser during the period since impoundment. The first relies essentially on running a water balance for the reservoir, whilst the second is based on change in storage estimates derived from records of the groundwater level response observed on the piezometric cross-sections. Results obtained from the simulation model described above provide additional control on these estimates for years after the lateral extent of the lake had more or less stabilized at top-water level.

3.19 Technical Report 14 edited by Todini and O'Connell (Reference 7) describes the development by the Water Master Plan Project of a simulation model of the High Dam reservoir. Most reservoir simulation studies are undertaken at the design stage and must, therefor, be based on many assumptions particularly with regard to their various loss components. The High Dam reservoir, however, has now been in operation for more than fifteen years and detailed records were kept of its behaviour. This reservoir simulation model could thus be calibrated by feeding it with historic data on inflows and releases and comparing the computed and observed response of reservoir levels on a monthly basis.

The iterative approach used to finalize calibration of this model is fully described in Technical Report 14 (op. cit). The high measure of agreement obtained between the recorded and simulated fluctuations in reservoir contents is particularly noteworthy. The model was calibrated using data of January 1968 through December 1977 and the resulting estimates of the net annual loss to groundwater during this period are given in the final column of Table 1.

3.20 As noted above, detailed records are available of water level changes on four piezometric cross-sections since impoundment. These data were used to estimate the annual change in the cross-sectional area of saturated aquifer on each of these lines. By way of demonstration, Annex II shows the graphical computation of these changes for the Toshka cross-section. Similar computations are deposited on Project files for the other sections. Mean changes in saturated aquifer were computed for both eastern and western sides of the lake using this data and the line lengths of aquifer subject to these changes were estimated in accordance with the progressive rise in lake levels. The resulting change in storage was derived by applying a specific yield of 10% to the estimated change in volume of saturated aquifer. The results of this computation are summarized in Table 1. This also shows a breakdown of the proportion of the storage change term that occurs directly under areas submerged by expansion of the lateral extent of the lake in each year.

3.21 As Table 1 lists the estimates of losses from Lake Nasser to groundwater obtained by both the approaches described above, these results can be compared. In principal such a comparison requires that an additional allowance

Year	Mean Lake Level	Mean Change in Area of Cross - Section (m^2)	Saturated	Inferred Length of Nubian Contact (km)		Computed Change in G.W. Storage Total ($10^9 m^3$)	Computed Change in G.W. Storage Percent beneath Submerged Portion	Simulated Loss to G. Water * ($10^9 m^3$)
		West	East	West	East			
1965	126.3	7325	11513	331	313	0.6	40	-
1966	131.9	13815	21387	336	336	1.2	66	-
1967	142.9	32425	33733	345	377	2.4	75	-
1968	151.1	18125	41433	357	408	2.3	78	3.09
1969	156.2	20875	30533	383	426	2.1	82	2.90
1970	159.8	24950	13667	403	442	1.6	46	3.02
1971	164.1	28650	10867	424	457	1.7	79	4.13
1972	165.2	12450	4867	428	461	0.8	32	2.77
1973	162.9	9400	5733	414	452	0.6	14	2.12
1974	165.8	15300	21033	432	464	1.6	60	2.87
1975	170.4	20550	16567	455	480	1.7	65	5.15
1976	174.8	22875	15533	478	496	1.9	45	1.98
1977	174.9	17225	16467	478	496	1.6	20	1.71

* Results obtained via calibration of Hydrological model as described in Technical Report 14, Reference 7.

for the regional throughflow to the aquifer be added to the estimate based on incremental groundwater level changes. This will have changed little since pre High Dam conditions and from the conclusions presented in Paragraph 3.17 can be taken to be of the order of $10^7 m^3$/year. Hence it is of little importance relative to the scale of the losses which have gone to make up net additions to groundwater storage in the vicinity of the lake since impoundment. Comparison of these estimates shows good agreement in the early and later years with consistent under estimation by the incremental groundwater level change approach in the middle years when the size of the submerged area was increasing rapidly. The fact that both methods close to give agreement in later years tends to confirm that the assumed value of 10% for specific yield is reasonable. It is, therefor, rational to conclude that the procedure of averaging the change in volume of saturated aquifer on the four cross-sections has resulted in an under estimation of the total change in groundwater storage during the period when the area of the lake was changing rapidly. This is obviously quite possible when it is recalled that the results obtained from these four cross-sections had to be extrapolated over a total reservoir length of upwards of 500 km. Moreover, it has been reported that the lake has a high ratio of shoreline to surface area. The dendritic shape of the submerged khors results in a change of total shore line length of from around 5,000 km at reservoir elevations around SSL+160 to about 8,000 km at top-water level. No allowance for such effects were made in the storage change method of estimation. In conclusion, therefor, it would seem rational to accept the results obtained from the reservoir simulation studies as the best estimates of losses to groundwater in the first half of the 1970's.

3.22 The model of a typical cross-section of the aquifer described in Paragraph 3.01 also enables an estimate to be made for losses to groundwater from the reservoir. As explained, this model assumes a fixed shore line so such estimates are only valid once the reservoir level has stabilized. When due allowance is made for this constraint the model predicts a loss of $1.88\times10^6 m^3$ per km per year for 1976 and $1.80\times10^6 m^3$ per km per year for 1977. Accepting a total (smoothed) contact line with the aquifer - both east and west - of 974 km yields estimates of the total loss from the lake of $1.83\times10^9 m^3$ in 1976 and $1.76\times10^9 m^3$ in 1977. It is noteworthy that these estimates are in close agreement with those obtained by both the methods described above for these years - see Table 1.

3.23 Forecast of Long-term Losses. In view of the good agreement between the various estimates of losses from the reservoir to groundwater under stabilized top-water level conditions,it is rational to use results obtained from the model of a typical cross-section to derive estimates of these losses in the longer term. As noted in Paragraph 3.15 the model was used to provide a forecast of the response of a typical cross-section to holding the mean level in the reservoir at SSL+175. This forecast was run-out to the time-point of 100 years after the start of impoundment. Although there will be a tendency to over estimate losses as rather large fluctuations in reservoir level are anticipated in the future, corresponding changes in the lateral extent of the lake will mitigate against this effect introducing a large biase. The results inferred from these computations are summarized below :

Year	Annual Loss to Groundwater	
	Cross-Section ($10^6 m^3$/km)	Total ($10^9 m^3$)
1980	i.6	1.6
1985	1.5	1.5
1995	1.2	1.2
2015	0.9	0.9
2065	0.7	0.7

(Assumes effective flow-front of 974 km.

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ANNEX ONE

Simulated Two Dimensional Piezometric Response for Typical Cross-Section

(Sample Print-outs)

Pre-Impoundment Steady State Piezometry for nodal points of typical cross-section, as defined by Figure 10.

YEARS SINCE START 0.0 RES LEVEL 120.0 LOSS RATE 18190.9 m^3/Km/Year

VERT.ZONE	ONE	TWO	THREE	FOUR	FIVE	SIX	W.TABLE
Kms .5>	120.0	120.0	120.0	120.0	120.0	120.0	120.0
Kms 1.5>	119.9	119.9	119.9	119.9	119.9	119.9	119.9
Kms 3.0>	119.8	119.8	119.8	119.8	119.8	119.8	119.8
Kms 5.0>	119.6	119.6	119.6	119.6	119.6	119.6	119.6
Kms 7.5>	119.4	119.4	119.4	119.4	119.4	119.4	119.4
Kms 10.0>	119.2	119.2	119.2	119.2	119.2	119.1	119.2
Kms 15.0>	118.8	118.8	118.8	118.8	118.8	118.8	118.8
Kms 20.0>	118.3	118.3	118.3	118.3	118.3	118.3	118.3
Kms 30.0>	117.5	117.5	117.5	117.6	117.6	117.6	117.6
Kms 40.0>	116.7	116.7	116.7	116.7	116.7	116.7	116.7
Kms 50.0>	116.0	116.0	116.0	116.0	116.0	115.9	115.9
Kms 75.0>	114.3	114.3	114.3	114.3	114.3	114.3	114.3
Kms100.0>	112.8	112.8	112.8	112.8	112.8	112.8	112.8
Kms150.0>	111.0	111.0	111.0	111.0	111.0	111.0	111.0

Key

- Years since Start : ie years since start of reservoir filling.
- Res Level : elevation + SSL of water in reservoir at end of current year.
- Loss Rate : Subsurface flow to typical cross-section (one side) from reservoir.
- Vert Zone : the seven sub-divisions of vertical of typical cross-section as defined in Figure 10.
- kms : kilometrage from fixed lake for which heads in vertical are given.

YEARS SINCE START 5.0 RES LEVEL 162.0 LOSS RATE 1964529.7 m^3/Km/Year

VERT.ZONE	ONE	TWO	THREE	FOUR	FIVE	SIX	W.TABLE
Kms .5>	160.1	160.0	159.8	159.4	158.5	154.9	143.5
Kms 1.5>	156.2	155.9	155.3	154.2	152.3	148.8	133.1
Kms 3.0>	150.6	150.1	149.0	147.2	144.0	138.7	126.7
Kms 5.0>	143.8	143.2	141.8	139.5	136.0	130.7	123.4
Kms 7.5>	136.8	136.2	134.8	132.7	129.8	125.9	121.6
Kms 10.0>	131.4	130.9	129.8	128.1	125.9	123.1	120.5
Kms 15.0>	124.8	124.5	123.9	123.0	122.0	120.7	119.4
Kms 20.0>	121.1	121.0	120.7	120.3	119.8	119.2	118.6
Kms 30.0>	118.3	118.2	118.2	118.1	117.9	117.8	117.6
Kms 40.0>	116.9	116.9	116.9	116.9	116.8	116.8	116.8
Kms 50.0>	116.0	116.0	116.0	116.0	116.0	116.0	115.9
Kms 75.0>	114.3	114.3	114.3	114.3	114.3	114.3	114.3
Kms100.0>	112.9	112.9	112.9	112.9	112.9	112.8	112.8
Kms150.0>	111.0	111.0	111.0	111.0	111.0	111.0	111.0

YEARS SINCE START 10.0 RES LEVEL 175.0 LOSS RATE 2070552.9 m^3/Km/Year

VERT.ZONE	ONE	TWO	THREE	FOUR	FIVE	SIX	W.TABLE
Kms .5>	172.7	172.6	172.4	172.1	171.3	167.5	157.9
Kms 1.5>	168.1	167.8	167.3	166.3	164.7	162.0	148.2
Kms 3.0>	161.4	160.9	160.0	158.3	155.6	151.5	137.9
Kms 5.0>	153.1	152.5	151.1	148.9	145.5	140.4	130.5
Kms 7.5>	144.3	143.6	142.1	139.8	136.6	132.1	125.9
Kms 10.0>	137.2	136.6	135.3	133.3	130.5	126.9	123.2
Kms 15.0>	128.1	127.7	126.9	125.8	124.3	122.6	120.8
Kms 20.0>	122.9	122.7	122.3	121.7	120.9	120.0	119.2
Kms 30.0>	118.8	118.7	118.6	118.5	118.3	118.0	117.8
Kms 40.0>	117.1	117.1	117.0	117.0	116.9	116.9	116.8
Kms 50.0>	116.0	116.0	116.0	116.0	116.0	116.0	116.0
Kms 75.0>	114.3	114.3	114.3	114.3	114.3	114.3	114.3
Kms100.0>	112.9	112.9	112.9	112.9	112.9	112.9	112.8
Kms150.0>	111.0	111.0	111.0	111.0	111.0	111.0	111.0

Year

W.TABLE
143.5
133.1
126.7
123.4
121.6
120.5
119.4
118.6
117.6
116.8
115.9
114.3
112.8
111.0

/Year

W.TABLE
157.9
148.2
137.9
130.5
125.9
123.2
120.8
119.2
117.8
116.8
116.0
114.3
112.8
111.0

YEARS SINCE START 15.0 RES LEVEL 175.0 LOSS RATE 1002932.2 m^3/Km/Year

VERT.ZONE	ONE	TWO	THREE	FOUR	FIVE	SIX	W.TABLE
Kms .5>	172.9	172.9	172.7	172.5	171.9	168.9	162.9
Kms 1.5>	168.8	168.6	168.2	167.5	166.4	164.6	155.5
Kms 3.0>	162.7	162.3	161.6	160.4	158.6	156.1	146.0
Kms 5.0>	155.0	154.5	153.5	151.9	149.4	145.9	137.2
Kms 7.5>	146.6	146.0	144.8	143.0	140.3	136.7	130.6
Kms 10.0>	139.6	139.0	137.9	136.1	133.5	130.1	126.2
Kms 15.0>	130.0	129.6	128.8	127.7	126.3	124.5	122.4
Kms 20.0>	124.1	123.9	123.5	122.8	122.0	121.0	120.0
Kms 30.0>	119.3	119.2	119.1	118.9	118.6	118.3	118.1
Kms 40.0>	117.2	117.2	117.2	117.1	117.0	117.0	116.9
Kms 50.0>	116.1	116.1	116.1	116.1	116.0	116.0	116.0
Kms 75.0>	114.3	114.3	114.3	114.3	114.3	114.3	114.3
Kms100.0>	112.9	112.9	112.9	112.9	112.9	112.9	112.9
Kms150.0>	111.1	111.1	111.1	111.0	111.0	111.0	111.0

YEARS SINCE START 20.0 RES LEVEL 175.0 LOSS RATE 1444427.7 m^3/Km/Year

VERT.ZONE	ONE	TWO	THREE	FOUR	FIVE	SIX	W.TABLE
Kms .5>	173.1	173.0	172.9	172.8	172.3	169.9	165.5
Kms 1.5>	169.3	169.1	168.8	168.4	167.5	166.2	159.8
Kms 3.0>	163.7	163.4	162.9	162.0	160.7	159.0	151.5
Kms 5.0>	156.5	156.2	155.4	154.1	152.3	149.8	142.5
Kms 7.5>	148.5	148.0	147.1	145.5	143.4	140.6	134.8
Kms 10.0>	141.6	141.1	140.1	138.5	136.2	133.1	129.2
Kms 15.0>	131.7	131.3	130.6	129.6	128.2	126.5	124.2
Kms 20.0>	125.4	125.1	124.7	124.0	123.1	122.0	120.9
Kms 30.0>	119.8	119.7	119.6	119.3	119.0	118.7	118.4
Kms 40.0>	117.4	117.4	117.4	117.3	117.2	117.1	117.0
Kms 50.0>	116.1	116.1	116.1	116.1	116.1	116.0	116.0
Kms 75.0>	114.4	114.4	114.4	114.4	114.3	114.3	114.3
Kms100.0>	112.9	112.9	112.9	112.9	112.9	112.9	112.9
Kms150.0>	111.1	111.1	111.1	111.1	111.0	111.0	111.0

YEARS SINCE START 30.0 RES LEVEL 175.0 LOSS RATE [illegible] m^3/Km/Year

VERT.ZONE	ONE	TWO	THREE	FOUR	FIVE	SIX	H.TABLE
Kms .5>	173.3	173.3	173.2	173.1	172.8	170.9	168.1
Kms 1.5>	170.0	169.9	169.7	169.4	168.9	168.0	163.9
Kms 3.0>	165.0	164.8	164.5	164.0	163.2	162.3	157.6
Kms 5.0>	158.6	158.4	157.9	157.1	156.0	154.5	149.5
Kms 7.5>	151.3	150.9	150.3	149.2	147.8	146.0	141.3
Kms 10.0>	144.7	144.4	143.6	142.4	140.6	138.0	134.6
Kms 15.0>	134.6	134.3	133.7	132.8	131.6	130.2	127.8
Kms 20.0>	127.6	127.4	126.9	126.3	125.3	124.2	122.9
Kms 30.0>	120.8	120.7	120.6	120.3	120.0	119.6	119.1
Kms 40.0>	117.8	117.8	117.7	117.6	117.5	117.4	117.2
Kms 50.0>	116.3	116.2	116.2	116.2	116.2	116.1	116.1
Kms 75.0>	114.4	114.4	114.4	114.4	114.4	114.4	114.4
Kms100.0>	112.9	112.9	112.9	112.9	112.9	112.9	112.9
Kms150.0>	111.1	111.1	111.1	111.1	111.1	111.1	111.0

YEARS SINCE START 50.0 RES LEVEL 175.0 LOSS RATE 924059.3 m^3/Km/Year

VERT.ZONE	ONE	TWO	THREE	FOUR	FIVE	SIX	H.TABLE
Kms .5>	173.6	173.6	173.5	173.5	173.3	171.9	170.2
Kms 1.5>	170.8	170.7	170.6	170.5	170.2	169.7	167.3
Kms 3.0>	166.6	166.5	166.3	166.1	165.7	165.3	162.8
Kms 5.0>	161.1	161.0	160.8	160.4	159.9	159.2	156.5
Kms 7.5>	154.7	154.6	154.2	153.6	152.9	152.0	149.0
Kms 10.0>	148.8	148.6	148.1	147.4	146.2	144.5	142.2
Kms 15.0>	139.0	138.8	138.4	137.8	137.0	136.1	133.9
Kms 20.0>	131.4	131.2	130.8	130.2	129.4	128.3	127.0
Kms 30.0>	122.9	122.8	122.6	122.4	122.0	121.6	121.0
Kms 40.0>	118.7	118.7	118.6	118.5	118.3	118.1	117.9
Kms 50.0>	116.5	116.5	116.5	116.5	116.4	116.4	116.3
Kms 75.0>	114.4	114.4	114.4	114.4	114.4	114.4	114.4
Kms100.0>	112.9	112.9	112.9	112.9	112.9	112.9	112.9
Kms150.0>	111.1	111.1	111.1	111.1	111.1	111.1	111.1

YEARS SINCE START 75.0 RES LEVEL 175.0 LOSS RATE 741614.4 m^3/Km/Year

VERT.ZONE	ONE	TWO	THREE	FOUR	FIVE	SIX	W.TABLE
Kms .5>	173.8	173.8	173.8	173.8	173.6	172.5	171.4
Kms 1.5>	171.5	171.4	171.4	171.3	171.1	170.8	169.2
Kms 3.0>	168.0	167.9	167.8	167.7	167.5	167.3	165.0
Kms 5.0>	163.4	163.3	163.2	163.0	162.7	162.4	160.8
Kms 7.5>	157.8	157.7	157.5	157.2	156.8	156.4	154.5
Kms 10.0>	152.6	152.5	152.2	151.7	150.9	149.8	148.3
Kms 15.0>	143.4	143.3	143.0	142.7	142.2	141.7	139.8
Kms 20.0>	135.7	135.6	135.2	134.7	134.0	133.0	131.8
Kms 30.0>	125.8	125.8	125.6	125.3	124.9	124.5	123.8
Kms 40.0>	120.2	120.2	120.1	119.9	119.7	119.5	119.2
Kms 50.0>	117.2	117.2	117.1	117.1	117.0	116.9	116.8
Kms 75.0>	114.5	114.5	114.5	114.5	114.5	114.5	114.5
Kms100.0>	113.0	112.9	112.9	112.9	112.9	112.9	112.9
Kms150.0>	111.1	111.1	111.1	111.1	111.1	111.1	111.1

YEARS SINCE START 100.0 RES LEVEL 175.0 LOSS RATE 682414.2 m^3/Km/Year

VERT.ZONE	ONE	TWO	THREE	FOUR	FIVE	SIX	W.TABLE
Kms .5>	173.8	173.9	173.9	173.8	173.7	172.8	171.9
Kms 1.5>	171.6	171.6	171.6	171.6	171.5	171.3	170.2
Kms 3.0>	168.3	168.3	168.3	168.3	168.3	168.2	167.3
Kms 5.0>	164.0	164.0	164.0	164.0	164.0	163.9	163.1
Kms 7.5>	158.8	158.8	158.8	158.7	158.6	158.6	157.6
Kms 10.0>	153.9	153.9	153.8	153.6	153.3	152.6	152.0
Kms 15.0>	145.1	145.1	145.1	145.1	145.0	144.9	143.7
Kms 20.0>	137.5	137.5	137.4	137.1	136.7	136.1	135.3
Kms 30.0>	127.2	127.2	127.1	127.0	126.9	126.6	126.1
Kms 40.0>	121.0	121.0	120.9	120.8	120.7	120.5	120.3
Kms 50.0>	117.5	117.5	117.5	117.4	117.4	117.3	117.2
Kms 75.0>	114.6	114.6	114.6	114.6	114.6	114.6	114.6
Kms100.0>	113.0	113.0	113.0	113.0	113.0	113.0	112.9
Kms150.0>	111.1	111.1	111.1	111.1	111.1	111.1	111.1

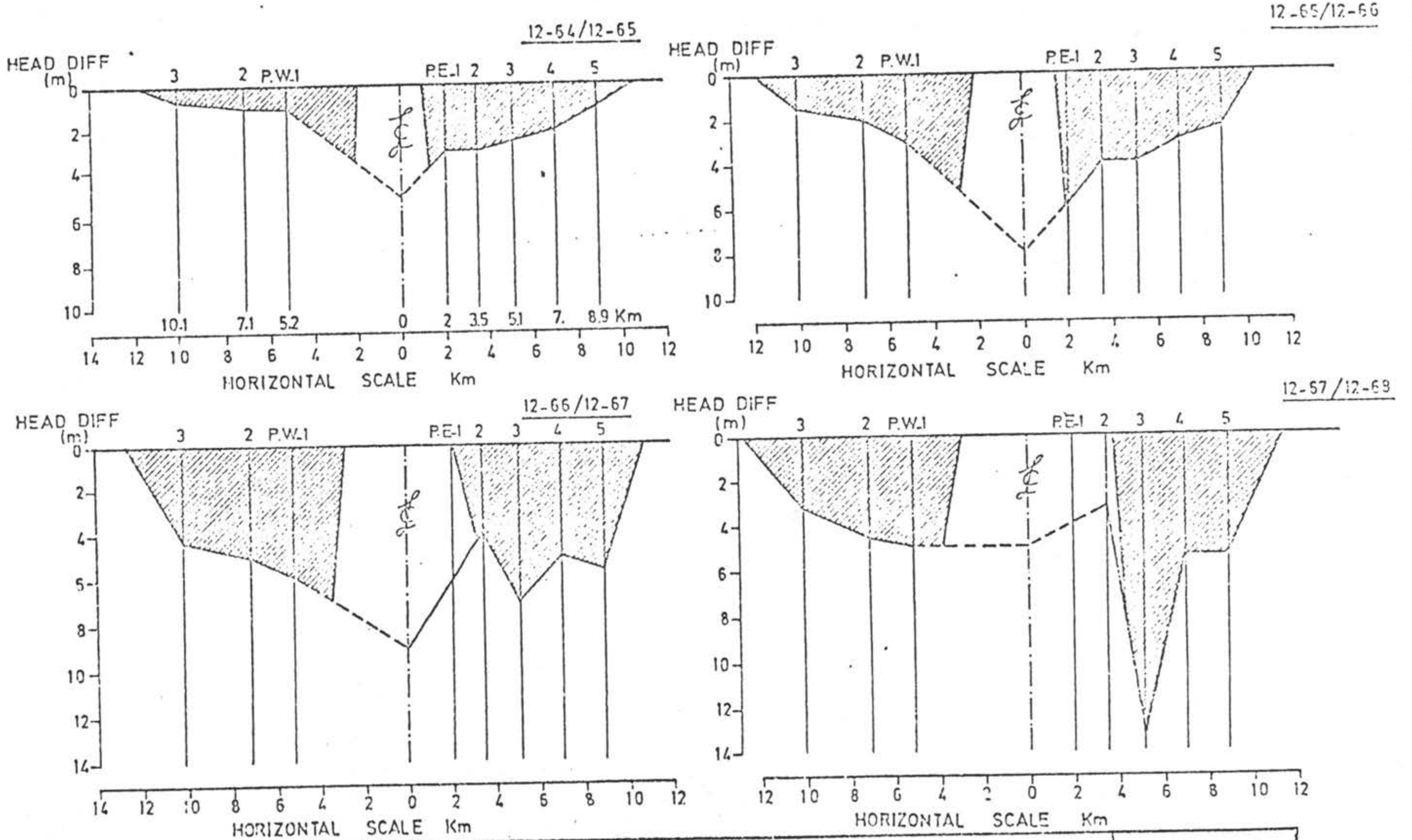
Year
W.TABLE
168.1
163.9
157.6
149.5
141.3
134.6
127.8
122.9
119.1
117.2
116.1
114.4
112.9
111.0

Year
W.TABLE
170.2
167.3
162.8
156.5
149.0
142.2
133.9
127.0
121.0
117.9
116.3
114.4
112.9
111.1

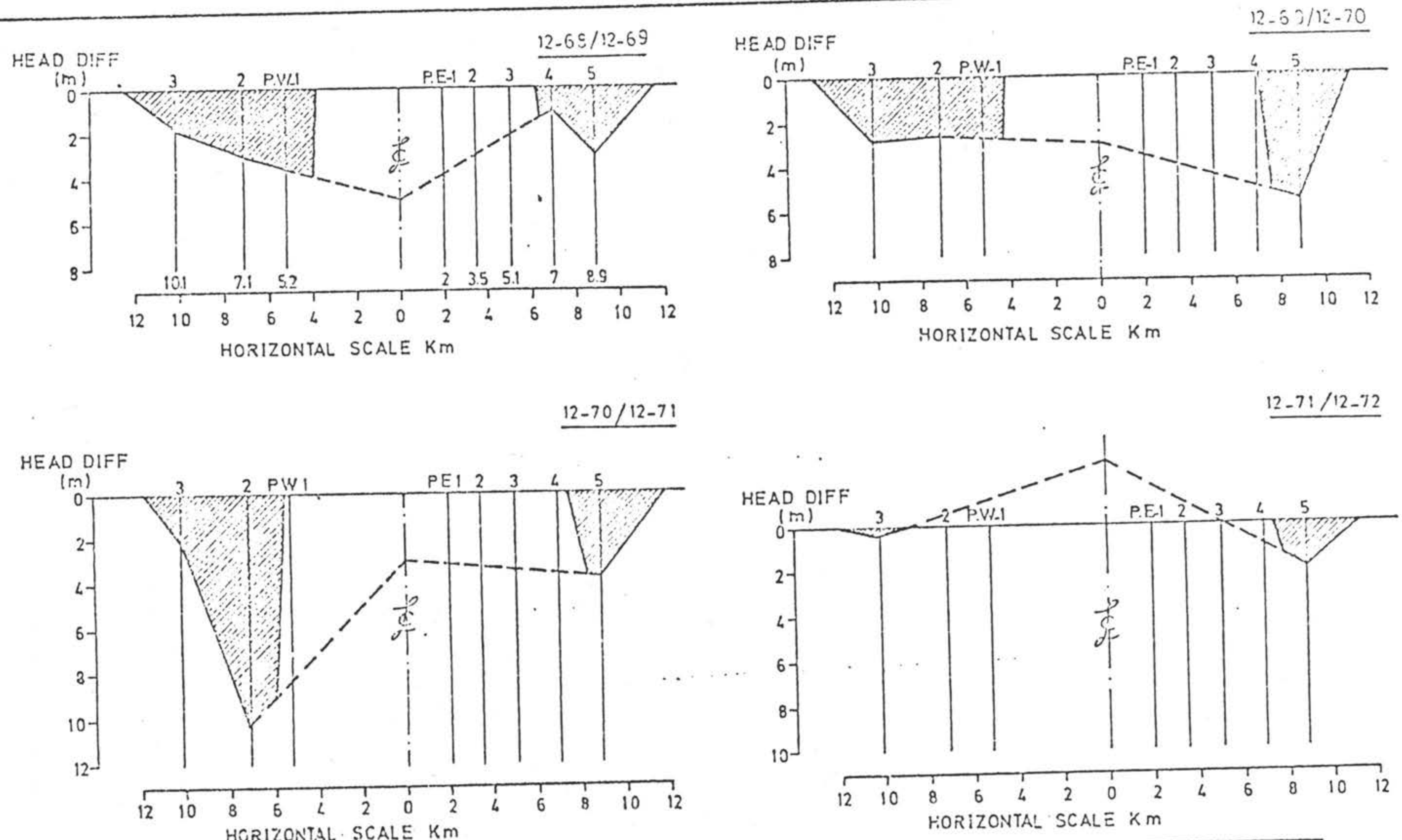
ANNEX TWO

Sample Graphical Computations of Annual Change in Volume of Saturated Aquifer

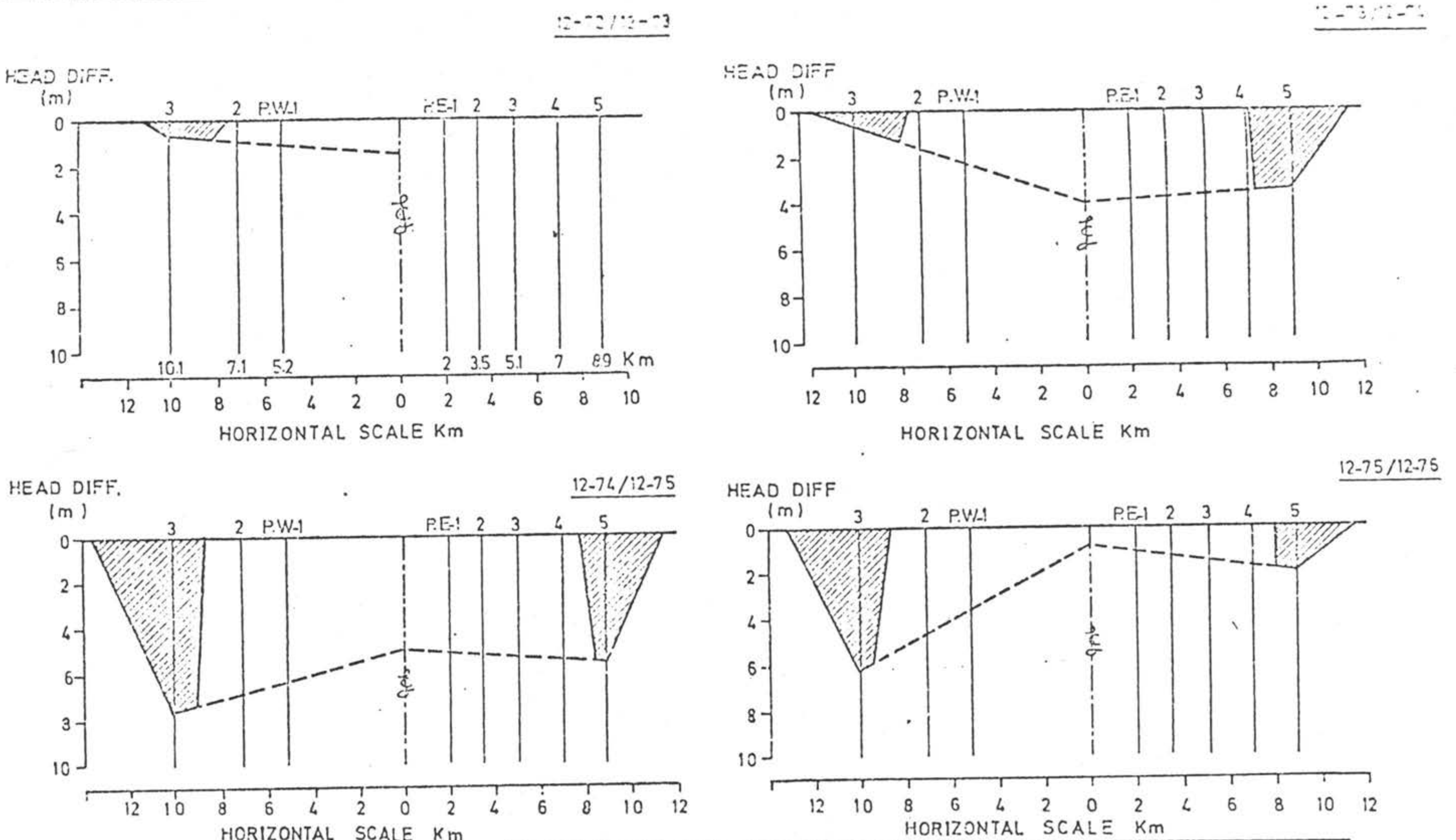
- Toshka Cross-Section, 1965 through 1979 -



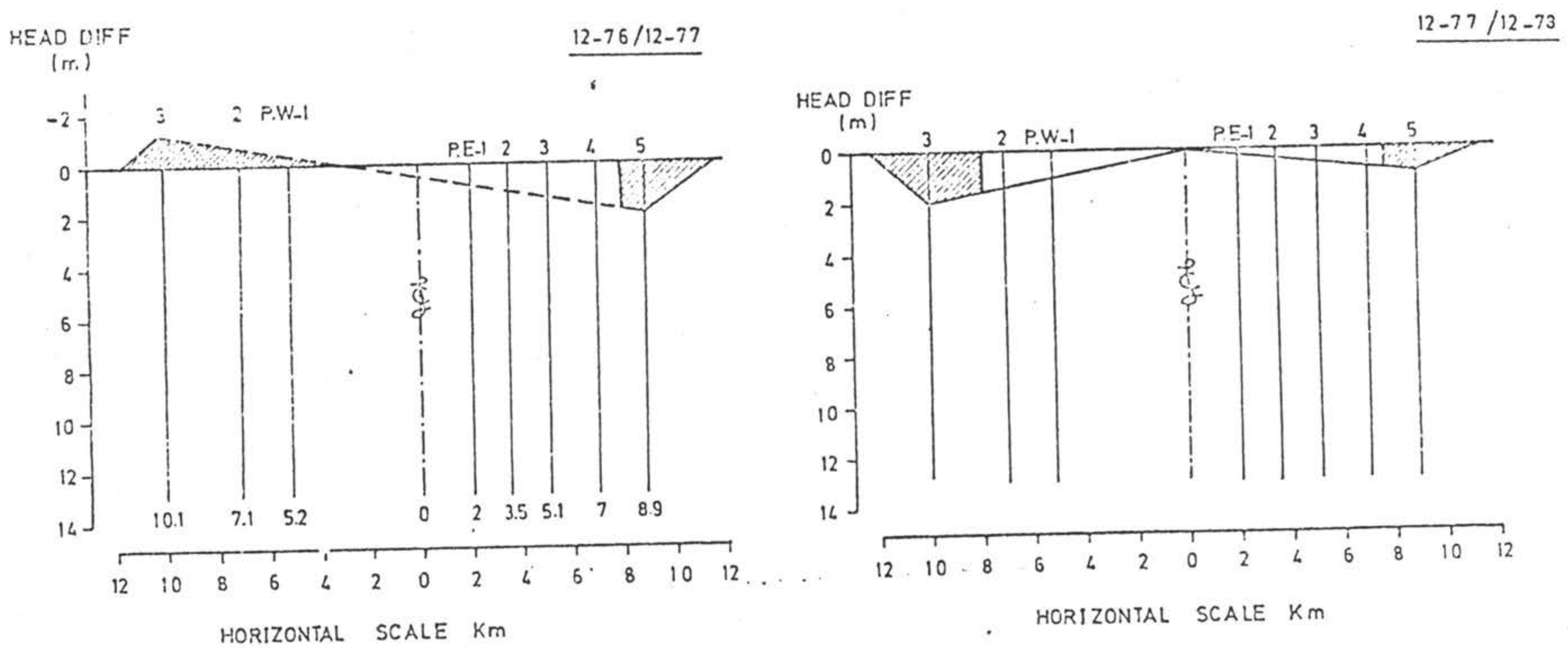
MASTER PLAN FOR WATER DEVELOPMENT & USE STUDY OF SEEPAGE LOSS FROM LAKE NASSER	CHANGE IN SATURATED AREA TOSHKA CROSS SECTION	ANNEX II FIGURE 1



MASTER PLAN FOR WATER DEVELOPMENT & USE STUDY OF SEEPAGE LOSS FROM LAKE NASSER	CHANGE IN SATURATED AREA TOSHKA CROSS SECTION	ANNEX II FIGURE 2



MASTER PLAN FOR WATER DEVELOPMENT & USE STUDY OF SEEPAGE LOSS FROM LAKE NASSER	CHANGE IN SATURATED AREA TOSHKA CROSS SECTION	ANNEX II FIGURE 3



MASTER PLAN FOR WATER DEVELOPMENT & USE STUDY OF SEEPAGE LOSS FROM LAKE NASSER	CHANGE IN SATURATED AREA TOSHKA CROSS SECTION	ANNEX II FIGURE 4