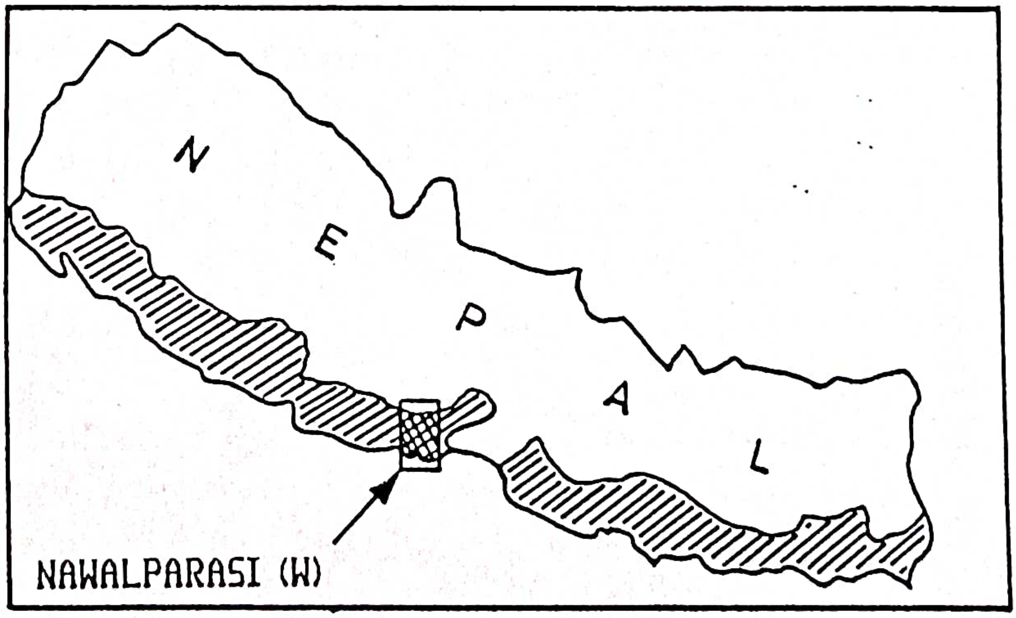
UNITED NATIONS DEVELOPMENT PROGRAMME
AND
HIS MAJESTY's GOVERNMENT OF NEPAL
NEP/86/025

SHALLOW GROUND WATER INVESTIGATIONS IN TERAI

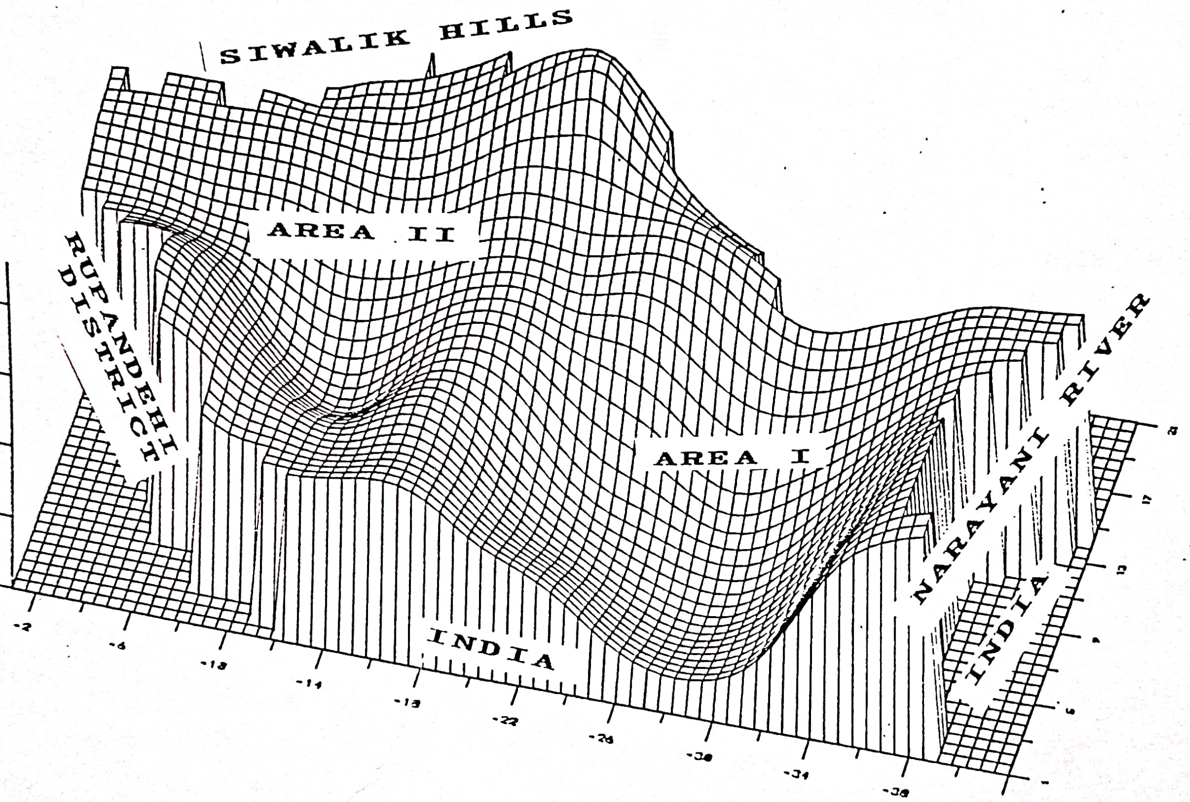
NAWALPARASI (WEST)

MATHEMATICAL MODEL
OF SHALLOW GROUND WATER SYSTEM

TECHNICAL REPORT NO. 6



KATHMANDU, MARCH 1989



NAWALPARASI MODEL - DECLINE OF WATER LEVELS AFTER 4-YEAR OF PUMPING

GWRDB-UNDP PROJECT NEP/86/025

SHALLOW GROUND WATER INVESTIGATIONS IN TERAI

TECHNICA L REPORT No. 6

NAWALPARASI DISTRICT (WEST)

MATHEMATICAL MODEL

OF SHALLOW GROUND WATER SYSTEM

Executing Agency: United Nations Department of Technical Co-operation for Development

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KATHMANDU, MARCH 1989

EXECUTIVE SUMMARY

The model of the shallow ground water system of the Nawalparasi (west) district was primarily made to arrive at a global water balance of the whole western part of the district and to indicate a maximum development potential for future intensive shallow ground water exploitation. In the process, all components of the system have been verified. The model also checked and verified the conclusions of a companion report recently released by the project NEP/86/025: "Nawalparasi District (West) - Shallow Wells Drilling, Testing and Monitoring in 1987/88. Basic Documentation and Preliminary Interpretation."

The modelling work reported herein confirmed the following typical one-year water balance. The recharge from rainfall which directly infiltrates into the subsurface in 1988/89 amounts to about 97 MCM (million cubic meters) per year. Considering the size of the active model of only 590 km^2, the average percentage of infiltrated rainfall in a typical year, in which about 1500 mm of rain falls, is about 11. The total input into the shallow ground water system is augmented by some 18 MCM of inflow from the hill sides. Out of 115 MCM, which may be a typical annual recharge, some 87 MCM are lost through the evaporation directly from water table where water levels come close to the land surface; additional 18 MCM outflows into India, and about 10 MCM could be feeding the Narayani River.

From this distribution of water one may easily conclude where are the sources of shallow ground water development in the future. The evaporation loss can be reduced, although not eliminated, by lowering the water levels to a depth that will prevent or diminish the losses. The outflow into the Narayani River can be reduced or reversed, by inducing the recharge from the river into the subsurface, by pumping from shallow wells located along a stretch parallel to the river. The favourable fact in this sense is in that the shallow aquifer near the Narayani is the most promising, having clean "lithology" and best transmissivity in the whole district. The unfavourable fact, from the standpoint of water resources management, is the existence of a surface irrigation system, the Gandak, which makes the use of shallow ground water superfluous. Actually, the area covered by the Gandak irrigation system could have been better "serviced" by shallow ground water irrigation.

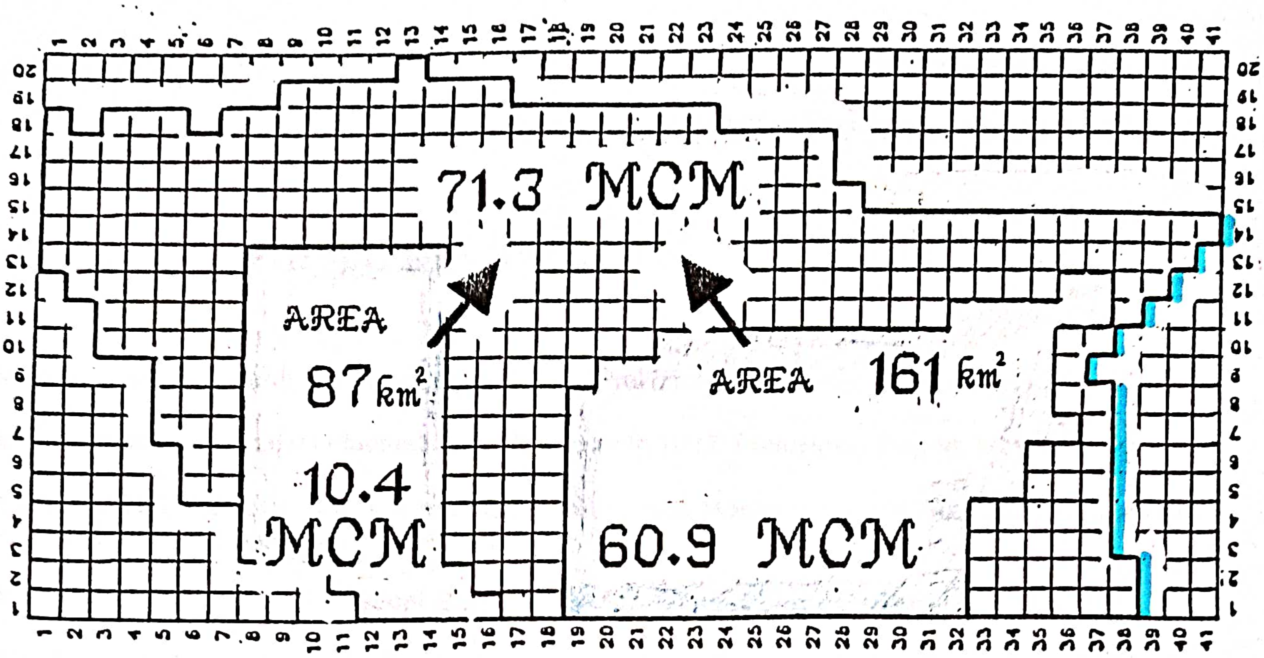
Both the Basic Documentation study (Technical Report No. 5) and this modelling work have clearly delineated the zone of good development potential, which is to the east of Parasi all the way to the Narayani River, excluding a 4-5 km stretch towards the hills. Thus, the east-southern one half of the district (its western part) is by far superior to the north-western one half.

After successful calibration and verification of the model on the basis of the past ground water levels record (water levels in about 20 points over one-year period), three hypothetical future development schemes have been tested. The ultimate development scheme included an area of 181 km^2 in the central-eastern part of the model, from which a maximum of 60 MCM could be produced annually without causing an adverse effect to the system, plus an area of some 87 km^2 to the west (around and near Parasi), which is much inferior for development but which still can augment the development for another 10 MCM *per season. Thus the total development potential of the shallow ground water system in Nawalparasi west may be close to 70 MCM per year. The declines of levels after the fourth year of simulation were at maximum about 6 m. What is more important is that the levels were approaching a steady or balanced state. This is illustrated with sketches shown here below, where the hydrograph traces implicate that the levels will not go deeper after the fourth year. The simulation in the scheme No. 3 (maximum development) showed that in the fourth year the pumping of some 70 MCM plus evaporation losses of 60 MCM are offset by cumulative recharge from direct rain infiltration and inflow from hilly sides of 115 MCM, plus induced recharge from the Narayani River of about 22 MCM. (This volume, equivalent to some 700 l/sec, is a very small percentage of the Narayani flow, which, in minimum, may carry 300 or more cubic meters per second.)*

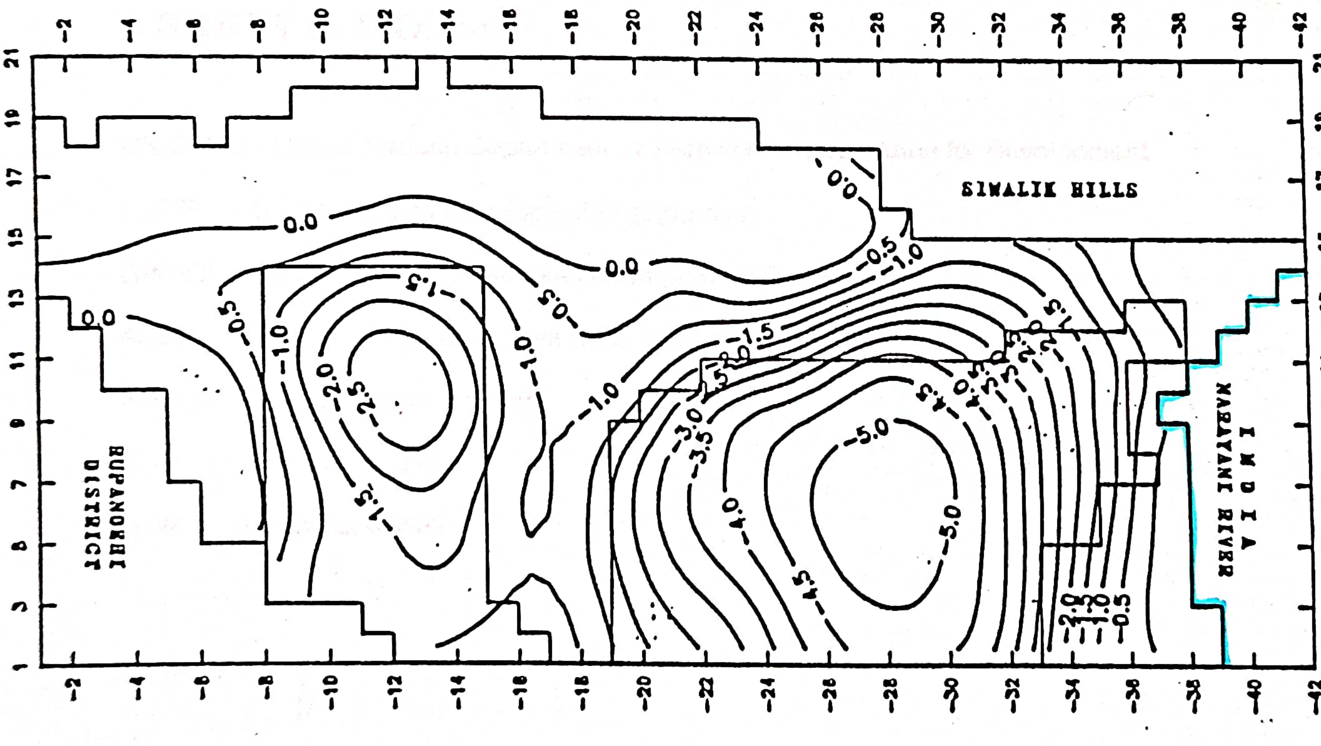
The model of the Nawalparasi (west) district is an example of modelling of shallow ground water system in the Terai. It offers a sound base for ADBN development plans. The conclusions formulated in the study are believed to be on the safe side. The indicated development potential of some 70 MCM per four-month pumping season implicates that between 5000 and 6000 STW's can be constructed over the pumping area of some 248 km2. The volume of water could be sufficient to satisfy the agricultural demand on an area of some 7,000 ha. The model and its conclusions can be improved by drilling several more shallow exploratory wells, and by conducting pumping tests in at least 50 of existing 200 plus shallow wells drilled in recent years.

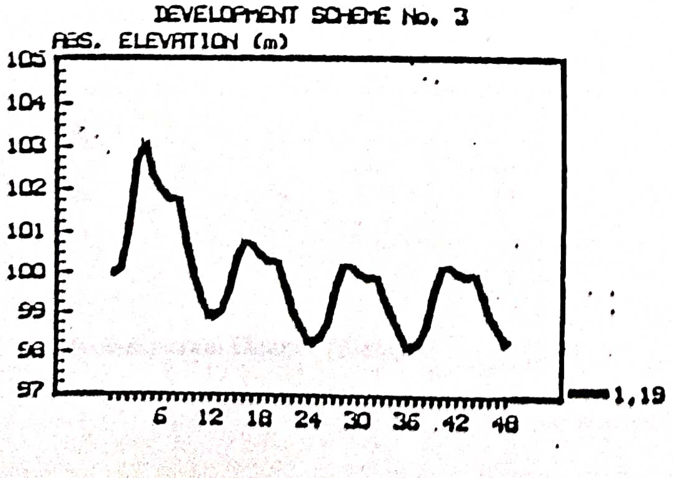
The results of this modelling study and conclusions of both technical reports Nos. 5 and 6 should be consulted prior to making decisions on new shallow well drilling program which is recently announced by His Majesty's Government. According to the planning, some sixty shallow tubewells shall-be drilled in Kapilvastu and Nawalparasi districts with loan assistance from the World Bank to imrove the irrigation facilities to farmers. The number of sixty wells is small compared to the overall shallow ground water development potential of either of districts, but a relative failure of wells, which may result if wells are not carefully located and constructed, may lead to wrong conclusions and discourage future shallow ground-water sustained irrigation.

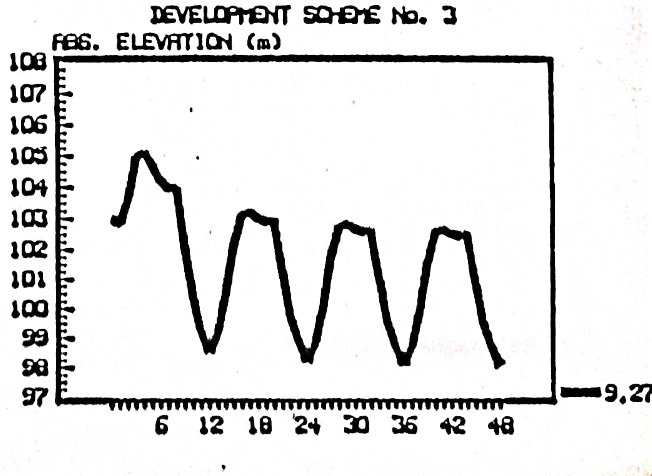
FUTURE DEVELOPMENT SCHEME No. 3: PROPOSED PUMPING AREAS



FUTURE DEVELOPMENT '3: DECLINE OF LEVELS AFTER 4 YEARS







GWRDB-UNDP NEP/86/025

SHALLOW GROUND WATER EXPLORATIONS IN TERAI

EARLIER TECHNICAL REPORTS:

1. Bhairawa-Lumbini Ground Water Irrigation System Preliminary Mathematical Modelling. May 1988

2. Shallow Ground Water Level Fluctuations in the Terai in 1987. Preliminary Report. May 1988

3. RAUTAHAT DISTRICT. Shallow Wells Drilling, Testing and Monitoring in 1987/88. Basic Documentation and Preliminary Interpretation. November 1988

4. RAUTAHAT DISTRICT. Mathematical Model of Shallow Ground Water System. December 1988.

5. NAWALPARASI (WEST) DISTRICT. Shallow Wells Drilling, Testing and Monitoring in 1987/88. Basic Documentation and Preliminary Interpretation. March 1989.

ABBREVIATIONS:

UN/DTCD - United Nations Department of Technical Co-operation for Development

UNDP - United Nations Development Programme

GWRDB - Ground Water Resources Development Board

ADBN - Agricultural Development Bank of Nepal

ADB - Asian Development Bank

STW - Shallow Tube Well

DTW - Deep Tube Well

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APPENDICES

1. INTRODUCTION

1.1. NEP/86/025 Project Document Details

The project NEP/86/025 - Shallow Ground Water Investigations in the Terai - is executed by the United Nations Department of Technical Co-operation for Development. It is designed as a four-year project primarily oriented to field-data collection, establishment of ground water data base, and to assessment of development potentials of shallow aquifers all over the Terai. The government counterpart agency is the Ground Water Resources Development Board (GWRDB) of the Department of Irrigation of the Ministry of Water Resources. The project's activities started in June 1987.

Among project outputs, reports on mathematical modelling of various parts of the Terai are expected to provide the means for evaluation and assessment of shallow ground water development potentials.

In the first year of the project, the drilling and pump testing activities have been carried out in the following districts of the Terai: Rautahat, Nawalparasi, Kapilvastu, and Dang. Technical Report No. 5 has been recently prepared on shallow wells drilling, testing of shallow aquifers, and monitoring water levels in 1987/88 in Nawalparasi District (West). The present report is its companion report.

1.2. Basis for This Report

This report is based on the following:

(a) NEP/86/025 project wells (for ease of reference called "project" wells) - 17 newly drilled shallow wells (wells are drilled between January and June 1988.

(b) Shallow drilled wells for the Nepal Drinking Water Supply Scheme in the Narayani Zone by the Japanese Red Cross Society and its contractor Nissaku Co., Ltd., between 1983 and 1986 - about 200 wells.

(c) Pumping tests conducted in project wells in 1988.

(d) Water level observations since May 1987, notably maps of water levels in May and September 1988.

Most, if not all, of previous information is compiled and reported in Technical Report No.5, titled **"NAWALPARASI DISTRICT (WEST), SHALLOW WELLS DRILLING, TESTING AND MONITORING IN 1987/88, BASIC DOCUMENTATION AND PRELIMINARY INTERPRETATION".**

1.3. Location, Size, Climate, Rivers in Nawalparasi District

Nawalparasi district belongs to the Western Region. The whole area of the western part of the district of about 580 km^2 is included into the model. The location of Nawalparasi district within Nepal is shown in Appendix 1. The model area is completely within a plain commonly known as the Terai of Nepal. The Terai plain is composed of interlocked alluvial deposits of the wider Ganges Plain and that of fans, channels, flood plains of numerous rivers flowing from the Siwalik (Churia) Range. For the sake of economy of drilling and well construction, the whole sequence of unconsolidated materials is divided into shallow and deep ground water systems. In the context of this model, the shallow ground water system includes the first significant permeable layer of at least 6 meter thickness, directly or indirectly recharged from local rainfall. As will be clear from appendices, this is normally down to a depth of 20 to 35 meters. The contour line of 150 m is considered to be the physical end of the Terai's Quaternary sediments.

The main characteristics of the climate in Nawalparasi district, as well as in the whole Terai, is monsoon rainfall which occurs between June and September and which delivers an average of 85% of the total annual rainfall. Locations of two rainfall stations (Parasi and Semari) are shown in Appendix 2 along with monthly sums of rainfall in 1987 and 1988. The mean annual rainfall is close to 1600 mm, and pan evaporation is also about 1500 mm. Average monthly rainfall exceeds average evaporation during only 4 months, June to September. For better understanding of the shallow aquifer behaviour in the period of calibration (May 1988 - February 1989) it should be pointed out that the rainfall in 1988 was much above long-term average (in Semari over 2300 mm compared to average of about 1600 mm).

For this modelling study, the rainfall record from the above two stations was used, but evaporation data were "imported" from another Terai district, that of Rupandehi (Bhairawa). The major potential surface water source for supplementing natural rainfall is the Narayani River which makes the eastern boundary to the model area. In the model, it is also the state boundary between India and Nepal. The Narayani River is one of the most important rivers in Nepal. Unfortunately, the only river flow record that was available comes from a site at Narayan Gath, which is some 60 km northeast of the Tribeni Gath, the place where the Narayani enters the model area (Appendix 2). Its average monthly flow is also shown in Appendix 2 (second page). Before entering the Terai the Narayani receives the flow from the Rapti River. The Narayani River is important for the shallow ground water system of the Terai in Nawalparasi because it makes a hydraulic barrier to shallow ground water flow from Nawalparasi district into or from neighboring India.

Since there is no Narayani River hydrograph available for this study, it is assumed that, within the Terai, in the months of July and August, about 6000-7000 m^3/sec of water has to flow through the river bed. Assuming a width of the river bed at the entrance into the Terai of some 600 m (at Tribeni) and a velocity of flow between 1.5 and 2 m/sec, the rise of river stage may be about 5 m in the July-August period. The hydrograph is probably "smoother" in the southward direction because the river bed becomes extremely wide and the flow is distributed in several channels.

While the role of the Narayani River may be that of a constant-head boundary preventing any shallow ground water exchange across its banks, the role of other rivers in Nawalparasi district is not clear. Most of streams are intermittent, flowing only during the monsoon time. The Siwalik (Churia) hills within the Nawalparasi district appear to be more compact and less dissected than in other districts of the Terai. The consequence is twofold: (1) there is less Bhabar material (coarse-grained, generally very permeable, clastic material, which resulted from river fan and colluvial deposition); (2) there are no surface streams of importance rather than the Narayani.

Although the Terai of Nepal is in the subtropical zone, the mean monthly temperature reaches a low of 16.1°C in January compared to a high of 30.5°C in May.

2. MODEL SETUP

2.1. Model Size and Network

The shallow ground water system of Nawalparasi district, which is the subject of this modelling work, has two natural and two artificial boundaries. The natural boundaries are the Narayani River on the south-east, and the Churia (Siwalik) hills in the north - northeast. The artificial boundaries are the state boundary with India in the south and southwest and the western boundary with the neighboring district Rupandehi in the west. The modelled area, and its boundaries, are shown schematically in Appendix 3. The size of each cell is 1000 m by 1000 m, i.e. the area occupied by one cell is 1,000,000 m^2 big. The model's coordinates are expressed in columns (I), which may be taken as an equivalent to "X" coordinate axis, and in rows (J), which may be taken as an equivalent to "Y" coordinate axis. The orientation of the model is northwest-southeast (columns) and northeast- southwest (rows). The labelling starts in the south-western corner. (The minus sign for rows in some appendices should not confuse the reader. It is only for the convenience of a graphical computer program.)

The total area occupied by the model is 840 km^2, which is discretized into 840 equal-size cells. The number of columns is 20, and that of rows is 41. It is a small-size model. Considering the spacing of 1000 m in either direction, the model is of a preliminary nature, sufficiently accurate for global balance and assessment of overall recharge and discharge components of the system. It is not to be used for detailed location of water- supply and/or irrigation wells. The model is two-dimensional, meaning that all lithological layers along the vertical to the depth of representation are averaged into one layer.

The area on the left bank of the Narayani River is eliminated from simulation. This is a standard procedure since the aquifer in India, on the other side of the river is not hydraulically (and physically) connected with the water in Nawalparasi district in the west. In other words, the Narayani River is taken as a constant-head boundary which is the physical termination of the Nawalparasi shallow ground water system.

The area to the north declared with T=0 (transmissivity equal zero) coincides with the Siwalik hills above the absolute elevation 150 m. There is no Quaternary (alluvium) aquifer in the hills, and the boundary is the natural one. All cells declared with T=0 are also eliminated from the modelling.

However, the area to the west, which is also eliminated and which is in Rupandehi district, does contain a shallow ground water system, very similar to the one in Nawalparasi district. That area was eliminated from the modelling on the following grounds: (a) one of targets of the modelling is to produce the water balance for Nawalparasi district alone, (b) the ground water flow is from the north to south, i.e. from the hills towards India, and, in natural state, there is very little flow from east to west or vice versa. This is not to say that this is a natural condition, since, in nature, any large-scale shallow water development near the district border would have produced additional "import" of shallow ground water from Rupandehi district. However, the planning of shallow ground water development calls equally for increased pumping in Rupandehi as well as in Nawalparasi district. It is on the safe side to assume that any development in Nawalparasi should count only with the water recharged in that district. To conclude, there is an error introduced when the Rupandehi portion of the system is eliminated, but that error is on the safe side. It is also noted that the shallow aquifer in the western part of the modelled district is much inferior to the rest of the area. Its very low permeability and transmissivity makes the "volumetric" transfer of shallow ground water between the two districts almost negligible.

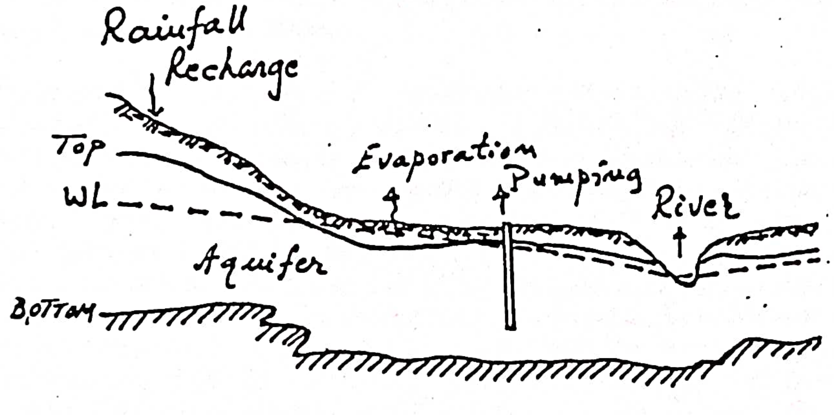
The southern boundary of the model, towards India, is also an artificial one. The model assumes a physical end of shallow aquifer in the southern direction, which implies that there is no outflow of ground water into India. This is not true, but the shallow ground water flow rate is much less when compared with other components of the system. Yet, the flow is simulated with discharging wells, reducing thus the error.

2.2. Modelled Processes and Aquifer Parameters

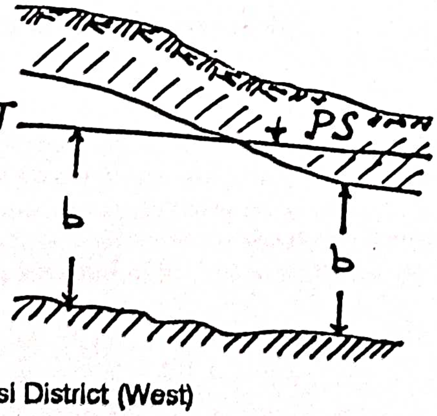
The shallow ground water system of the Terai is recharged directly from the surface in places in which a more or less permeable layer occurs near the land surface. It receives the water which infiltrates after rainfall, or which originates from rivers and other surface streams. Although the water from surface sources (rainfall, surface streams) may infiltrate almost everywhere, the major source of shallow aquifer recharge in most of the Terai comes from a zone along the hills, known as the Bhabar zone. It is a very permeable zone composed of gravel with pebbles, some coarse sand and minor amount of finer clastics. Although generally permeable, it is characterized by extremely poor sorting. Because it was formed as a result of river fan and colluvial deposition, the Bhabar zone is not continuous. In Nawalparasi district the extension of the Bhabar zone is only about 80 km^2, and that is mostly in the northeastern extension of the district.

The shallow ground water, which infiltrates after rains and recharges the aquifer, flows down the gradient mostly in the southern direction. On its way it is being consumed by evapotranspiration processes which may be active in places in which the water table comes close to the surface.

The Narayani River, as well as any other perennial or intermittent surface stream, may either recharge the shallow ground water system or discharge from it. The direction of water exchange depends on the difference of water levels between the river and the shallow aquifer. The sketch of shallow ground water system behaviour is shown here below.



Although the ground water system modelled in this study is two-dimensional, with only one value of hydraulic conductivity (permeability) and storage coefficient representing one cell, the modelling code permits the distinction between fully saturated aquifer, and its semi- or totally confining layer above. The model also takes care to calculate the real transmissivity of the permeable layer on the basis of saturated thickness and hydraulic conductivity. This is shown in the sketch here below.



WT - Water table
PS - Piezometric surface
T=Kb T - Transmissivity
K - Hydraulic conductivity
b - Thickness of saturated layer

Likewise, the model also takes care to distinguish between water table conditions (when the water table is inside the permeable formation) and confining conditions (when the water table, or more correctly piezometric head, rises above the top of permeable formation).

Although the shallow system is not homogeneous and unique water-bearing layer, but composed of a sequence of permeable and impermeable layers, the model treats such a sequence as only one layer and characterizes it with an averaged value of conductivity. Numerous lithological logs are available from "project" wells and wells drilled for water supply by Japan Red Cross Society (see Appendix 3 for schematic locations). The nonhomogeneity of the system is clearly evidenced in lithological cross-sections in Appendix 5. The appendix contains six typical lithological cross-sections, with permeable layers coloured blue and impermeable layers red.

In only eight wells pumping tests have been conducted to define the transmissivity of the shallow ground water system. The location of pump-tested wells is shown in Appendix 6, along with the contour lines of equal transmissivity. The highest transmissivities are found in the eastern part, notably toward the Narayani River. The range of values is from less than a hundred square meters per day to over 1,000 m^2/day. Actually there is a clear distinction between western and eastern parts of the modelled area. Typical figures in the west for transmissivity are 55 m^2/day, 124, 156. There are also some abandoned wells ("dry") from the Japanese drilling program. The hydraulic conductivities of shallow aquifer materials are on average between 40 and 50 m/day, exceptionally over 100 m/day. The average permeable thickness within the upper 30 or so meters is about 16 m, or 48% of the total "shallow" penetration.

The storage coefficient values from pumping tests are unreliable and not representative for an unconfined ground water system. This is typical for many tests of short duration in similar environments. The values obtained prove that the shallow aquifer is overlain by several meters of less permeable material in which vertical permeability dominates over the horizontal one (anisotropic medium), and which may permit the exchange of water in vertical direction (recharge from infiltrated water and evapotranspiration loss), but which offers very little storage of water.

The modelling of the Nawalparasi shallow ground water system is made possible by monitoring water levels in shallow tube and dug wells in the period from May 1988 through February 1989 (see Appendix 4 for locations). In the said period two extremes are observed: minimum water levels (or maximum depths to water) in May-June 1988, and maximum water level in September of 1988. Two maps of water level contours are reproduced in Appendices 15 and 26, and compared with the model output. The actual measurements in nature are expressed in depths to water table below land surface. These are shown in Appendices 16 and 27 for the months of May and September 1988. The map of maximum depths to water table, Appendix 16, shows that in some parts of the district the water table is still within 2 m from the land surface (Banjariya, 1.2 m; Rampurwa, 1.7 m). In most of the model area the levels in May 1988 are deeper than 3.0 m under the land surface. Although not directly measured, it is expected that near the hills the depth to water is much greater. The map of minimum depth to water table (Appendix 27, September 1988) shows that water table is close to the land surface in the greatest part of the district. In the whole central and southern part, the water table is within 1 m from the land surface. These facts shall be discussed in more detail when comparison is made between the model output and the nature.

2.3. Phases of Modelling

The modelling started with steady-state calibration of the model. The month of May 1988 was selected for the initial phase of the modelling. The water-level contour map (Appendix 15) is taken as an end of a long dry period. Although there is no "steady-state" in nature, it is assumed that the minimum levels would have prevailed should there be almost no rainfall for a long period of time. In a steady-state modelling, the dominant parameters in the simulation are: (a) recharge, (b) hydraulic conductivity, (c) evaporation control, plus the connection with the Narayani River. (Also, the flow into the model from the hilly sides and as underflow in dry creeks, as well as outflow into India along the southern border, are very important.)

The second phase of the modelling was to confirm the rise of levels over the period from May 1988 through September 1988 and subsequent decline after monsoon rains in the period from September through February. For this many points all over the modelled area were used, as shown in Appendix 4.

Coupled to the second phase, the third phase of the modelling was to simulate the system behaviour over one year period. This is more the verification of the model than the calibration, because no aquifer or system parameters are matched. The period of simulation was between the months of February and May 1989. The model should have proved that the May levels in 1989 would have come close to the ones in May 1988, provided that all input parameters are globally correctly taken. (In the case of the simulated period, it is more accurate to say that the May 1989 levels should be slightly above the May 1988 levels because of over-average rains in 1988.)

The final, fourth, phase of the modelling is to find an optimum distribution of hypothetical "future" shallow tube wells and their cumulative pumping rate, which could be interpreted as a "safe yield" of the shallow aquifer.

2.4. Background and Introduction on Mathematical Modelling in General

The use of microcomputers in ground water resources has grown rapidly within the past few years. A model is a system of finite-difference equations that replace partial differential equations that govern the ground water flow. One such finite- difference equation is written for each cell of the model. The user does not necessarily need to be involved in mathematics behind the modelling or programmer's code and mode of solution.

The software used for the modelling of the Nawalparasi shallow ground water system is proprietary United Nations ground water software, being, incidentally, prepared by the author of this report.

The finite difference grid is superposed over a map of aquifer, such as shown in Appendix 3. The aquifer is thus divided into volumes having dimensions m x y, where m is the saturated thickness of the aquifer. The system of finite-difference equations is solved for the principal unknown h (head). The method of solution used is an iterative alternating direction implicit method. Between two iterations a residual error remains which is either reduced in successive iteration or accepted as suitable solution.

Essentially the modelling process can be thought of a black box such as the following sketch demonstrates.

INPUT DATA + PROGRAM FOR SOLUTION = OUTPUT

Input Data	Output
Boundary data	Water Balance
Land Surface	Map of Levels
Top of Aquifer	Hydrographs
Bottom of Aquifer	Depth to Water
Permeability	Evaporation
Storage Coefficient	Distribution of Permeability
Recharge	Distribution of Storage Coeff.
Evaporation	Distribution of Effective Porosity
Narayani River	
Initial Levels	

The role of input data cannot be overemphasized. A model is only as good as the data used to make it. As far as the Nawalparasi model is concerned, it is believed that the data are sufficiently good to warrant its construction. (During the modelling process it was discovered that some of information is not to be trusted: (a) driller's description of lithology, (b) some water level measurements, (c) reported dates of measurements.)

2.5. Aquifer Geometry

The geometry of an aquifer includes the elevation of land surface, the top of permeable sequence, and the bottom of permeable sequence. The land surface is important for having a means of controlling the evaporation process. It is a known fact that the shallow ground water shall be lost through the process of evaporation when the water table comes within several meters from the land surface. There is an empirical formula by Schoeller according to which there is a critical depth of the water table below which there shall be no water loss on account of evaporation. This depth is found from a mean monthly or annual air temperature:

$$d_{cr} = 8 \times t_o +/- \ 15 \text{ cm}$$

where d_{cr} is the critical depth expressed in cm, t_o is the mean temperature. In the Terai of Nepal, the mean annual temperature is about 23°C, but in the months of highest evaporation potential the temperatures are well above 30°C. Thus the maximum depth below which there should be no evaporation loss from the water table could be between 2 and 3 meters. (The evaporation control in the model shall be discussed in Section 2.6.)

The land surface elevation is also important for limiting the rise of water table above the land surface. Only in parts of the model in which the aquifer is covered with completely impermeable clays, the modelling permits the piezometric surface to rise above the land surface.

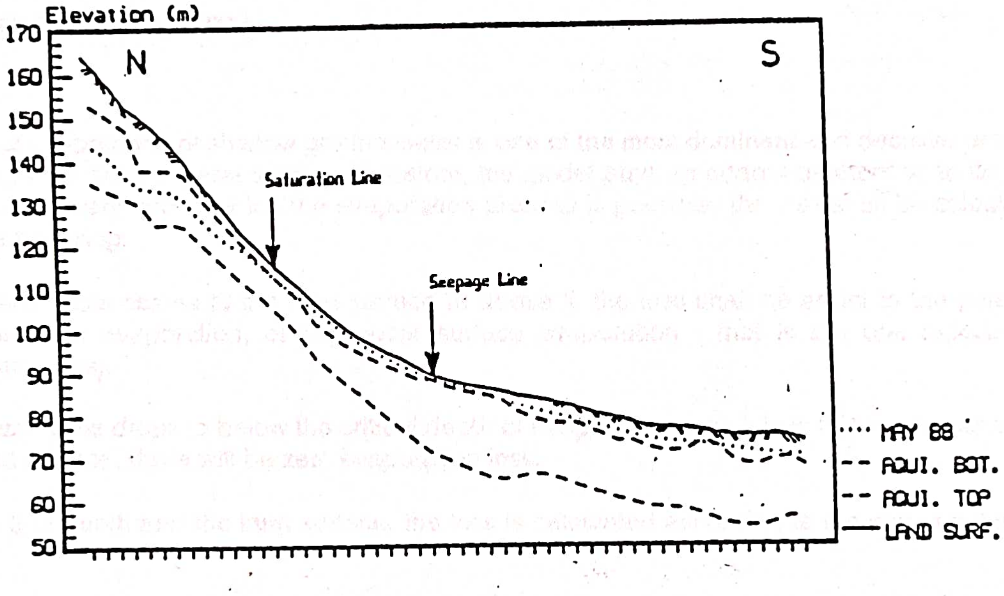
The top-of-aquifer elevation is important for two reasons: (1) to check whether the cell is under water table or confined conditions, (2) to recalculate the transmissivity if and when water table drops to below the top of aquifer.

The bottom of aquifer elevation is used to calculate the saturated thickness of the aquifer which is then used to obtain the transmissivity by multiplying it by the hydraulic conductivity. It is also used to assign a minimum thickness to the saturated aquifer of 0.01 m should the level ever fall below the aquifer bottom. Thus the aquifer transmissivity always has some positive value, and this allows refilling of the aquifer if the opportunity ever occurs.

The geometry of the shallow ground water system is amply illustrated in Appendices 5,7,8,9,10,11,12 (land surface, top-of- aquifer, bottom-of-aquifer, depths to top and bottom, saturated thickness, etc.)

The cross-sections through various parts of the model are shown in Appendices 14. The blue-coloured layer is the shallow aquifer which is the subject of this modelling study. Although shown as uninterrupted unit, this is in essence a sequence of several permeable and impermeable layers, which are all hydraulically connected and have the same source of recharge and discharge.

The geometry of the shallow aquifer, in its north-south direction, is also sketched here below.



The change of land surface slope is evident some 6 or so kilometers from the hills (Appendices 14, row 13, row 32). Although the sketch shows the "bottom" of the shallow aquifer, it is in no way an indication of the absence of permeable layers underneath. Rather than that, it is a subjective indication of what one may call "shallow aquifer", that is the uppermost sequence of permeable layers directly recharged from rainfall and surface streams.

The break of the land surface slope is mostly responsible for the introduction of two terms: "phreatic seepage line" and "saturation line". The seepage line is defined as the line where shallow water table emerges at the land surface. If it is assumed that the near-the-surface layer is permeable, than along this line there will be a loss of shallow ground water in the form of dispersed seepage. In Nawalparasi district, the water table is everywhere deeper than 1 m below the land surface and there is no any "seepage" in the above sense. However, in September the water table may rise all the way to the land surface and be discharged in either form: evaporation, seepage.

The saturation line is an artificial projection onto the land surface of the line where the first permeable layer becomes fully saturated. In the sketch, the saturation line may be somewhere near the 6th kilometer from the northern edge of the plain. Evidently both lines are constantly shifting, depending on the season and the vertical position of the water table.

In Appendices, some other geometric features are also presented. Each is the outcome of an automatic modelling opportunity which "crossinterprets" the geometry of the system. The depth to the top of aquifer in each model cell is shown in Appendix 10, the depth to the bottom of shallow aquifer is shown in Appendix 11, and the saturated thickness of aquifer at the beginning of simulation (May 1988) is shown in Appendix 12.

The geometry of the shallow aquifer was interpreted from many recently drilled shallow wells. Their schematic locations within the model network are shown in Appendix 4. All of recently drilled wells (UN project) have their land surface elevations accurately surveyed under the subcontract with Swissair Photo + Surveys Ltd. For others, the land surface elevation was read from a 1:125,000 topographic map (English version), with an accuracy of some 0.5 m in most cases, except in the very north where the accuracy could be several meters.

2.6. Evaporation Control

The process of evaporation of shallow ground water is one of the most dominant and decisive processes in the Nawalparasi ground water system. Therefore, the model pays an adequate attention to its role. It is assumed that in every cell in which the evaporation process is possible, the loss shall be calculated according to the following:

(a) When water table comes to the land surface or above it, the loss shall be equal to the potential evaporation (maximum evaporation, or free-water surface evaporation - that is the one reported in meteorological manuals).

(b) When water table drops to below the critical depth of evaporation, which is in this model set at 3.0 m below the land surface, there will be zero evaporation loss.

(c) Between 3 m depth and the land surface, the loss is calculated according to the exponential formula:

$$E = E_o \exp(-0.6d)$$

where E is the current loss (function of space, depth, and, indirectly, time), E_o is the free-water surface evaporation rate, d is the current depth of water table below the land surface.

If the shallow aquifer is covered by a semiconfining layer (silty, sandy clay) and "water table" is within this semiconfining zone, the evaporation loss shall be reduced when compared to the loss that would have occurred had the permeable medium reached the land surface. Between ten and thirty per cent may be a reasonable "guess". Although this parameter may dominate the simulation, especially when water table is very close to the surface, yet it will be hardly ever known better than "guessing". The model keeps an account of cumulative evaporation losses which are then compared to cumulative recharge.

2.7. Narayani River

The Narayani River makes the eastern boundary of the shallow ground water flow system. The elevation of the water table in the river cells is taken from the topographic map, scale 1:125,000. At one point, near the bridge at Tribeni Gath, the river surface was surveyed in February. The elevation was 104.5 m. The river's actual hydrographs, at various cells, throughout the period of simulation, are shown in Appendix 25.

3. STEADY-STATE CALIBRATION (MAY 1988)

3.1. Water Level Contour Map in May 1988

The basis for the steady-state calibration is the contour map of water levels in May 1988. The map is produced by subtracting the depth to water table in selected wells from absolute land surface elevation. The map of depths to water table from the land surface is shown in Appendix 16. In absolute elevations, the water table contour map is produced in Appendix 15. The model is expected, in the steady-state calibration to duplicate this map. The map (Appendix 15) was produced from some 20 measured values in the observation network, covering all parts of the model.

The land surface elevations in observation wells are shown in **Technical Report No. 5** (Basic Documentation, Nawalparasi West). They are also indicated on hydrographs (Appendices 24) here in.

3.2. Input Data Files

The model demands the following input data files:

(a) General Data: number of columns, number of rows, size of one time step (DELTA) (in the steady-state calibration the size of time step is very large; normally $1x10^{10}$ days is sufficient), maximum permitted number of iterations, error convergence criterion (ERROR).

(b) Hydraulic conductivity (permeability) data file.
(c) Recharge data input file.
(d) Evaporation data control file.
(e) Land surface elevation data file.
(f) Top of aquifer elevation input data file.
(g) Bottom of aquifer input data file.
(h) Initial water levels (May 1988).
(i) Storage coefficients and/or effective porosities.

The hydraulic conductivity input data file is reproduced in Appendix 19. The first line contains the values of different categories of permeabilities (hydraulic conductivities) and the remaining 41 lines contain the categories for each cell, one row by row. The format of input is 5x,20I1, which means that in the first five columns anything can be typed since it shall be ignored by the computer. (This "free" space is used for typing numbers of rows.) There is also a legend, which explains the relationship between the values and categories. For example, the code 4 means the permeability of 7.5 m/day, etc. As mentioned before, these are a kind of artificial values of permeabilities, because they are averaged over the whole saturated thickness, irrespective of the proportion of permeable versus impermeable material. (The real value of the hydraulic conductivity must be higher than the one used herein.)

The distribution of hydraulic conductivities as shown in Appendix 19 is the final outcome of the modelling (calibration) process.

The recharge data input file is shown in Appendix 20. It is also an outcome of the modelling calibration process. Similar to the hydraulic conductivities, the first line in the file contains the values, expressed in percentages of rainfall, and the remaining 41 lines the codes (categories) which are translated by the model into the values of recharge. There is also one line at the end of the file, which shows the rainfall (daily rate) for a particular time interval. Thus, the value of 0.002 is 2 mm/day, or 60 mm/month, because the basic units in this model are meter for length (distance), day for time. (There are two more basic units: m^2/day for transmissivity, m^3/day for pumping rates.)

The evaporation input data file is shown in Appendix 23. There are only two categories of data, zero (or blank) and 1. The first implies that there will be no evaporation process, either because the cell is outside of the model, or the aquifer is covered by completely impermeable formation. The last line (the 42nd in this case) contains the daily maximum (free-surface) evaporation rates for each time interval. (In the steady-state calibration only the first value is used, since, by definition, the steady-state is achieved in only one time step.)

The land surface elevation file is numerical data file, with one line for one model row. The individual values (from one column to next) are separated by either blank space or a comma. This is so-called "free" format. The map shown in Appendix 7 is only for reporting. (The program cannot read graphical input.) Similarly, other two "geometric" files are prepared: top of aquifer, bottom of aquifer. Their graphical equivalents (used only for reporting) are presented in Appendixes 8 and 9, respectively.

The initial water levels input data file, with its graphical equivalent shown in Appendix 17, is prepared in the similar way. It is absolutely required that each cell in the model be given one value for each of input parameters. Also, in the case of initial water levels, it is very important that the input file contains as close initial levels as possible to what is believed to be the real water level configuration. The importance comes from the fact that these levels are used to calculate initial transmissivities of the shallow aquifer, and initial evaporation rates. Both of these will prevail throughout the steady-state calibration without any modification.

3.3. Comments on Available Data

The aerial distribution of locations with known lithology is shown in Appendix 3. At least 38 wells (somewhere more than one in one model cell) have available lithological description of formations drilled through. However, two factors should be considered. First, the spread of information is not adequate, and wells are not covering some parts of the area. There is a gap in the central part between rows 13 (Parasi) and 20 (Jamuniya). (As it appears, the boundary between very promising area for extensive ground water development and very poor area lies between the two sites.) Likewise, there is no information in the southeast corner near the Narayani River and in a belt of 3 km near the hills. Second, lithological description of drilled formations is often misleading. The driller reports "gravel" when the formation contains gravel mixed with silt and/or clay. Thus the 10-m thick gravel and sand layer, as reported by driller, is not commensurate with transmissivity of only 50 m^2/day.

It was mentioned before that there are about 200 recently drilled STW's (Japan Red Cross Society, ADBN). Out of these only about 15 wells could be located and their lithological logs utilized. Map of locations is not appended to the report on drilling by Japan Red Cross Society and present officers-in- charge are not familiar with the project. There is no doubt that this information could be unearthed. More than lithology, these wells could be used for additional pump testing and providing more values of transmissivity and permeability.

3.4. Results of Steady-State Calibration

The steady-state calibration is necessary to produce a good initial map of water levels. The levels must be in equilibrium (recharge-flow-discharge) so that any subsequent non-steady state deviation from the balanced state produces changes in wanted direction. E.g., the levels should decline in dry season or rise in wet. They will not do so unless the map of initial levels is perfectly balanced in the antecedent period.

After many computer runs, in which the hydraulic conductivities, boundary inflow and outflow, recharge rates and evaporation distribution were changed (sometimes also geometry of aquifer, including double check of land surface elevations, lithology, etc.) the final outcome was the map of levels in May 1988, as produced by the model. This is presented in Appendix 17 in graphical form. The success of the steady-state calibration becomes evident when two maps are compared: Appendix 15 (initial levels, subjectively input by the modeller) and Appendix 17 (model final outcome). Clearly, the flow net (direction of flow and absolute elevations of contour lines) in both maps are very close one to the other. The slope (gradient) of ground water flow is steeper in northwestern part, and much milder in the southern part toward India and the Narayani River.

Since the only known water level elevations in May 1988 are in observation wells (17 "project" wells), the quality of match can be assessed only in these cells. This is illustrated in table on the next page (for locations see Appendix 4).

Cell	Location	May 88 (m)	Model (m)	Difference (m)
14,5	Rampurwa	128.1	128.1	0.0
16,12	Badera	124.1	124.1	0.0
9,13	Parasi	108.4	108.6	0.2
14,20	Jamuniya	110.0	110.1	0.1
16,26	Paldanda	120.4	120.0	-0.4
10,23	Dablia	104.7	104.2	-0.5
11,34	Kuniya	104.7	104.0	-0.7
12,38	Raninagar	106.4	106.0	-0.4
9,27	Khairani	103.1	102.7	-0.4
10,6	Banjariya	113.6	113.5	-0.1
11,6	Parsawal	115.8	116.3	0.5

3,8	Lalpati	105.0	105.1	0.1
5,9	Hakual	106.1	106.0	-0.1
7,22	Gobrahlya	102.0	102.4	0.4
4,29	Surajpura	101.2	101.0	-0.2
3,32	Guthi Pars.	100.5	100.6	0.1
1,14	Bisnupura	101.1	101.1	0.0

Average: 0.25 m

The match between "nature" and model is acceptable in the whole model, being mostly in the range from -0.4 to +0.4 m. In two cells, the level is strongly influenced by the presence of the river (Raninagar and Kuniya). In others, artificial outflow conditions prevent from better fit. Yet it is believed that the map as shown in Appendix 17 is a good starting point for the unsteady-state calibration of the rise of levels in the monsoon season of 1988 and their subsequent decline in the postmonsoon period.

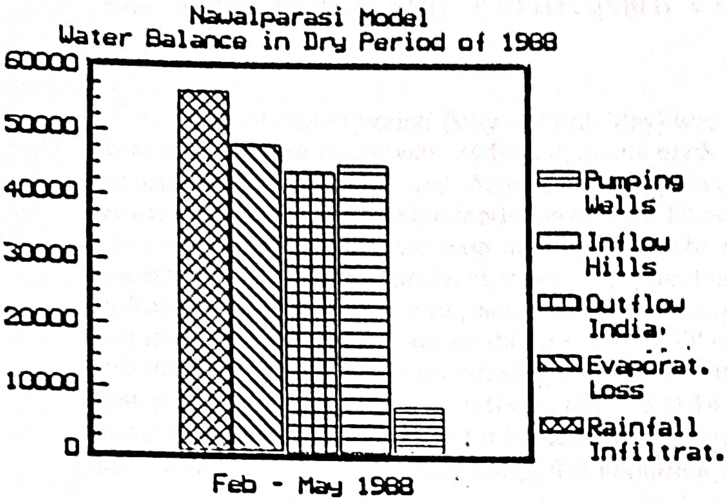
The map of levels in Appendix 17 is obtained with the following input data distributions: (a) transmissivities as shown in Appendix 13 (or permeabilities in Appendix 19), (b) evaporation codes as shown in Appendix 23, (d) recharge rates and distributions as shown in Appendix 20. Although the modeller has a certain freedom to modify some parameters, the modifications may not exceed some tolerances. The values of conductivities and recharge rates, in particular, must be based on the conclusions of previous hydrogeological studies. The final distribution of transmissivities (Appendix 13) is not materially too much different from the map of transmissivities produced in Report No. 5 (Nawalparasi District, Basic Documentation and Preliminary Interpretation from shallow wells drilling, pumping tests and water levels monitoring) (see Appendix 6). In both maps the western part of the area is very much inferior to the eastern part. The contour line 200 m^2/day is at about the same place, both in model output and in "field- measured" (pumping tests). The model proves a higher transmissivity near the Narayani River which is to be expected considering greater gravel content and very clean shallow aquifer.

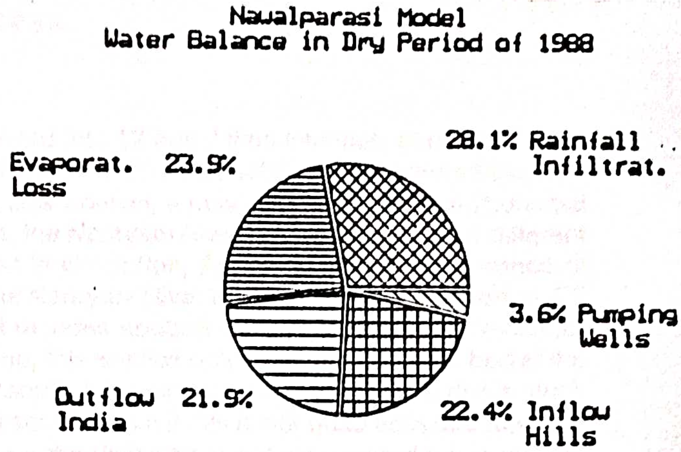
The model also keeps an account of the water balance and shows the total convergence "error", plus indicates the cell (I,J coordinates) in which the error is the largest in each particular iteration. In the final steady-state calibration computer run, the convergence was achieved in 36 iterations (on an IBM AT equipped with numerical co-processor, the total processing time was slightly over 3 minutes), and the cumulative error was less than 1.0 m for all 592 active cells. (This "cumulative" error implies an average "error" of only 1.7 mm per cell.)

The total recharge from infiltrated rain, as shown by the model, in the dry season was about 56,360 m^3/day, which makes an equivalent of 1.7 MCM/month (million cubic meters). The evaporation loss is equal to 55,147 m^3/day, or 1.6 MCM per month. The outflow into India across 27 km section is about 45,000 m^3/day, or 1.5 MCM/month. The inflow from the hilly side (either as underflow below dry river beds, or springs discharge, or surface runoff) amounts to about 46,000 m^3/day, or 1.5 MCM/month.

Thus, what remains as a surplus of recharge flows into the Narayani River. This is a very small volume of only about 2073 m^3/day, or 62,000 m^3/month.

One must admit that the model did not take into account any pumping from shallow tube wells. There may be about 200 STW's (shallow tube wells) in western part of Nawalparasi District. If, in the dry period and average number of 100 wells is being pumped for 4 hours daily throughout the dry season at an average rate of 5 l/sec, this would amount to a total of 7200 m^3/day. This is a minor amount which is, in this simulation, lumped into the evaporation loss. Thus, the more accurate water balance could be as shown in the sketch below (for the dry period February-May 1988).





It appears that the recharge from direct infiltration of rainfall balances with evaporation loss plus pumping from shallow irrigation and water-supply wells, and that the inflow from hill sides balances with outflow into India.

4. UNSTEADY-STATE CALIBRATION MAY 1988 - FEBRUARY 1989 and MODEL VERIFICATION THROUGH MAY 1989

4.1. Basis for Calibration

Twenty plus observation wells were under once-a-month monitoring in the period from May 1988 through February 1989 (Appendix 4). On the basis of observations, a contour map of water levels in September (in absolute elevations) was drawn as shown in Appendix 26. Individual hydrographs, as observed in the nature, are presented in Appendices 24.

The rainfall record was available through the end of 1988 in Parasi, and through the end of 1987 in Semari (both are unauthorized records to be used in draft form for the model). On the basis of this, the daily rainfall was input into the model.

4.2. Calibration and Verification Process

The twelve-month period (May through May) was divided into 12 equal time intervals, each of 30 days (one attempt was made with 24 time intervals each of 15 days, but the benefits did not warrant the time needed for preparing the run). At the beginning of each time interval, a new value of rainfall and potential evaporation was read into the model (in m/day). Likewise, the Narayani River cells were assigned different values in each time interval (see river hydrographs used in simulation, Appendix 25). In the absence of realistic river stage measurement, it was accepted that the Narayani River rises in the monsoon period 4.2 m from the pre-monsoon level, and that by November it recedes about 3 meters remaining in November still more than one meter above the May levels. Of course, this applies only to the narrow river bed at the exit from the gorge, and upon entering the Terai. Further south, the amplitude of the monsoon rise is much less (2.8 m some five kilometers south, and 1.5 m 14 km south). Even if this is not quite accurate the error should not be decisive. The error influenced the area near the river and is not propagated too much into the interior. Yet, for future modelling, it is important to have more information on the Narayani River.

For the period from February through May 1989 (three time steps, or three months), the "missing" parameters were taken from one year before: (1) rain, almost negligible (Appendix 20): in February 0 mm, in March 24 mm/month, in April 54 mm/month; (2) evaporation (Appendix 23): in February 4.1 mm potential (free water surface evaporation), in March 5 mm/day, in April 6 mm/day; (3) Narayani River water stage (Appendix 25), (4) inflow from hill sides and outflow into India constant, the same as in other steps.

In the process of calibration major changes were made in the distribution of different storage coefficients, both under water table conditions (effective porosity) and under confined conditions (storativity). The final outcome is presented in Appendices 21 (effective porosity) and 22 (storativity).

Three of simulated river stage - distance cross-sections are shown in Appendix 25. These are the graphs of absolute river elevation starting from cell 14,41 and ending at cell 1,38. The cross-sections are shown for the months of May, July and September 1988. The simulated river slope is greater in the upper half of the model than in the lower part of the model, but on average it is only about 8 m per 14 kilometers, or 0.06%.

Some changes have been made also in the distribution of recharge and hydraulic conductivity. The outcome is discussed next.

4.3. Results of Unsteady-State Calibration

The model produced several outputs in this phase of simulation:

(a) Map of Water Levels in September 1988 (Appendix 28), which matches a similar map constructed from field observations (Appendix 26).

(b) Hydrographs at selected points, shown in Appendices 24, and compared to the hydrographs constructed from field observations.

(c) Depth to water in September 1988, shown in Appendix 29, which should be compared with a similar map (Appendix 27) constructed from field observations.

(d) Rise of levels from May to September 1988, shown in Appendix 31, which should be compared with a similar map in Appendix 30.

(e) Distribution of Storage Coefficients, under water table and confined conditions, as shown in Appendices 21 and 22, respectively.

(f) Evaporation losses in September 1988 (when water table is nearest the land surface), as shown in Appendix 32.

(f) Water Balance, which is shown in Appendices 33 and 34, and reproduced in the table here below.

NAWALPARASI (WEST) MODEL ....
WATER BALANCE (MONTHLY) FROM MAY 1988 THROUGH APRIL 1989

STEP	RECHARGE M3/DAY	RECHARGE L/SEC	EVAPORATION M3/DAY	EVAPORATION L/SEC	OUTFLOW to India	INFLOW from hills
MAY	-95750.	-1108.	133599.	1546.	50540.	-49500.
JUNE	-622375.	-7203.	104086.	1205.	50540.	-49500.
JULY	-1196875.	-13853.	156037.	1806.	50540.	-49500.
AUGUST	-813875.	-9420.	549840.	6364.	50540.	-49500.
SEPT.	-287250.	-3325.	457475.	5295.	50540.	-49500.
OCT.	-19150.	-222.	320565.	3710.	50540.	-49500.
NOVEM.	0.	0.	232635.	2693.	50540.	-49500.
DECEM.	-86175.	-997.	166019.	1922.	50540.	-49500.
JAN.	0.	0.	161259.	1866.	50540.	-49500.
FEBR.	0.	0.	191887.	2221.	50540.	-49500.
MARCH	-38300.	-443.	204280.	2364.	50540.	-49500.
APRIL	-86175.	-997.	219328.	2539.	50540.	-49500.
TOTAL:	97 MCM		87 MCM		18 MCM	18 MCM

In the above table, the recharge is shown under two headings: Recharge and Inflow. Inflow is the entrance of either surface, spring, or river water directly recharging the shallow aquifer in near-the-hills area (Bhabar zone), or contributing the recharge in a form of subsurface flow through the beds of river which enter the Terai plain from Siwalik hills. The "Inflow" is taken as a constant, i.e. not being so much influenced by seasonal rain. (This may not be true, but the results are on the conservative side.) Recharge is direct infiltration of rain water all over the model area. As shown in the last line of the data file "Recharge", Appendix 20, in the months of maximum rainfall the daily average is reduced to account for "rejected" recharge. This is a subjective criterion, which was modified in unsteady- state calibration runs. Its interpretation is as follows. In the middle of rainy season, when the soil is fully saturated, a sudden one-day high-rain event (more than a hundred mm of rainfall) results in a portion of rain being rejected by the soil cover and not contributing to ground water recharge. In such a case, the infiltration capacity of the soil is less than possible infiltration rate of rain water. This is to say that more water shall infiltrate and recharge the shallow aquifer if rain falls ten days in row 10 mm each day, than if it rains 100 mm in one day.

Inflow, as shown above, was simulated in 23 cells along the northern edge of the model in the form of artificial recharge (through wells). Individual rates amounted to 1500 to 3000 m^3/day per one cell of 1000 m length. This is equivalent to about 17 l/sec to 35 l/sec per one cell.

Outflow, which is shown in the table above, is simulated as artificial discharge through wells in 35 cells in boundary cells along column 1 and at the model boundary with Rupandehi district. This is a compensation for cutting off the aquifer which normally extends into India, and partially to Rupandehi. Contrary to expectations, this component of the water balance is not a minor one, especially not in dry period. Individual rates amounted to 900 to 2000 m^3/day per one cell, or an equivalent of 10 to 23 l/sec per cell.

The balance shown above may be interpreted in the following way. The total input of water into the shallow ground water system in one-year period between May and May is equal to about 115 MCM (million cubic meters). Out of this volume, about 97 MCM comes from direct infiltration of rain and ground water accretion on account of infiltrated rain reaching the water table, and 18 MCM come as inflow into the shallow ground water system from the hill sides. Clearly, on an annual basis, the infiltration of rainfall is much superior to the inflow from hills. The total discharge of water from the aquifer in one year period amounts to about 105 MCM, out of which to evaporation loss (coupled with some minor pumping from shallow wells) goes 87 MCM and to outflow across model boundaries to India another 18 MCM. Again, in one-year period, the evaporation loss outweighs the outflow into India by the factor of 5. What remains, i.e. 10 MCM, may either fill up the storage (levels in May 1989 could be higher than in May 1988), or outflow into the Narayani River. The model does not distinguish between the two.

The monthly water balance is shown in Appendices 33 and 34. The recharge from rainfall exceeds the evaporation loss in June, July and August, and evaporation exceeds the recharge in other nine months. The "pie" graphs in Appendix 34 indicate (1) the total transfer of water involved (diameter of circle, maximum in July, less in September, much less in May), (2) the relative proportions of each of four balance components. In July the recharge-from-rain component amounts to 82.4% of the total water involved (in and out), while evaporation is only 10.7%. In September the evaporation loss dominates in the balance (54.2% of all water taken in or from the system) over the recharge (34%), while in May the evaporation and recharge come closer (40.6% and 29.1%, respectively).

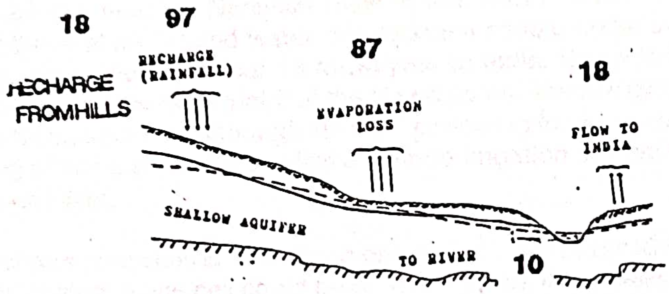
4.4. Comparison between Observed and Simulated Hydrographs

This comparison is actually the measure of "fit" and quality of the model. Eighteen hydrographs are presented in Appendices 24. The model did not make any attempt to "match" some portions of hydrographs which are unrealistic, or for which there is no explanation in nature (decline of levels from July in Kuniya, November-December levels in Paldanda, minimum levels in July in Rampurwa, etc.) Likewise, the model need not "duplicate" the absolute levels everywhere. It is enough if the shape of hydrographs is the same, meaning the same amplitude of rise and decline. In our opinion excellent fit is obtained in wells: Raninagar, Guthi Parsauni, Paldanda, Dabila, Bisnupura, Germi, Rampurwa, Parasi. Acceptable fit is in wells: Parsawal, Khairani, Gobrahiya, Lalpati, Hakuai, Badera, Sagaraha. Less acceptable fit is in wells: Banjariya, Kuniya, Surajpura. Banjariya well is peculiar showing in upper 30 or so meters mostly clay, its rise of water level is only 1 m compared to 3 meters or more in other wells. In Kuniya field observations of levels can't be fully trusted, and in Surajpura observation stopped altogether in October for unknown reason.

As a conclusion, the fit could have been better with more computer runs and manipulations with parameters (storage coefficients, recharge rates, geometry of shallow aquifer), but the water balance would not be appreciably affected.

From this water balance one may conclude that a future ground water development from shallow aquifers may come mostly on expense of reduced evaporation and outflow into India. The evaporation loss can be reduced by lowering the water levels to a depth that will prevent the losses. The outflow into the Narayani River, which is a small component of the balance, can be reduced or eliminated by pumping from shallow wells located along a stretch parallel to the river course. It is a favourable coincidence that along the right bank of the Narayani River the shallow aquifer in Nawalparasi district is the most promising, having clean sand and gravel content and almost the best transmissivity in the whole district. The outflow to India can be reduced or ceased by pumping on a larger scale near the border. However, this applies only to the southern one half of the district boundary with India where transmissivity is more promising.

The water balance is sketched here below.



5. HYPOTHETICAL FUTURE SHALLOW GROUND WATER DEVELOPMENT

5.1. Introduction

The final modelling attempt was made to find out a future potential development potential by locating shallow wells in areas in which water table comes closest to the surface, provided the aquifer has acceptable thickness and lithology (transmissivity).

Once the model is sufficiently successful in calibrating the past record of evolution of water levels, it could be used for future predictive purposes. The Nawalparasi model was shown to correctly duplicate the behaviour of shallow water table in the period from May through September 1988. Likewise, it was also successful in confirming the decline of levels in the post- monsoon period (September-May). None of input parameters was questionable. The map of transmissivities produced by the model at the end of the calibration process is very similar to the conclusions of the Report No.5 which preceded the modelling study. The recharge, evaporation loss, inflow and outflow volumes are all acceptable quantities.

Once the calibration process was successfully terminated the model was used to predict the future, hypothetic, behaviour of the shallow ground system, which was subjected to a stress. The term "stress" in this context means the drilling of numerous shallow wells, and their pumping in the dry portion of the year.

After several check runs, it was decided to fully test three development schemes, which are explained one by one.

5.2. Development Scheme No. 1

Development scheme No. 1 is believed to be at the lower end of promising scenarios for future shallow ground water development. Following the conclusions of the Basic Documentation Report (Technical Report No. 5) and the calibration of this model, it was decided to locate future wells in an area of some 161 km^2 in the south-central part of the district (Appendix 35). The total pumping rate in this scheme is 53.1 million cubic meters (MCM) in pumping season which starts in February and terminates in May. The criterion for locating the pumping wells (cells) was the following: (a) acceptable transmissivity, (b) water table close to the surface, (c) site near the Narayani River. It was learnt, from the modelling study before coming to this stage, that the shallow ground water development should come on expense of losses to evaporation (87 MCM/year) and outflow of about 18 MCM/year to India. Some induced recharge from the Narayani River may augment the total "safe yield" of the Nawalparasi shallow ground water system. However, about 40 km^2 near the Narayani River, although the most promising for development, deliberately are not included into the pumping scheme since there exists a surface-irrigation system Gandak which takes water directly from the Narayani River.

The number of pumping cells is 161. Since one cell is 1000 m by 1000 m large, the number of wells that may actually be located in one cell could be on average 25, if the wells are located at 200 m distance one from the other. Thus the total number of wells could be about 4000.

For the purpose of the forecast, it was assumed that each cell is producing 330,000 m^3/season each year. Actually, the daily pumping rate of almost all cells is 2,000 m^3 in February, and 3,000 m^3 in March, April, and May. This is equivalent to an average of about 32 l/sec from each square kilometer throughout the pumping season. With an average agricultural demand of 10,000 m^3/ha/season, with 330,000 m^3 one may irrigate about 33 ha, or one third of the total area. If wells are spaced at 200 m (25 wells in one sq.km) each well should be pumping about 14,000 m^3 in a season of four months.

It was further assumed that the recharge in the future shall be distributed in the same way as it was in the past, as shown in Appendix 33. The inflow from hilly sides is kept constant throughout the period of simulation (45,200 m^3/day or 16.3 MCM in a year), as shown in Appendix 33. This is also obtained from the calibration of the model. The Narayani River was modelled exactly the same as in the year 1988-89 (as shown in Appendix 25). The outflow into India is handled in the following way: (a) in the first year the rates are exactly the same as in the 1988-89 (unsteady-state calibration period); (b) in the second year the outflow rates are reduced for 25%, in the third for 50%, and in the fourth for 75% of the rates in the first year. This is an arbitrary condition which takes into account the fact that with more ground water development the gradient of flow from north to south shall be reduced and less flow shall leave the district. (In reality, one may eliminate all the outflow and, moreover, reverse the gradient and get the water from south into the cone of depression formed in Nawalparasi.) All input parameters are taken from the calibration phase (permeability, storage coefficient, effective porosity, distribution of evaporation, aquifer geometry). The starting levels are the May 1988 levels which were also used in unsteady-state calibration (Appendix 17). The period of simulation is four years.

The following objectives are specified:

(1) To confirm that water levels will stabilize within the period of simulation (4 years) at an acceptable depth (within an easy reach of pumping).

(2) To demonstrate that at least 60% of shallow aquifer shall remain fully saturated, i.e. that the decline of levels shall not appreciably dewater the shallow aquifer.

(3) To produce water balance which will indicate the source of water for development and trends in the four-year period.

The whole period of 4 years was divided into 48 equal intervals, each of 30 days duration. (In this model, each month has 30 days.) With 161 cells involved in ground water development, at an average rate of about 3,000 m3/day, the total ground water withdrawal is equal to about 53 MCM/season. This is about 62% of the total recharge into the model area. Evidently, this is a very high development rate, which may have chances to succeed provided wells are properly located to lower water table beyond the reach of evaporation, or to prevent the outflow into India and/or Narayani River.

Results

The results are shown in Appendices 36 (decline of levels after 1st year), 37 (decline of levels after fourth year), 38 (absolute levels after fourth year), 39 (water balance), 40 (selected hydrographs), and in the balance table here below.

STEP	RECHARGE M3/DAY	RECHARGE L/SEC	PUMPING M3/DAY	PUMPING L/SEC	EVAPORATION M3/DAY	EVAPORATION L/SEC	RETURN. IRR M3/DAY	RETURN. IRR L/SEC	OUTFLOW M3/DAY	INFLOW M3/DAY
1	-95750.	-1108.	0.	0.	133599.	1546.	0.	0.	50540.	-45200.
2	-622375.	-7203.	0.	0.	104366.	1208.	0.	0.	50540.	-45200.
3	-957500.	-11082.	0.	0.	156116.	1807.	0.	0.	50540.	-45200.
4	-718125.	-8312.	0.	0.	392808.	4546.	0.	0.	50540.	-45200.
5	-239375.	-2771.	0.	0.	443778.	5136.	0.	0.	50540.	-45200.
6	-19150.	-222.	0.	0.	280354.	3245.	0.	0.	50540.	-45200.
7	0.	0.	0.	0.	208866.	2417.	0.	0.	50540.	-45200.
8	-86175.	-997.	0.	0.	149357.	1729.	0.	0.	50540.	-45200.
9	0.	0.	322000.	3726.	149310.	1728.	-64400.	-745.	50540.	-45200.
10	0.	0.	483000.	5590.	153252.	1774.	-96600.	-1118.	50540.	-45200.
11	-38300.	-443.	483000.	5590.	164290.	1901.	-96600.	-1118.	50540.	-45200.
12	-86175.	-997.	483000.	5590.	169025.	1956.	-96600.	-1118.	50540.	-45200.
13	-95750.	-1108.	0.	0.	170639.	1975.	0.	0.	40130.	-45200.
14	-622375.	-7203.	0.	0.	156791.	1815.	0.	0.	40130.	-45200.
15	-957500.	-11082.	0.	0.	170097.	1969.	0.	0.	40130.	-45200.
16	-718125.	-8312.	0.	0.	273519.	3166.	0.	0.	40130.	-45200.
17	-239375.	-2771.	0.	0.	370354.	4287.	0.	0.	40130.	-45200.
18	-19150.	-222.	0.	0.	232529.	2691.	0.	0.	40130.	-45200.
19	0.	0.	0.	0.	188860.	2186.	0.	0.	40130.	-45200.
20	-86175.	-997.	0.	0.	141117.	1633.	0.	0.	40130.	-45200.
21	0.	0.	322000.	3726.	139134.	1610.	-64400.	-745.	40130.	-45200.
22	0.	0.	483000.	5590.	154522.	1788.	-96600.	-1118.	40130.	-45200.
23	-38300.	-443.	483000.	5590.	160020.	1852.	-96600.	-1118.	40130.	-45200.
24	-86175.	-997.	483000.	5590.	165853.	1920.	-96600.	-1118.	40130.	-45200.
25	-95750.	-1108.	0.	0.	167369.	1937.	0.	0.	29720.	-45200.
26	-622375.	-7203.	0.	0.	153604.	1778.	0.	0.	29720.	-45200.
27	-957500.	-11082.	0.	0.	167031.	1933.	0.	0.	29720.	-45200.
28	-718125.	-8312.	0.	0.	278071.	3218.	0.	0.	29720.	-45200.
29	-239375.	-2771.	0.	0.	355133.	4110.	0.	0.	29720.	-45200.
30	-19150.	-222.	0.	0.	234125.	2710.	0.	0.	29720.	-45200.
31	0.	0.	0.	0.	191321.	2214.	0.	0.	29720.	-45200.
32	-86175.	-997.	0.	0.	141991.	1643.	0.	0.	29720.	-45200.
33	0.	0.	322000.	3726.	140766.	1629.	-64400.	-745.	29720.	-45200.
34	0.	0.	483000.	5590.	154650.	1790.	-96600.	-1118.	29720.	-45200.
35	-38300.	-443.	483000.	5590.	174502.	1847.	-96600.	-1118.	29720.	-45200.
36	-86175.	-997.	483000.	5590.	166340.	1925.	-96600.	-1118.	29720.	-45200.
37	-95750.	-1108.	0.	0.	166982.	1933.	0.	0.	19310.	-45200.
38	-622375.	-7203.	0.	0.	153510.	1777.	0.	0.	19310.	-45200.
39	-957500.	-11082.	0.	0.	167617.	1940.	0.	0.	19310.	-45200.
40	-718125.	-8312.	0.	0.	284223.	3290.	0.	0.	19310.	-45200.
41	-239375.	-2771.	0.	0.	353438.	4091.	0.	0.	19310.	-45200.
42	-19150.	-222.	0.	0.	238335.	2759.	0.	0.	19310.	-45200.
43	0.	0.	0.	0.	191947.	2222.	0.	0.	19310.	-45200.
44	-86175.	-997.	0.	0.	143506.	1661.	0.	0.	19310.	-45200.
45	0.	0.	322000.	3726.	141322.	1636.	-64400.	-745.	19310.	-45200.
46	0.	0.	483000.	5590.	157121.	1819.	-96600.	-1118.	19310.	-45200.
47	-38300.	-443.	483000.	5590.	161923.	1874.	-96600.	-1118.	19310.	-45200.
48	-86175.	-997.	483000.	5590.	168773.	1953.	-96600.	-1118.	19310.	-45200.

Out of the total pumping volume, 20% is assumed to have returned into the subsurface, recharging the shallow aquifer, in the form of "return" irrigation. This is to say that any irrigation over a permeable surface is equivalent to artificial recharge by surface spreading. The percentage of 20 is assumed considering the method of irrigation, the one practiced with rice crop.

Thus the water balance in each of four years of simulation may look as follows (see also Appendix 39).

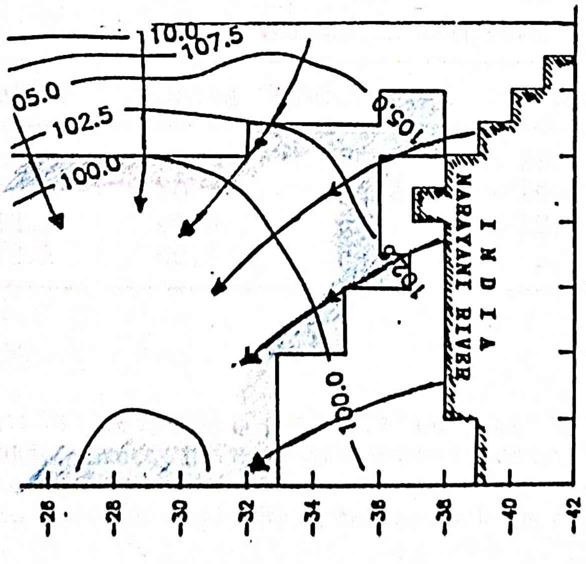
All values in MCM/year

Year	Recharge	Inflow	Return	Pumping	Evaporation	Outflow
1	85.9	16.3	10.6	53.1	75.2	18.2
2	85.9	16.3	10.6	53.1	69.7	14.4
3	85.9	16.3	10.6	53.1	69.7	10.7
4	85.9	16.3	10.6	53.1	69.9	6.9

In the last year, the input into the system (recharge from rainfall, return irrigation, inflow from hills) amounts to about 112.8 MCM. The discharge is equal to 129.9 MCM. There is still a de-balance between recharge and discharge. This is to say that the shallow ground system is not yet fully in equilibrium and additional decline of water levels beyond the fourth year could be foreseen. Alternatively, the system can be in full equilibrium and the "missing" volume comes from the Narayani River. That this second is the case is proven by the fact that water levels do not decline beyond the third year (see Appendices 40). The difference between input and output of 17.1 MCM is about 0.5 m^3/sec which is negligible compared to the minimum flow rate of the Narayani River of several hundred cubic meters per second.

The best demonstration of the evolution of water levels in the four-year pumping scheme is given in Appendices 36 and 37. After the first year of pumping the maximum decline of water levels is about 3.9 m; after the fourth year the maximum is about 4.3 m.

The map of water levels after the fourth year of extensive ground water development as shown in Appendix 38, indicates that the Narayani River contributes water to the zone of ground water development. This is clear from the curvature of water level contour lines. A portion of the flow net is reproduced in the sketch below.



The scheme of development as tested herein was not quite successful in utilizing the evaporation loss. The loss was diminished from 75.2 MCM/year to some 69.7 MCM/year, but this was insufficient. Still plenty of water is being lost through the evaporation process. Instead, the "unbalanced" development (pumping) was offset by the contribution from the Narayani River.

It may be concluded that the scheme of shallow ground water development as tested in this phase of the modelling is quite acceptable. It appears that such distribution of wells and their pumping rates are not the absolute development potential of the shallow ground water of the Nawalparasi district. Additional water can come from the Narayani River, if wells are located near by. Likewise, there is still about 6.9 MCM of shallow ground water outflowing into neighboring India. This could be "salvaged" by eliminating the boundary condition according to which this water still flows out of the modelled area. Also, some additional pumping, but not a large-scale development, can be spread all over the western part of the model, reducing the evaporation loss by lowering water level. This last scenario shall be tested in the Development Scheme No. 2, which is explained below.

5.3. Development Scheme No. 2

The second development scheme tested, in addition to wells from scheme 1, some development to the west and center of the district. Transmissivities in those areas are low, less than 200 m^2/day, and one does not expect favourable conditions for extensive and large-scale shallow ground water development. Yet it is up to the model to prove it!

In additional 87 cells, as shown in Appendix 41, pumping rates amount to 1,000 m^3/day throughout the pumping period of four months (120 days). Thus, the total additional pumping is 10.44 MCM. However, the pumping from the previous zone (Scheme 1) is slightly reduced in the northern part (columns 10,11,12). Thus the pumping from zone I is 50.1 MCM, or the total tested in this scheme is 60.5 MCM. The results are shown in Appendices 42 (decline of levels after fourth year of pumping), 43 (map of levels after four years of pumping), 44 (saturated thickness at the end of the fourth year), 45 (water balance in four years), 46 (selected hydrographs).

The hydrographs indicate that the spread of cone of depression beyond the fourth year shall be minor. The water balance for each of four years is shown here below.

All values in MCM/year

Year	Recharge	Inflow	Return	Pumping	Evaporation	Outflow
1	85.9	16.3	12.1	60.5	74.3	18.2
2	85.9	16.3	12.1	60.5	65.2	14.4
3	85.9	16.3	12.1	60.5	64.1	10.7
4	85.9	16.3	12.1	60.5	64.1	6.9

In the fourth year of pumping, the total input into the system is 114.3 MCM and output 131.5 MCM (Appendix 45). The difference is 17.2 MCM, which is exactly the same as in the first scheme. The additional 7.4 MCM of water available for development come from reduced evaporation (5.8 MCM) and from storage (1.6 MCM). One may assume that there will be additional decline for a year or so until the evaporation loss is reduced for 2 MCM. As in the case in the development scheme 1, the difference of some 17 MCM comes from the Narayani River in the form of induced recharge.

This scheme is also favourable with one caution. The wells in the zone with less transmissivity must be numerous and spread all over the selected zone. Individual pumping rate of a well should not be more than 5 l/sec, or the time of pumping should be less in a day. Ideally, each well should be producing about 5,000 m3 of water in 4-month season.

5.4. Development Scheme No. 3

The scheme of development occupies exactly the same area as in Scheme 2 with the same number of "producing" cells. The difference is in pumping rates in the central part of the area I which are almost doubled (from 2,000 and 3,000 m^3/day to 5,000 m^3/day). Thus, central cells (30 km^2) shall pump additional 7.2 MCM, making the total tested withdrawal in that area equal to 60.9 MCM, and the total from both areas equal to 71.3 MCM (see Appendix 47). The results are shown in Appendices 48 (decline of levels after the fourth year), 49 (map of levels after the fourth year), 50 (balance), 51 (selected hydrographs), and 52 (cone of depression).

The water balance for each of four years is shown here below.

All values in MCM/year

Year	Recharge	Inflow	Return	Pumping	Evaporation	Outflow
1	85.9	16.3	14.3	71.3	68.1	18.2
2	85.9	16.3	14.3	71.3	63.3	14.4
3	85.9	16.3	14.3	71.3	60.7	10.7
4	85.9	16.3	14.3	71.3	60.4	6.9

In the fourth year of pumping, the total input into the system is 116.5 MCM and output 138.6 MCM (Appendix 50). The difference is 22.2 MCM, which alone should not indicate that the development scheme is not acceptable. Also, hydrographs shown in Appendix 51 indicate that equilibrium between input and output has been reached after four years, or shall be reached a year or so afterwards. Additional decline beyond the fourth year could be anticipated but to a minor amount. Probably the development scheme No. 3 is close to the maximum development potential of the shallow ground water system of Nawalparasi West.

Concluding Remarks.

The model is ready to test some additional schemes of development, with different aerial distribution, different individual pumping rates, and diverse time schedules. The testing of additional schemes of development can be done in cooperation with other concerned agencies, such as the Agricultural Development Bank of Nepal.

6. CONCLUSIONS AND RECOMMENDATIONS

The model of the shallow ground water system of the western part of Nawalparasi district was primarily made to arrive at a global water balance of the modelled area, and to indicate a maximum development potential for future ground water exploitation. In the process, all components of the system have been verified.

The modelling study is a companion work to the UNDP-GWRDB project field activities. It could be considered as the state-of- the-art in quantitative evaluation of the natural system and its future development potential.

The whole simulation was divided into four phases. The phase I was to confirm an initial map of water levels which was constructed on the basis of field monitoring in May 1988. This is called the "steady-state calibration", and is equivalent to confirming the minimum water levels (maximum depths to water table) at the end of a long dry season. The primary result of the steady-state calibration was the distribution of permeability coefficients (hydraulic conductivity), setting up the geometry of the shallow aquifer, and arriving at correct recharge and evaporation values. The conclusion of the steady-state calibration was that the recharge (from infiltrated rainfall) in the dry portion of a year is equivalent to about 1.7 MCM/month (million cubic meters), and from inflow across model boundaries in the hilly north (either as underflow in dry river beds, or spring flow, or simply surface runoff from hills into the plain) to another 1.5 MCM/month. Out of this amount some 1.6 MCM are consumed by the evaporation process, 1.5 MCM outflows into India, and very little remains to feed the Narayani River (only 2073 m^3/day). This is to say that the recharge in the dry season comes from infiltrated rainfall (in March through May) and from hilly sides in the north (Siwalik hills), in a form of subsurface flow through dry river beds that cut the Siwalik hills. Both components are of about the same order of magnitude. The evaporation and outflow into India are also of about the same order. The evaporation loss is less than one would expect in other months because water levels are at maximum depths from the land surface. In the process of steady-state calibration, the map of transmissivities was produced, which did not differ materially from the one obtained from pumping tests.

The second phase was that of unsteady-state calibration of the model in the period from May 1988 through February 1989. This is the period of the rise of water levels in the monsoon season, and postmonsoon decline. The rise is well documented in some 17 observation wells which were the basis for the whole modelling. The unsteady-state calibration was considered successful since the model did reproduce both the water level rise and decline that were recorded in the nature.

The third phase of the modelling was to confirm that the "model" levels shall make a full cycle in one year, arriving at May levels at the end of the simulation. Only in that way, when the filling up and depletion of the storage are balanced, one may conclude about the recharge-discharge relationship. This phase was called the "verification" of the model. In this case, the period to "cover" was only three months (February-May). Also, since the year 1988 was with much more rain than in a long-term average, one would expect that the end May 1989 levels would be above the May 1988 levels. (However, this is in the domain of speculation since the May 1989 is two months ahead!) The model indicated that, in one-year cycle, most of the water recharged from infiltrated rainfall or entered from the hills is lost through evaporation process and that the flow into the Narayani River is a minor component of the total balance. The simulation indicated the source of water that may be utilized more beneficially than letting the water to flow into neighboring India, or be consumed by the evaporation. The water balance may be interpreted in the following way. The total input of water into the shallow ground water system in one-year period between May and May is equal to about 115 MCM (million cubic meters). Out of this volume, about 97 MCM comes from direct infiltration of rain and ground water accretion on account of infiltrated rain reaching the water table, and 18 MCM come as inflow into the shallow ground water system from the hill sides. Clearly, on an annual basis, the infiltration of rainfall is much superior to the inflow from hills. The total discharge of water from the aquifer in one year period amounts to about 105 MCM, out of which to evaporation loss (coupled with some minor pumping from shallow wells) goes 87 MCM and to outflow across model boundaries to India another 18 MCM. Again, in one-year period, the evaporation loss outweighs the outflow into India by the factor of 5. What remains, i.e. 10 MCM, may either fill up the storage (levels in May 1989 could be higher than in May 1988), or outflow into the Narayani River. The model does not distinguish between the two.

From this water balance one may conclude that any future ground water development from shallow aquifer may come mostly on expense of reduced evaporation and outflow into the Narayani River. The evaporation loss can be reduced by lowering the water levels to a depth that will prevent or diminish the losses. The outflow into the Narayani River can be reduced by pumping from shallow wells located along a stretch parallel to the river course. It is a favourable coincidence that along the right bank of the Narayani River the shallow aquifer is the most promising, having good thickness and almost the best transmissivity in the whole district. In the process, an average recharge into the shallow ground water system was calculated. The volume of 97 MCM of direct recharge from infiltrated rainfall in a year is equivalent to about 11% of the total average annual rainfall falling over an area of some 600 km^2 (active model area). This percentage may be accepted as an average recharge percentage for the whole district.

All the previous phases were a kind of establishing the model as a credible tool for forecasting an extensive future development of shallow ground water. The philosophy behind the last phase is the following. If the model is successful in reproducing the past, it could be used in predicting the future. The Nawalparasi model was shown to correctly duplicate the behaviour of shallow water table in the period from May through February 1988.

After several check runs, it was decided to fully test three development schemes. The criterion for locating the pumping wells (cells) was the following: (a) acceptable transmissivity, (b) water table close to the surface, (c) site near the Narayani River. It was learnt, from the modelling study before coming to this stage, that the shallow ground water development should come on expense of losses to evaporation (87 MCM/year) and outflow of about 18 MCM/year to India. Some induced recharge from the Narayani River may augment the total "safe yield" of the Nawalparasi shallow ground water system. However, about 40 km2 near the Narayani River, although the most promising for development, deliberately are not included into the pumping scheme since there exists a surface-irrigation system Gandak which takes water directly from the Narayani River. Following the conclusions of the Basic Documentation Report (Technical Report No. 5) and the calibration of this model, it was decided to locate future wells in an area of some 161 km^2 in the south- central part of the district (development scheme No.1), and to test expansion of development in the central western part between Parasi, Parsawal, Lalpati, Bisnupura (development schemes 2 and 3) over a n area of some 84 km^2. The total pumping rate in scheme No. 1 is 53.1 million cubic meters (MCM) in pumping season which starts in February and terminates in May. In schemes 2 and 3, the total withdrawal was higher, 60.5 and 71.3 MCM, respectively.

The central area (Gobrahiya-Dabila-Khairani-Guthi Parsauni) contains 161 pumping cells in each of three development schemes. Since one cell is 1000 m by 1000 m large, the number of wells that may actually be located in one cell could be on average 25, if the wells are located at 200 m distance one from the other. Thus the total number of wells could be about 4000 in that area alone. The individual rates of pumping from cells differ from scheme 1 to 3. In scheme no. 1 an average pumping from one cell in the whole pumping season of 120 days amounts to about 330,000 m^3. The same is in scheme no. 2, but in scheme no. 3 it is raised to 500,000 to 600,000 m^3. Thus this area alone is simulated as producing from 50.1 to 60.9 MCM in a pumping season.

The northern-central area is simulated in schemes 2 and 3 as producing additional 10.4 MCM of shallow water in one season. Individual cells are subjected to much lower stress, 1,000 m^3/day everywhere, on the grounds of much inferior transmissivity.

The pumping volumes of about 330,000 m3/season are equivalent to an average of about 32 l/sec from each square kilometer throughout the pumping season. With an average agricultural demand of 10,000

m^3/ha/season, with 330,000 m^3 one may irrigate about 33 ha, or one third of the total area. If wells are spaced at 200 m (25 wells in one sq.km) each well should be pumping about 13,200 m^3 in a season of four months.

The development schemes were tested over a period of four years, on a cyclic basis: pumping in 4 dry months, idling in the remaining eight months. The results are encouraging in each of tested schemes. The dynamic levels after four seasons of pumping are very close to being steady, and the total drawdown in most of the modelled area is less than 6 meters. In each of tested schemes of development there is a debalance between total input into the system (recharge from rain, from hills, and return irrigation) and output (evaporation, pumping, flow into India). However, the debalance is a minor component, between 17.1 and 22.2 MCM, which is actually "covered" by the contribution of the Narayani River. (This amounts to less than 600 l/sec of river "induced" recharge, compared with minimum river flow of several hundred cubic meters per second.)

The model of the Nawalparasi district is an example of modelling of shallow ground water system in the Terai. It offers a sound base for ADBN development plans. The conclusions formulated herein are believed to be on the safe side. The model did not count with any recharge from other rivers except the Narayani River. It, also, did not take into account an eventual inflow of water from neighboring districts. Although previous reports have speculated about the maximum permissible number of shallow wells in various districts of the Terai, mentioning the number of 2037 for Nawalparasi (which is an understatement considering that more low-capacity wells should be constructed in relatively low transmissivity area), this modelling study formulated not only the number of wells, but suggested the area which may be favourable for the overall development of the shallow ground water resource. In the simulation process, the model evaluated quantitatively all components of the shallow ground water system: recharge from infiltrated rain, evaporation loss from very shallow water table, filling up and depleting the storage, connection with the Narayani River.

In order to improve the model and its conclusions with respect to potential shallow ground water development the following is recommended:

(1) Drill several exploration shallow wells between Parasi and Jamuniya (between model rows 13 and 20). This is to make a better demarcation between favourable zone to the southeast and less favourable to the north west.

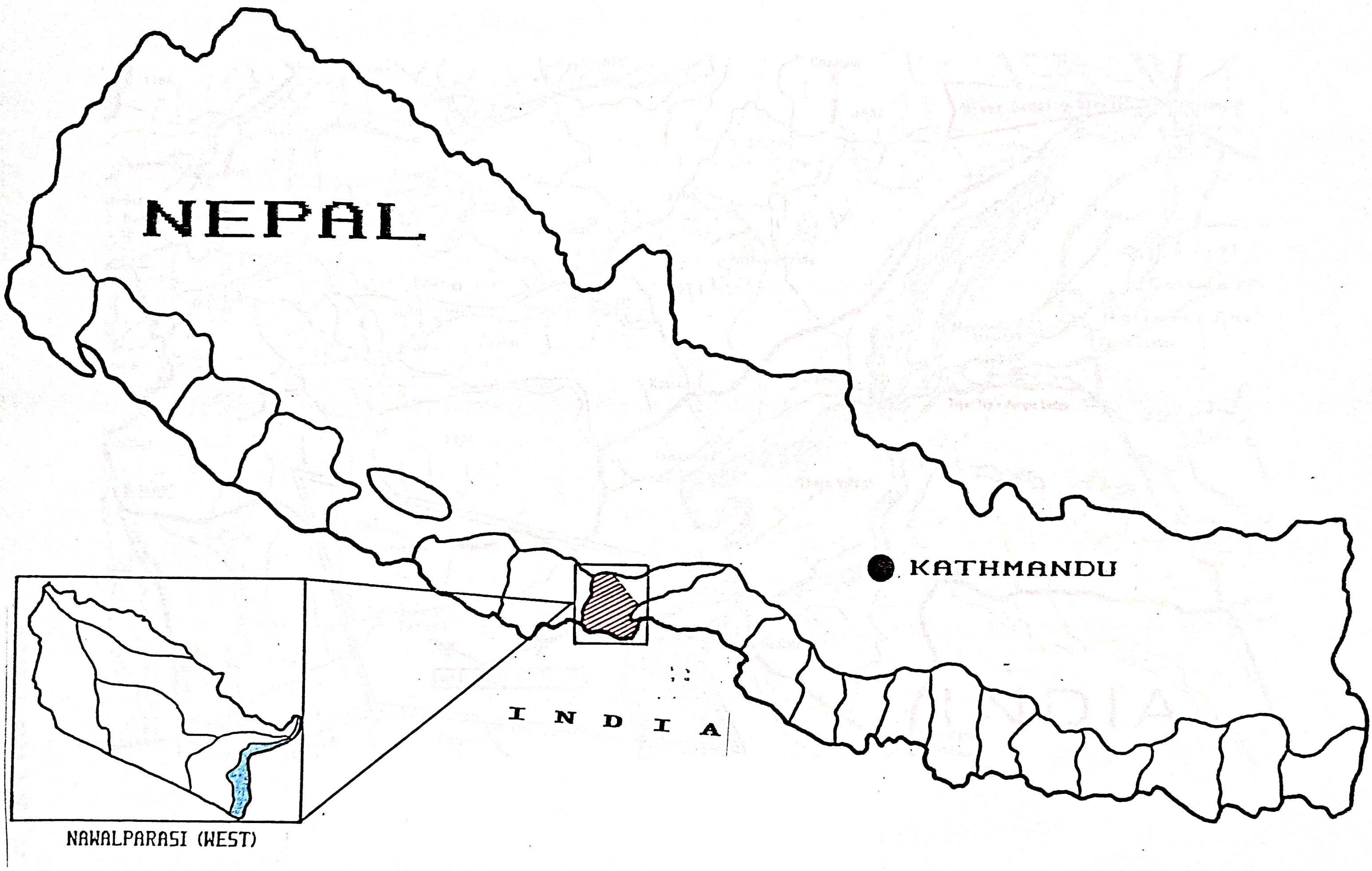
(2) Make additional drilling near the hills, on the line Badera - Jamuniya - Paldanda, to prove or disapprove the poor lithology of shallow zone near the Siwalik hills.

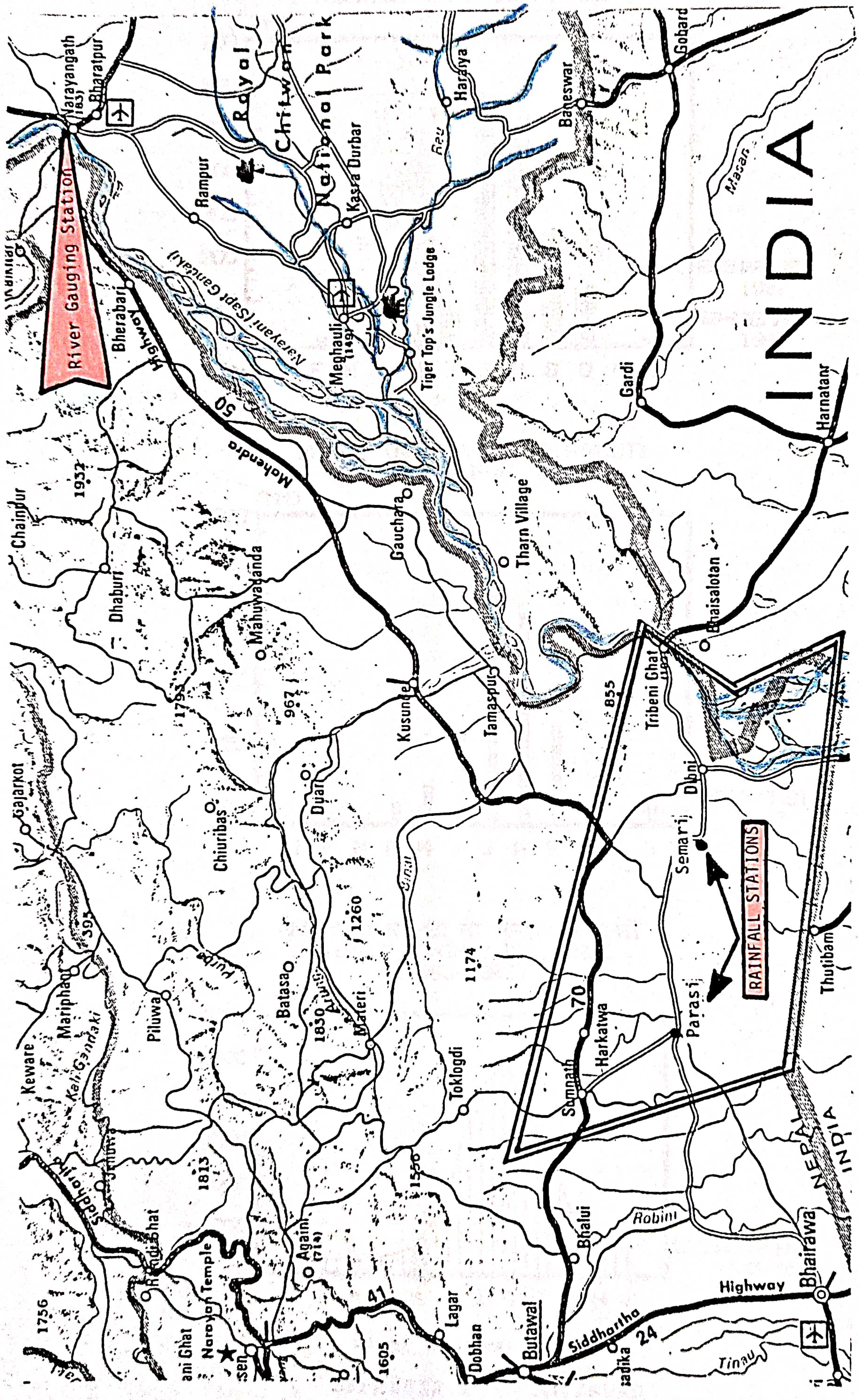
(3) Make pumping tests from as many as possible existing shallow tube wells. It is expected that at least 200 STW's exist in the area, and most of them were drilled in the last 5 years.

(4) Establish a river gauging station in Tribeni Gath. Describe the river flow in flood stage at the downstream end of the Narayani River in Nepal.

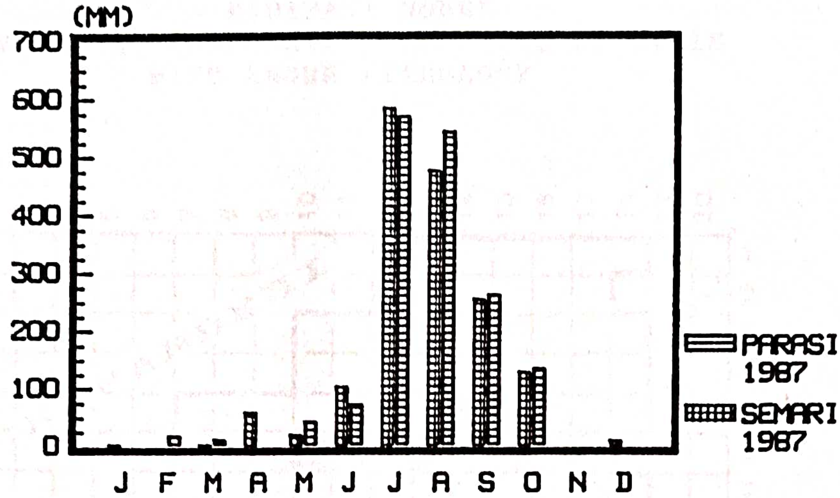
(5) Define the plans of future shallow ground water development in Nawalparasi district and test the planning alternatives with the present model.

APPENDIX 1

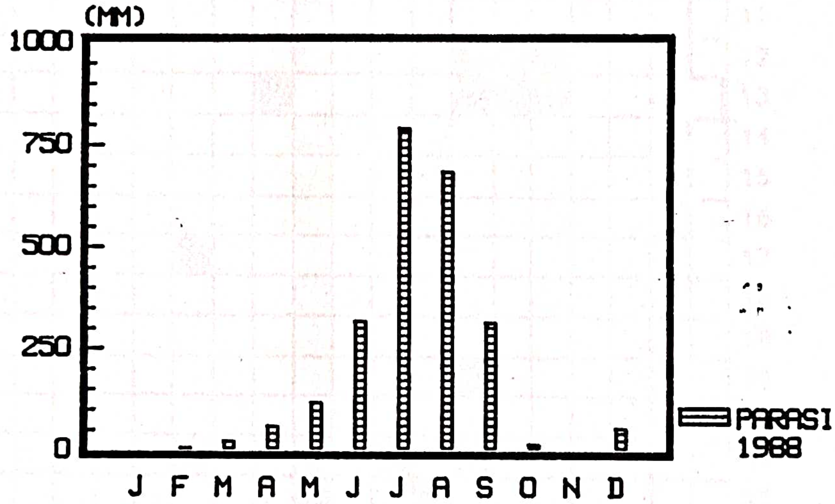



River Gauging Station
RAINFALL STATIONS
Royal Chitwan National Park
INDIA
NEPAL
Narayangath
Bharatpur
Rampur
Kasra Durbar
Meghauli
Tiger Top's Jungle Lodge
Tharn Village
Narayani (Sapt Gandaki)
Mahendra Highway
Bherabari
Chainpur
Dhaburi
Mahuwa Danda
Gauchara
Kusunde
Tamaspur
Tribeni Ghat
Bhaisalotan
Gardi
Harnatanr
Bagaha
Gobard
Dubi
Semari
Parasi
Thutibam
Harkatwa
Somnath
Toklogdi
Gajarkot
Chiuribas
Duari
Batasa
Piluwa
Mariphant
Keware
Kali Gandaki
Jhumsa
Ridi Ghat
Rudrubhat
Narayan Temple
Againi
Lagar
Dobhan
Butawal
Bhalui
Robini
Siddhartha Highway
Bhairawa
Tinau
Mareri
1932
1795
967
855
1260
1174
1830
1813
1556
1605
1756
595
50
70
41
24

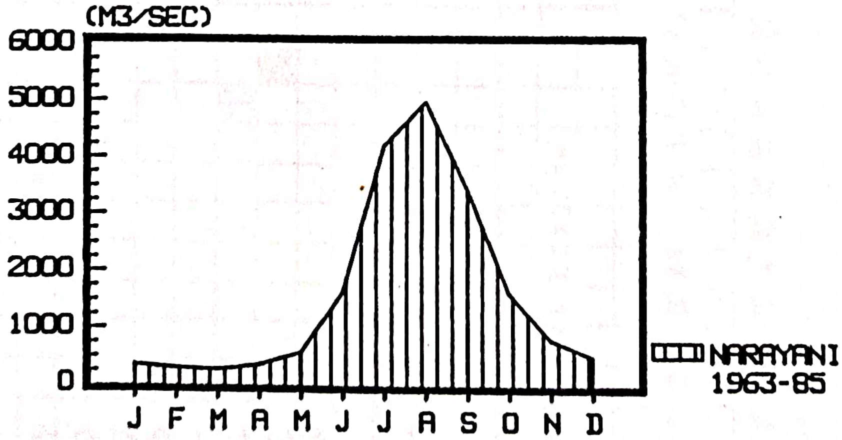
SEMARI & PARASI (NAWALPARASI DISTRICT)
MONTHLY RAINFALL IN 1987



PARASI (NAWALPARASI DISTRICT)
MONTHLY RAINFALL IN 1988



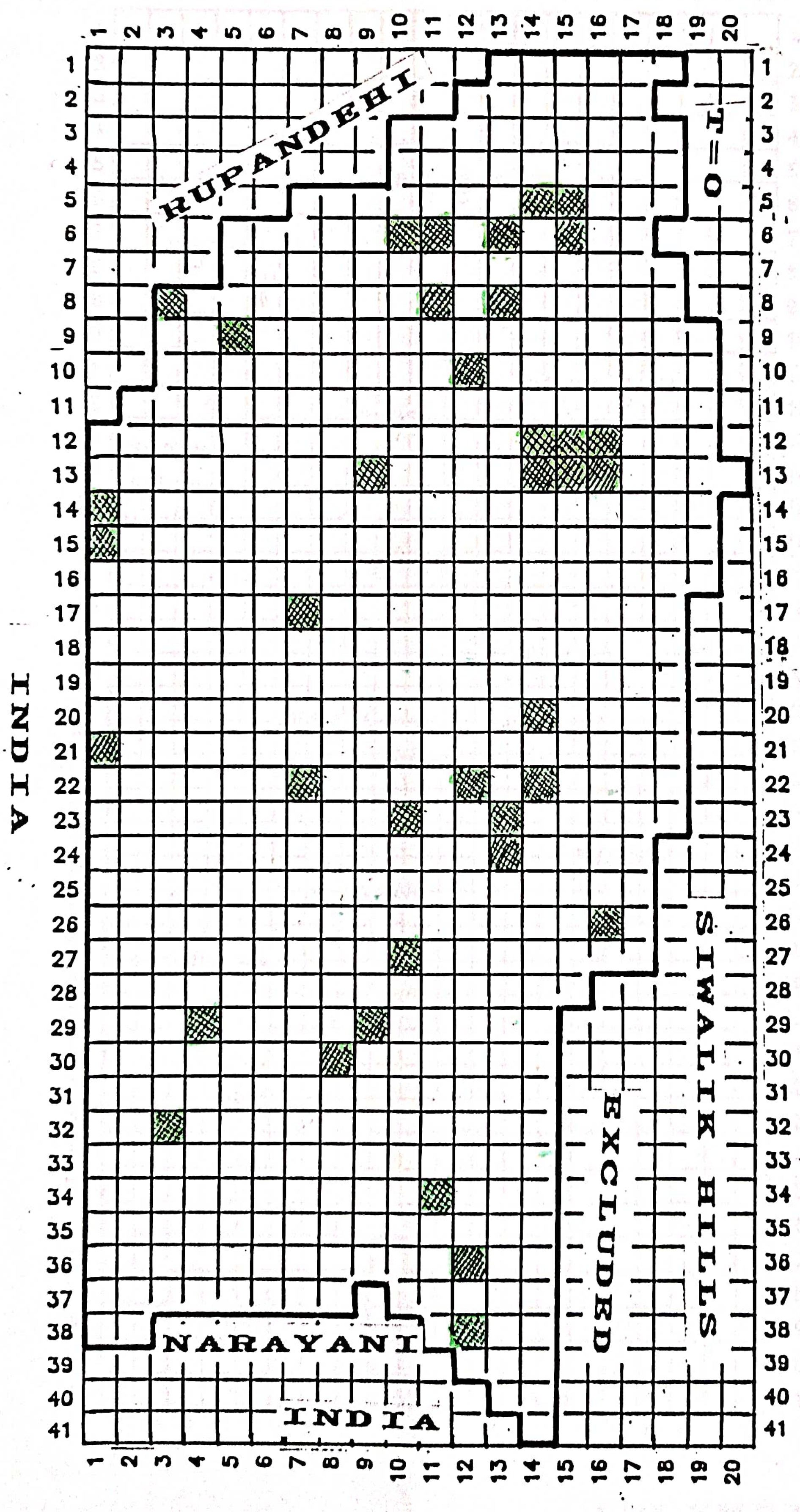
NARAYANI RIVER AT NARAYAN GHAT
AVERAGE MONTHLY DISCHARGE
(1963-1985)



River Station: 450

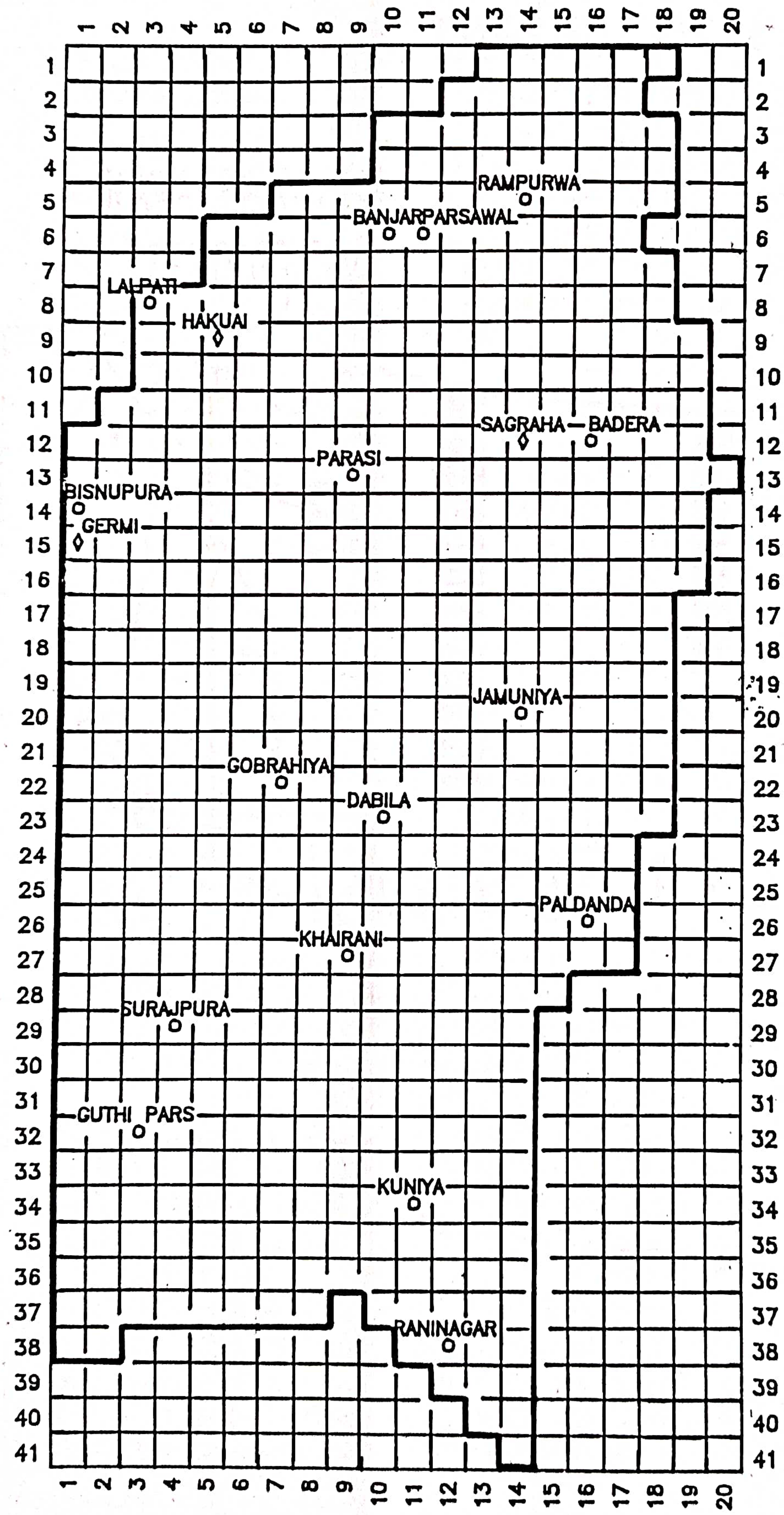
APPENDIX 2 - CONTINUED

NARAYANI MODEL
MODEL NETWORK, BOUNDARIES, LOCATION OF WELLS
WITH KNOWN LITHOLOGY



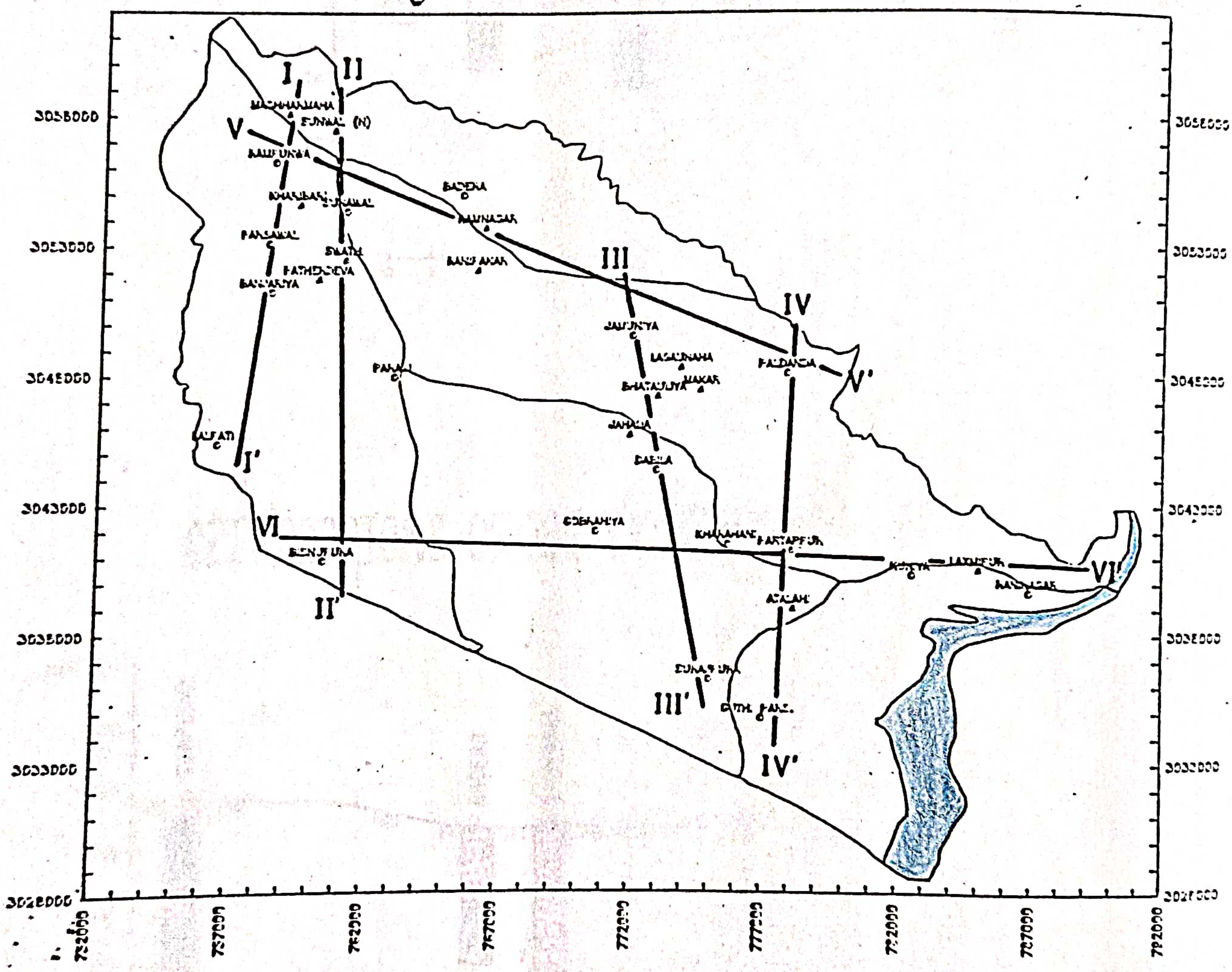
APPENDIX 3

NAWALPARASI MODEL
MODEL NETWORK AND LOCATIONS OF OBSERVATION WELLS

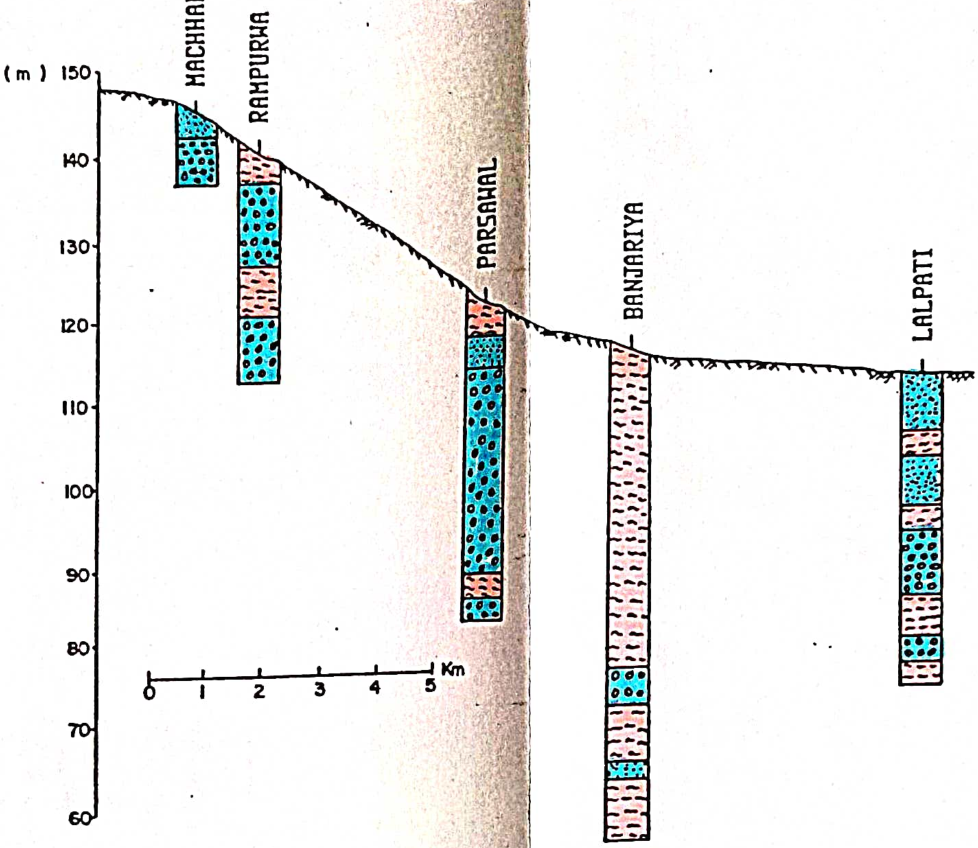


APPENDIX 4

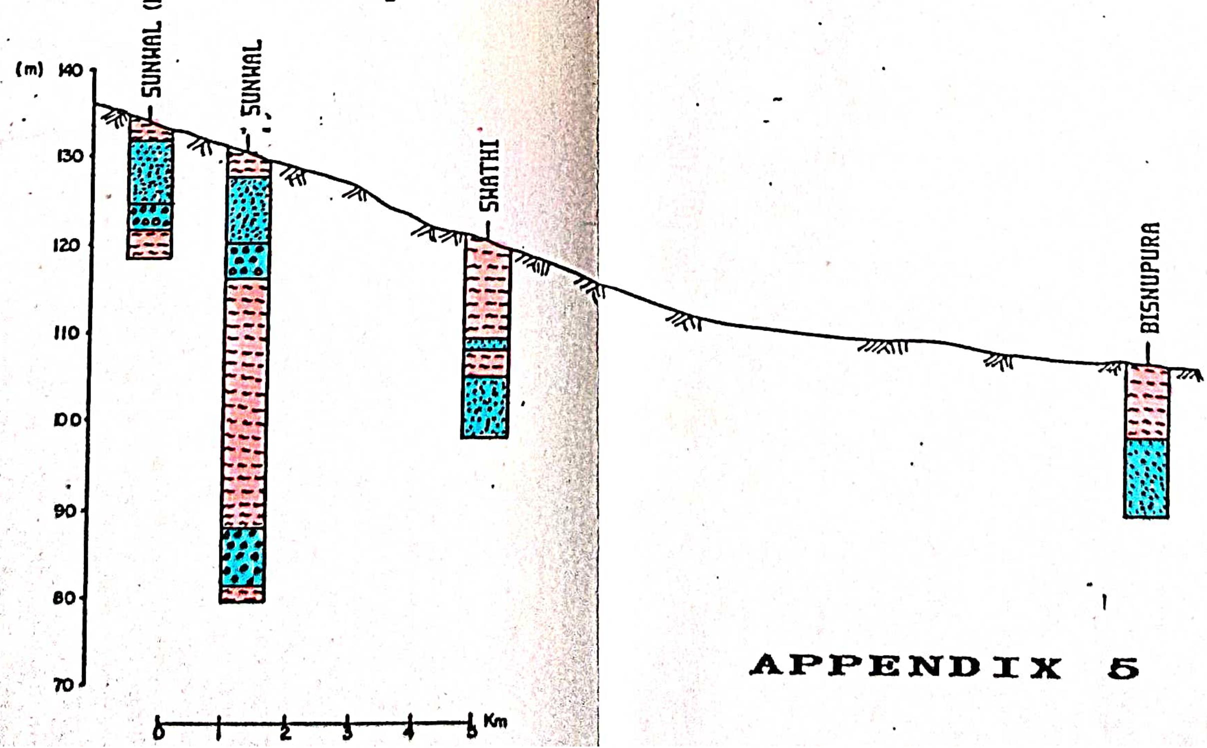
NAWALPARASI (W) – LOCATION OF WELLS
LITHOLOGICAL CROSS SECTION (I – VI)



LITHOLOGICAL CROSS SECTION I - I'

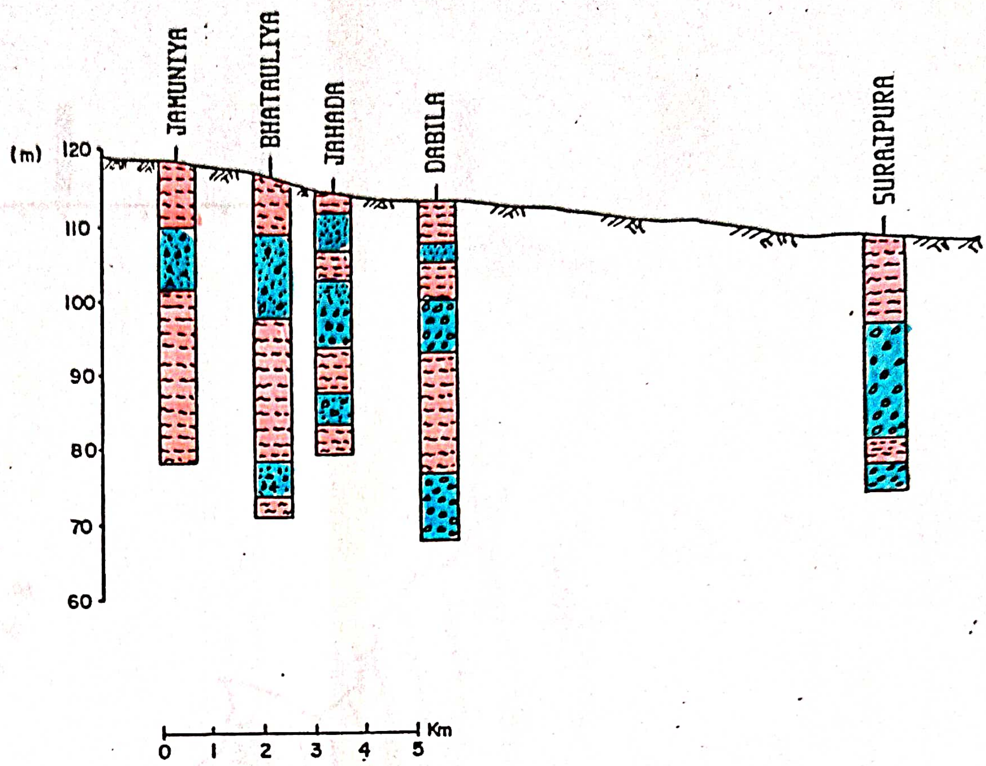


LITHOLOGICAL CROSS SECTION II - II'

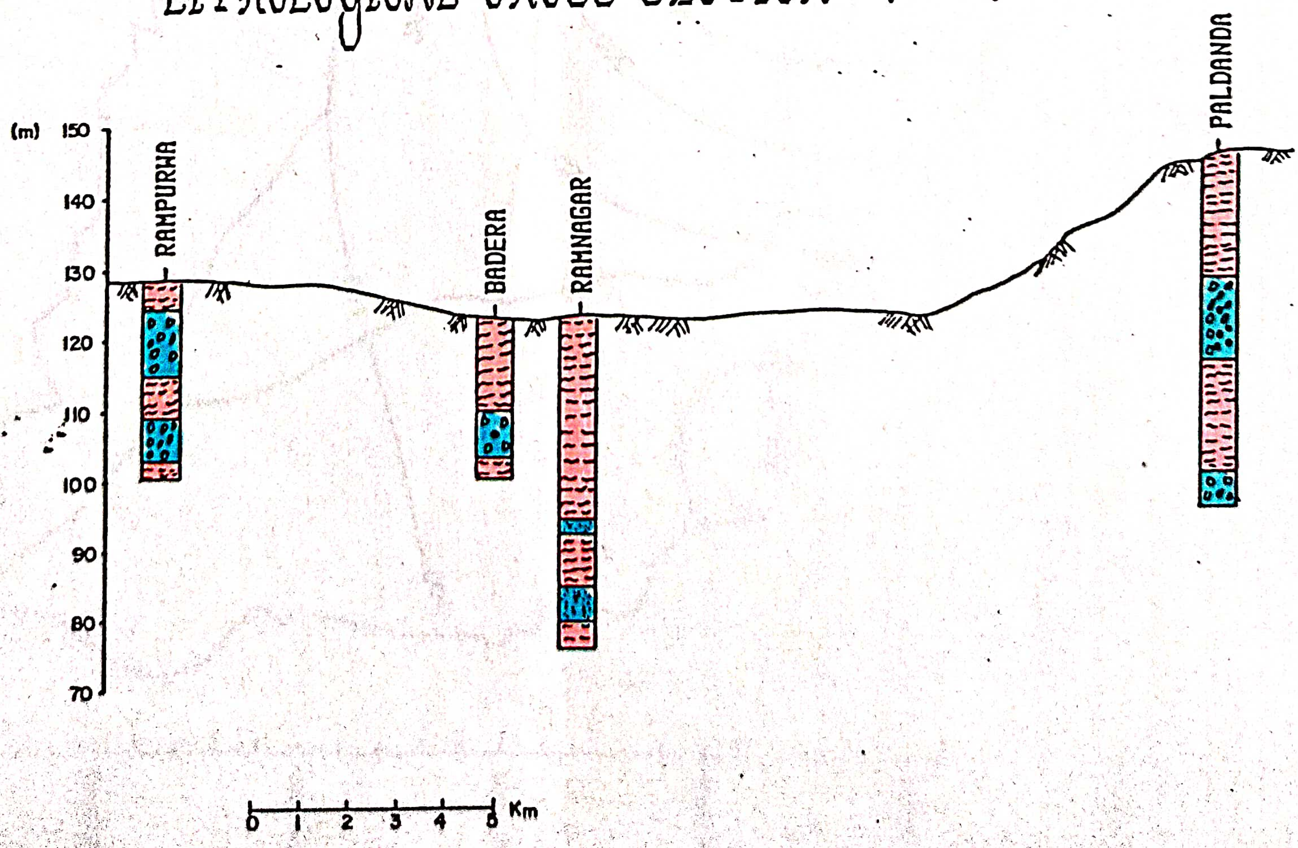


APPENDIX 5

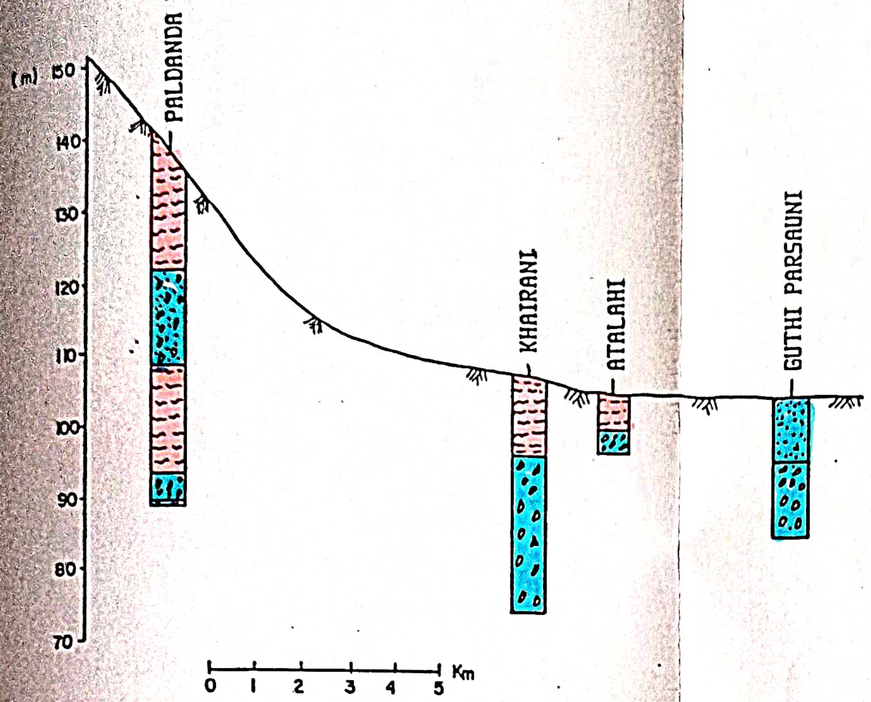
LITHOLOGICAL CROSS SECTION III - III'



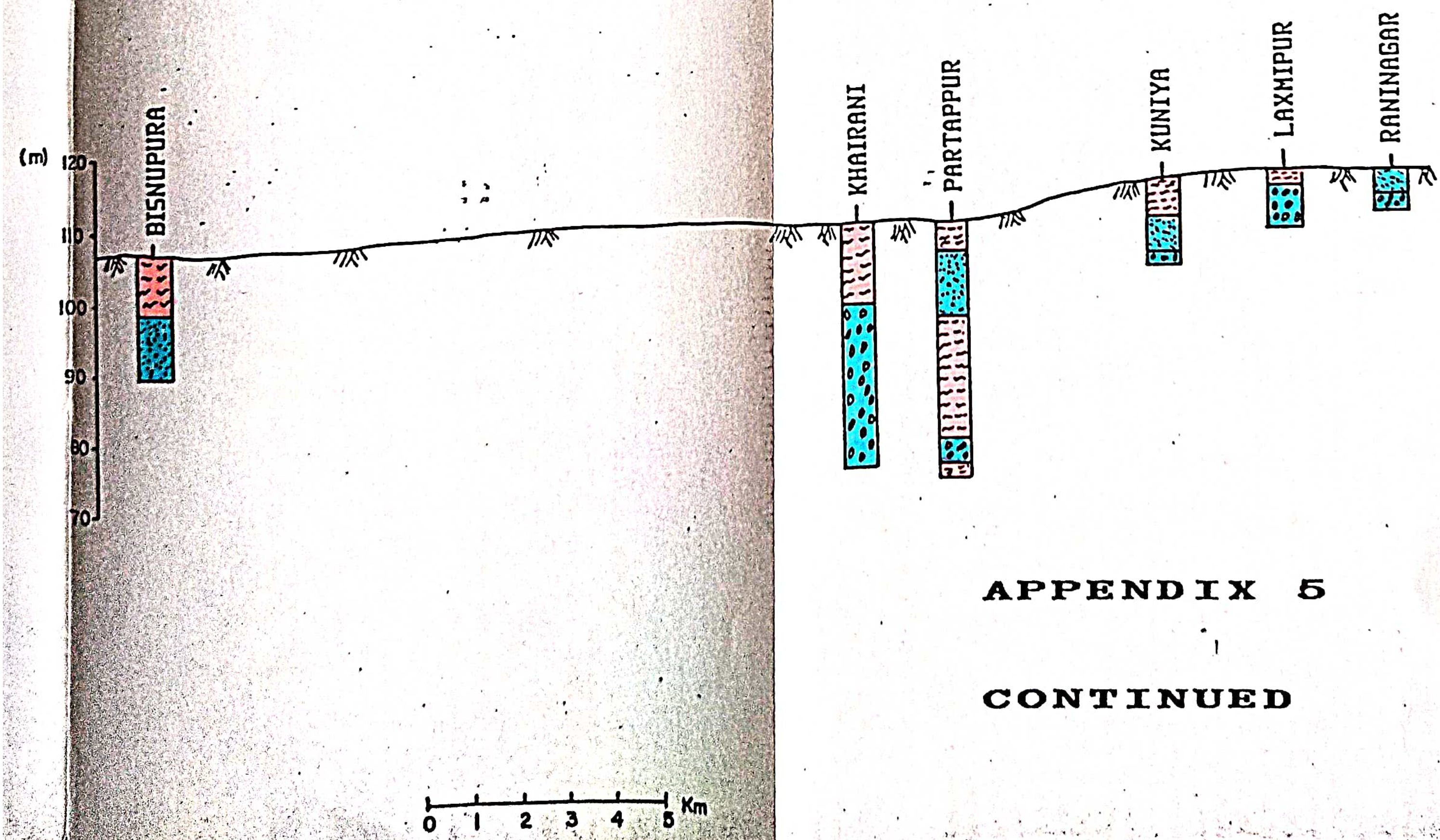
LITHOLOGICAL CROSS SECTION V - V'



LITHOLOGICAL CROSS SECTION IV - IV'



LITHOLOGICAL CROSS SECTION VI - VI'

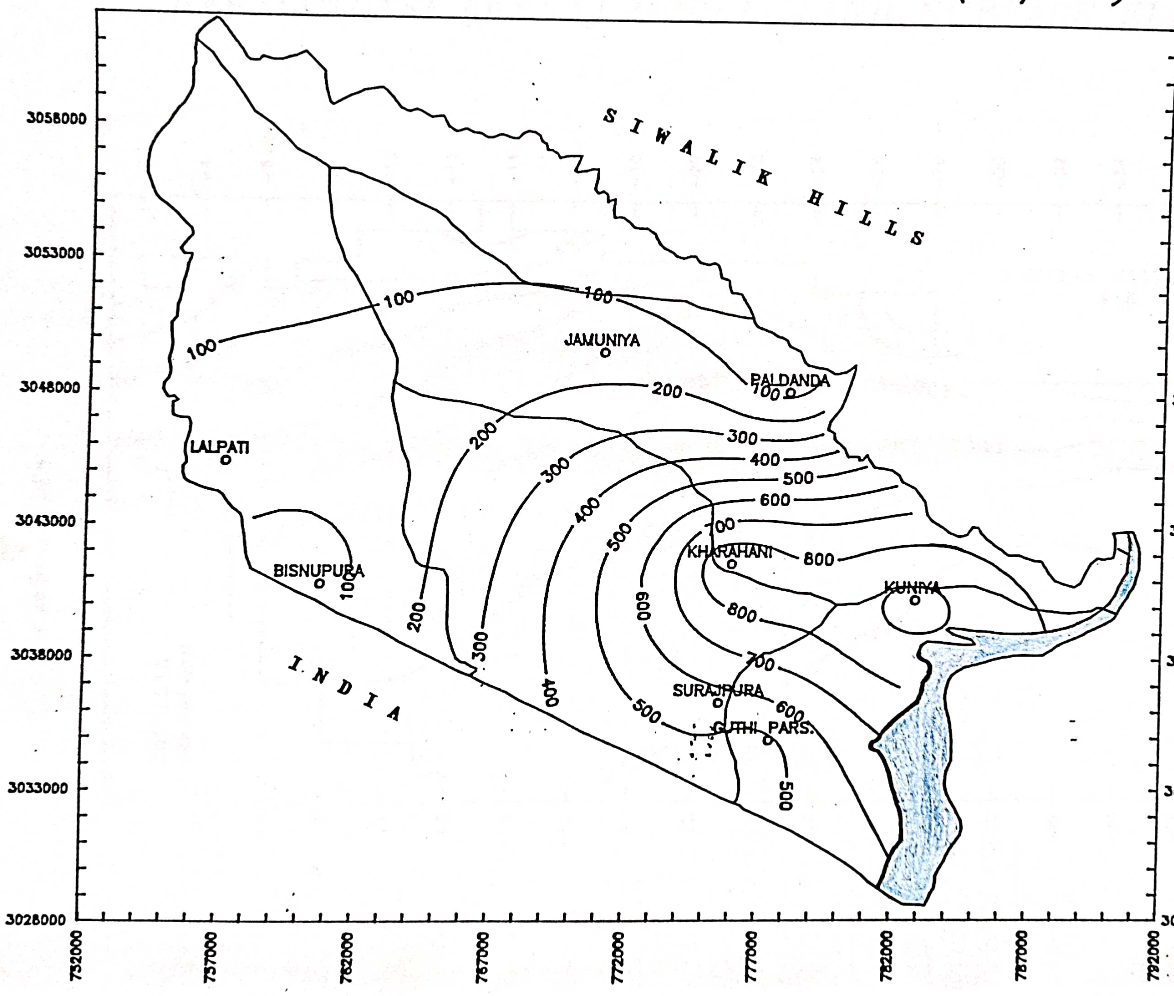


APPENDIX 5

CONTINUED

APPENDIX 6

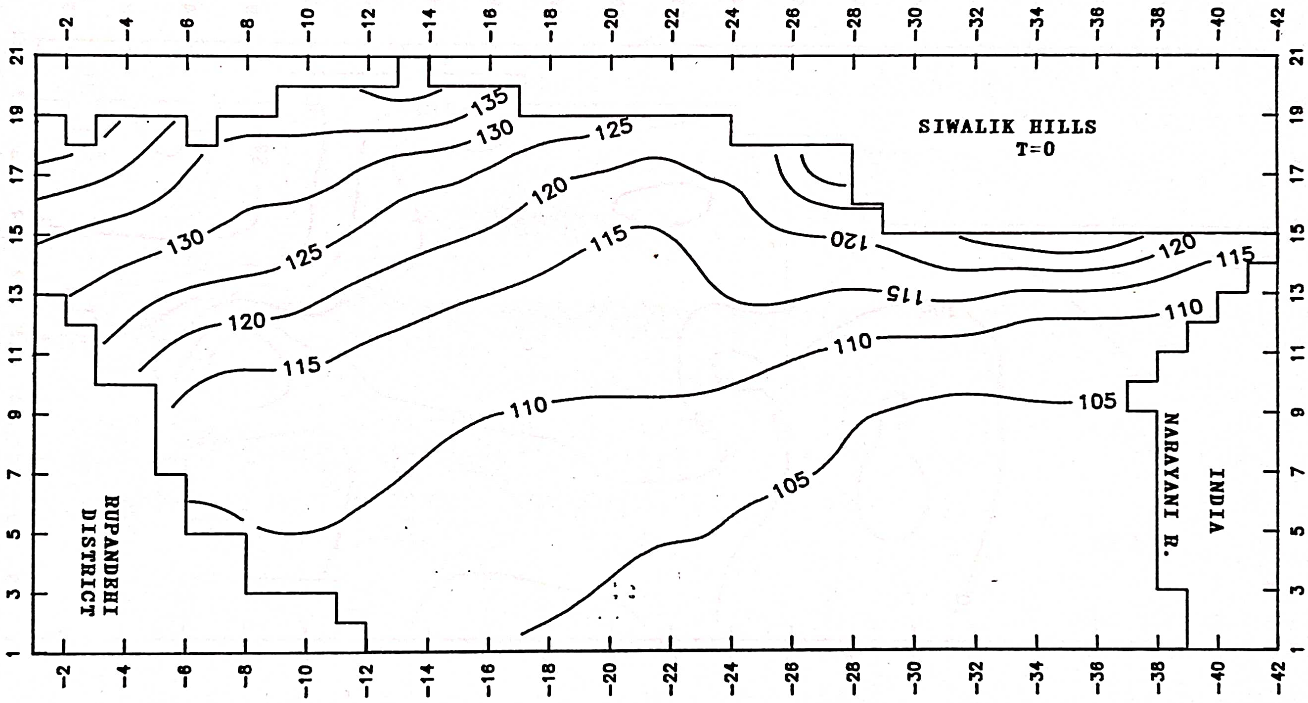
NAWALPARASI (WEST) TRANSMISSIVITIES (M2/DAY)



MAP PRODUCED FROM FIELD PUMPING TEST DATA IN UN PROJECT WELLS

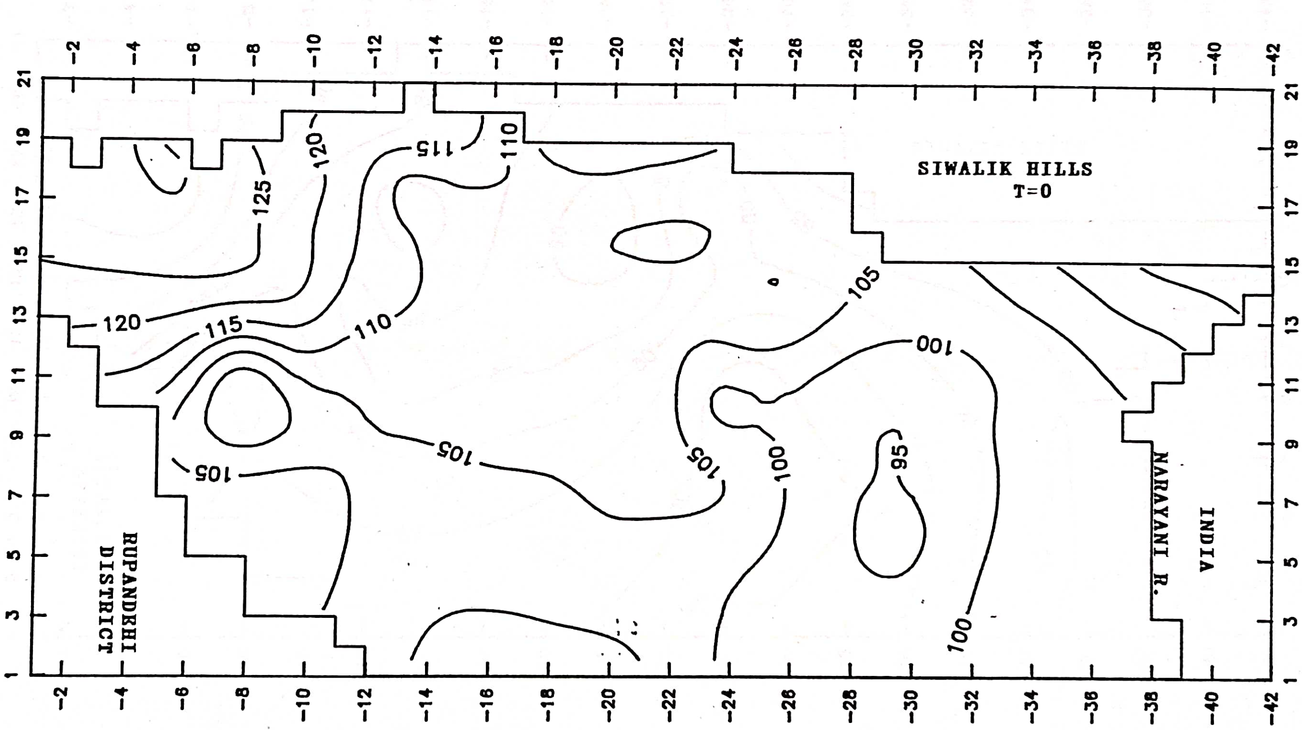
NAWALPARASI (WEST) MODEL: LAND SURFACE ELEVATION

APPENDIX 7



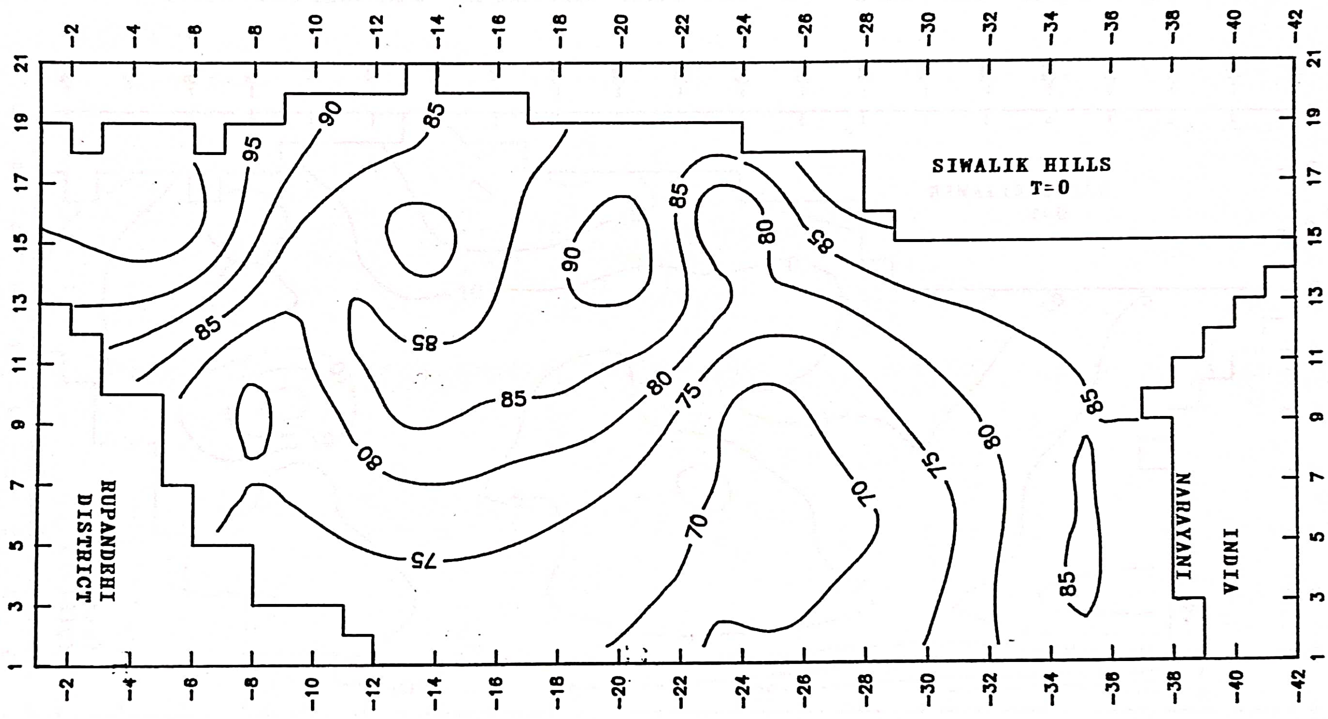
APPENDIX 8

NAWALPARASI (WEST) MODEL: TOP OF AQUIFER ELEVATION

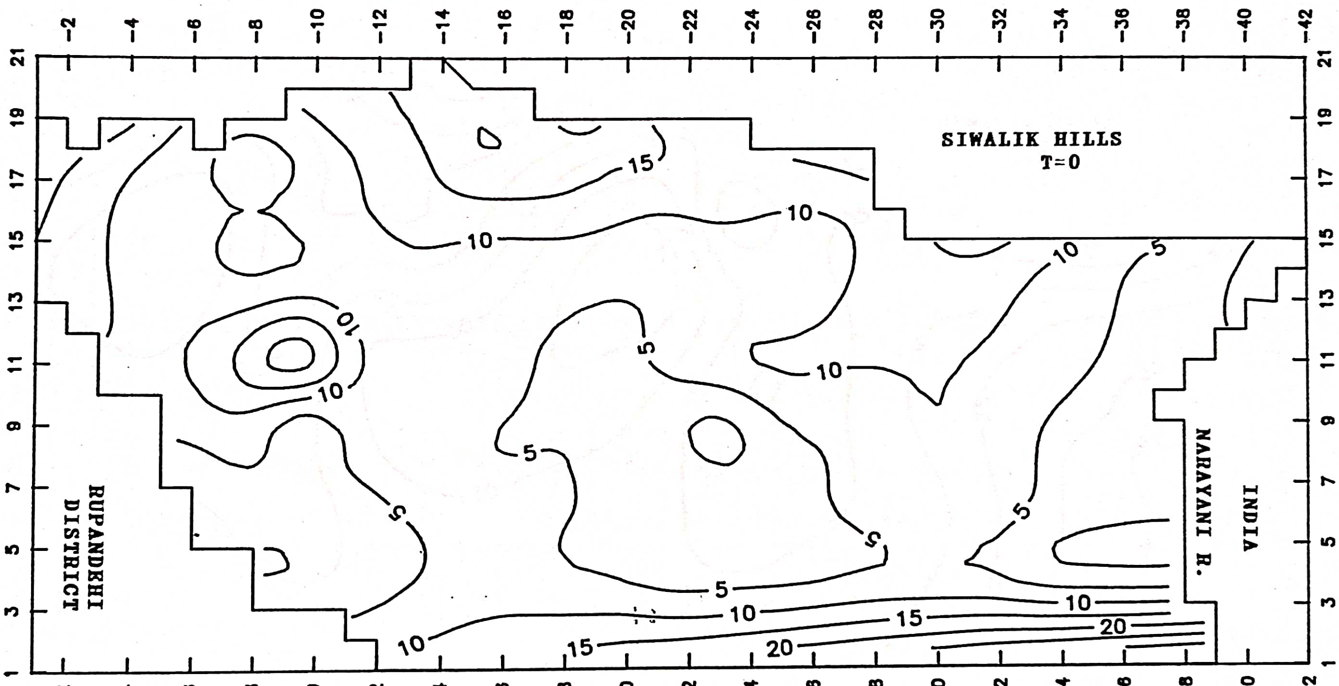


APPENDIX 9

NAWALPARASI MODEL: BOTTOM-OF-AQUIFER ELEVATION



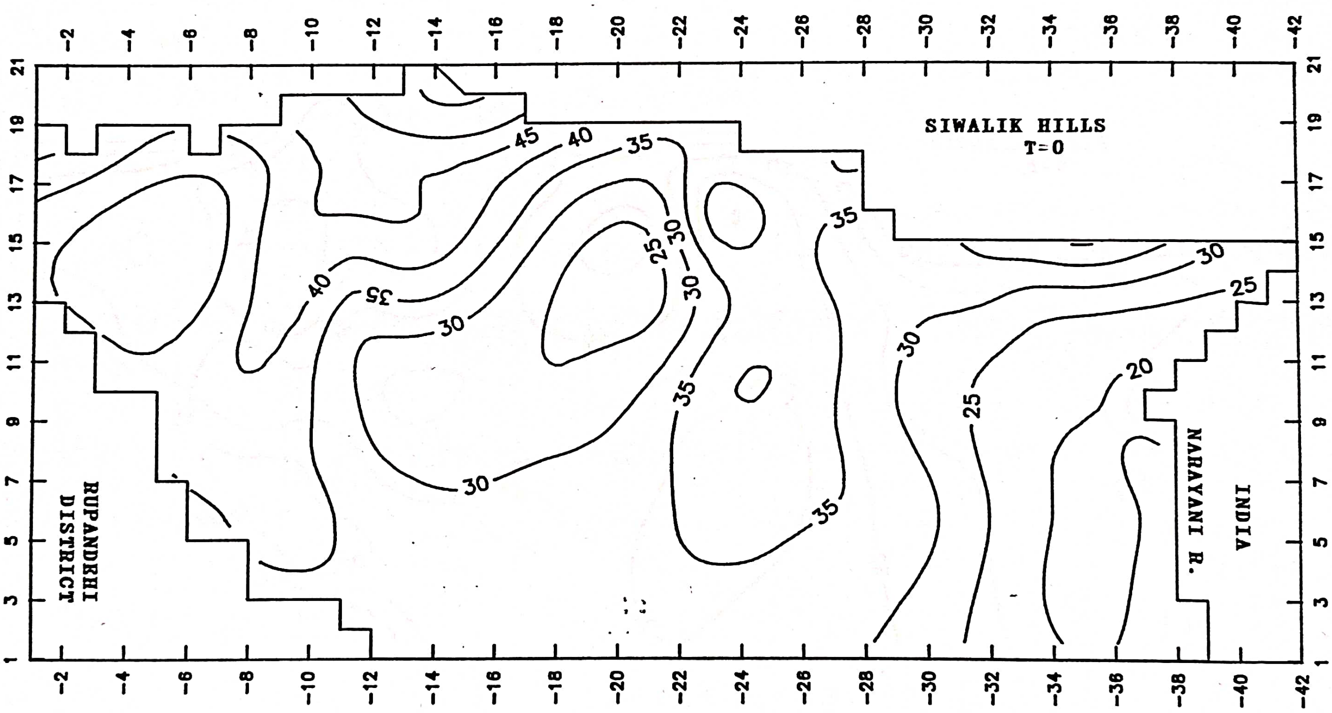
NAWALPARASI MODEL: DEPTH TO TOP OF AQUIFER



APPENDIX 10

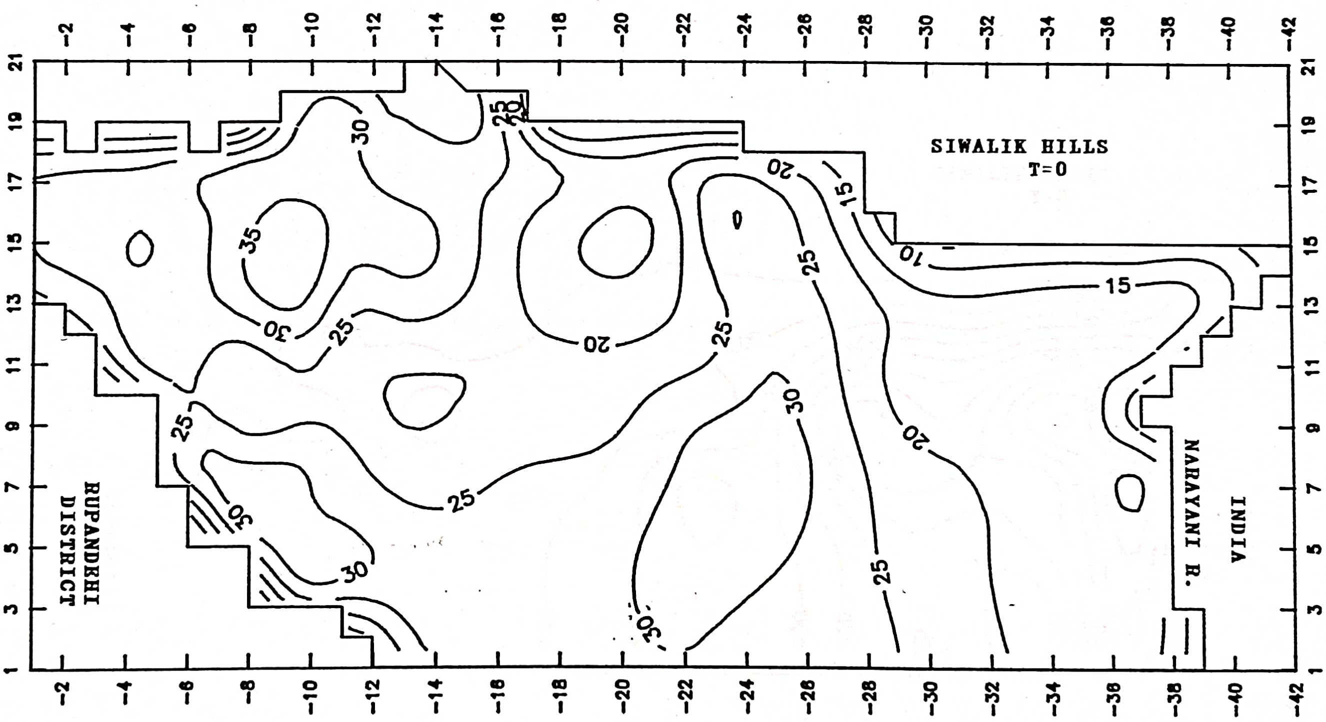
APPENDIX 11

NAWALPARASI MODEL: DEPTH TO BOTTOM OF AQUIFER



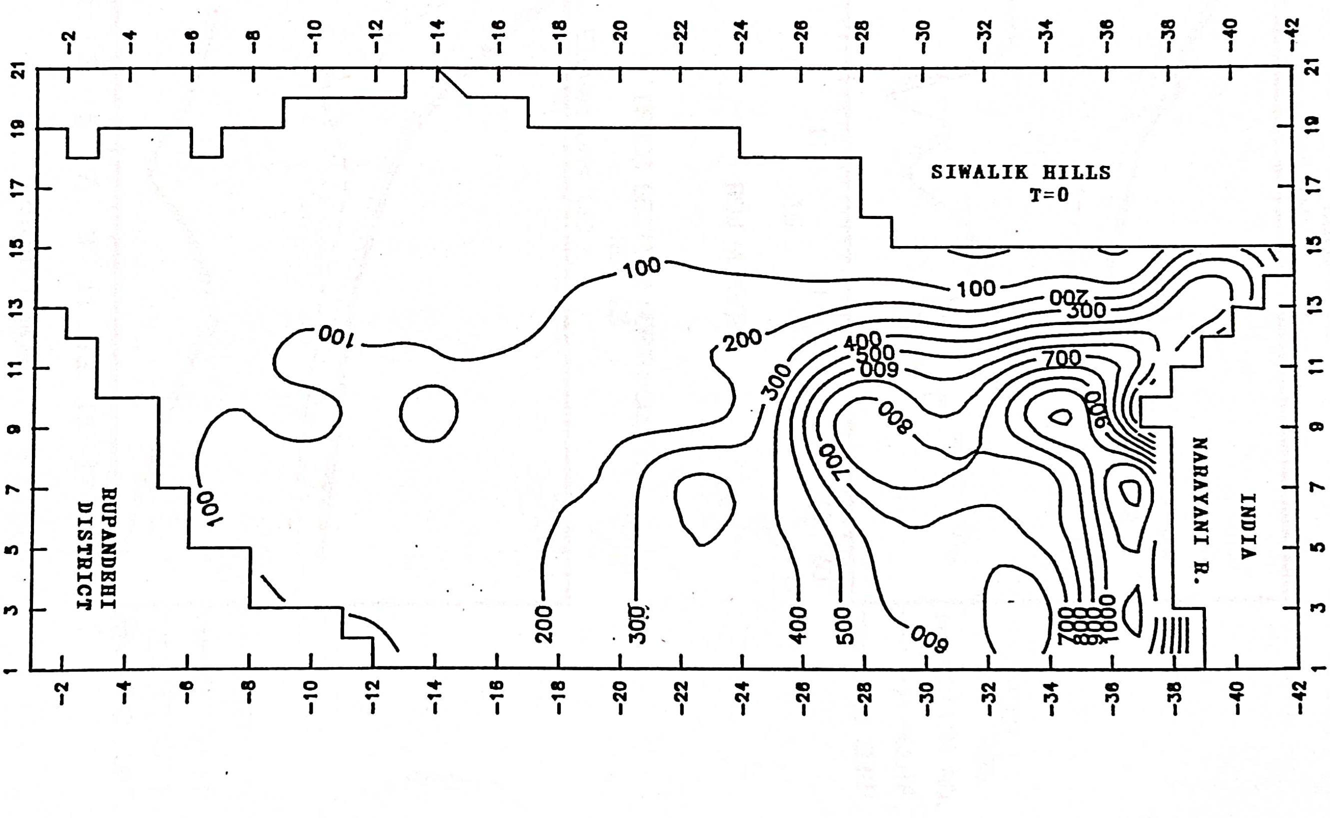
APPENDIX 12

NAWALPARASI MODEL: SATURATED AQUIFER THICKNESSS

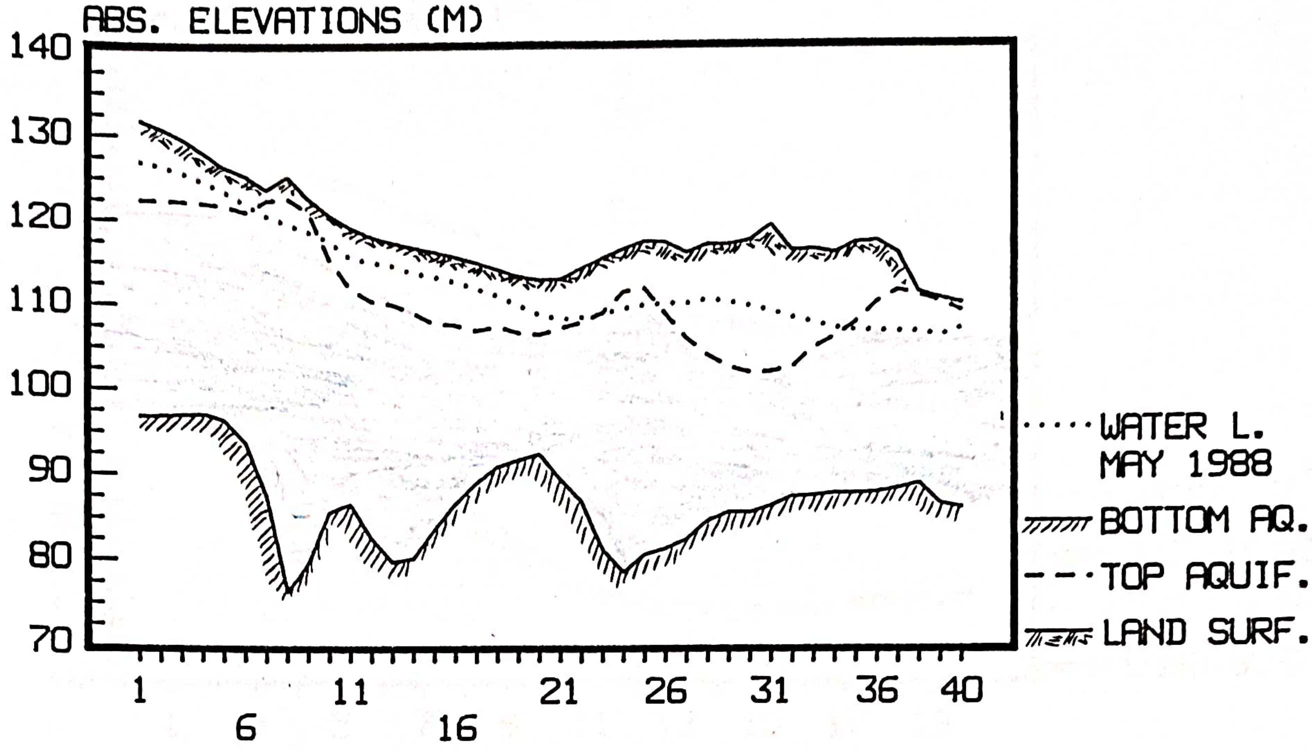


APPENDIX 13

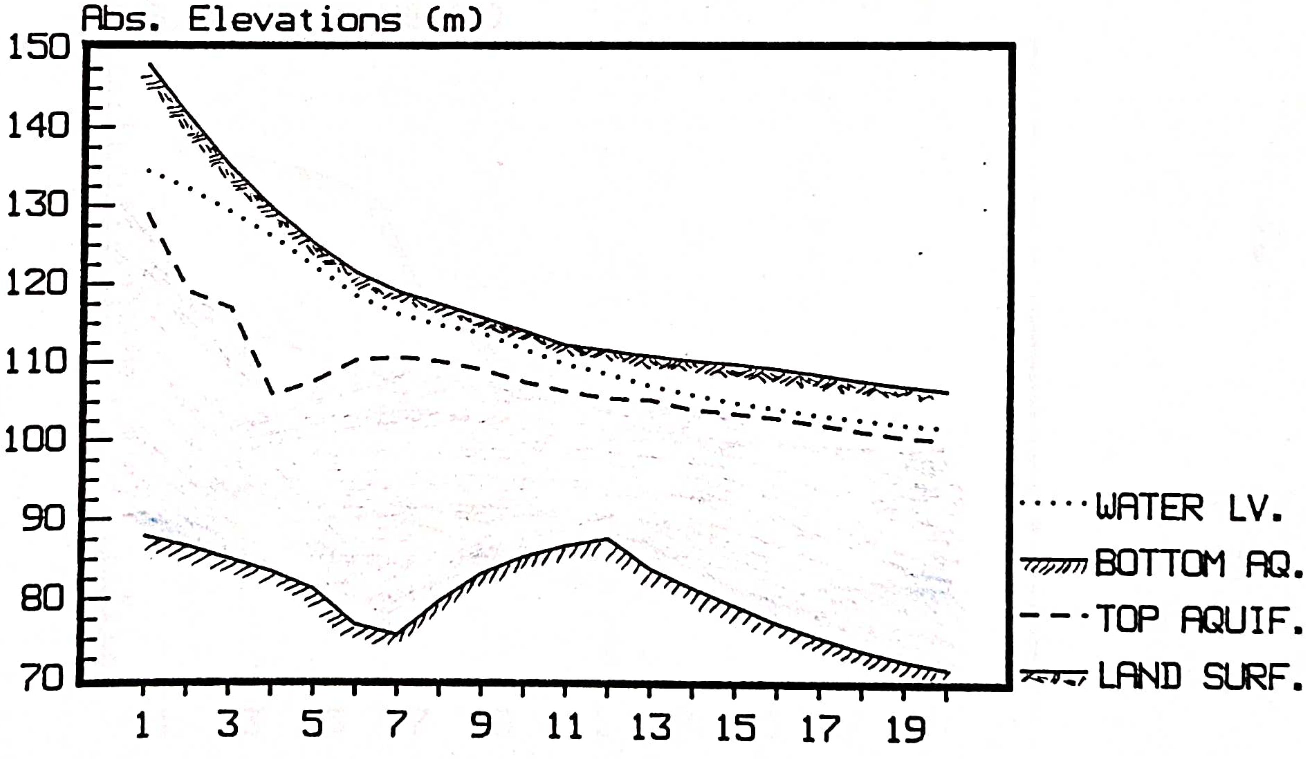
TRANSMISSIVITY DISTRIBUTION IN MAY 1988 (MODEL)



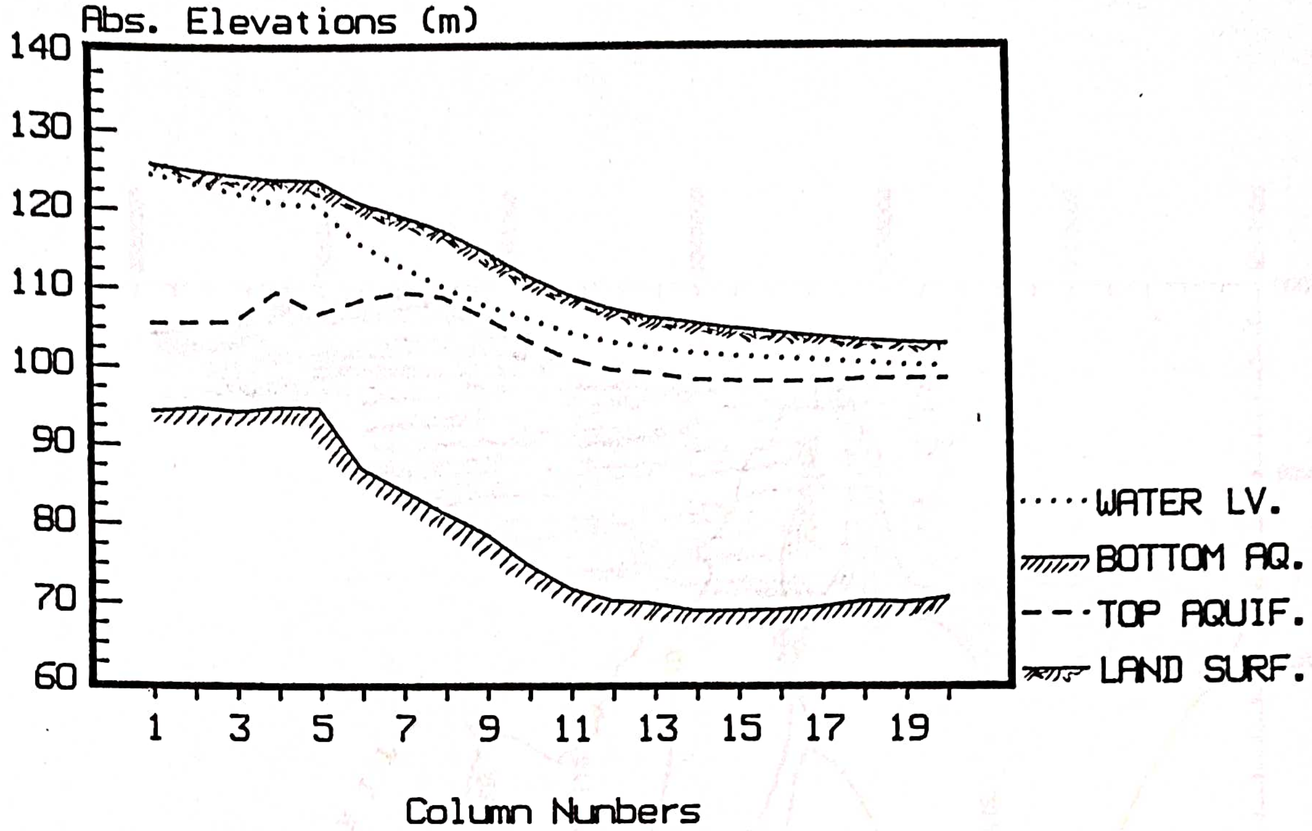
CROSS SECTION THROUGH SHALLOW AQUIFER
COLUMN 13



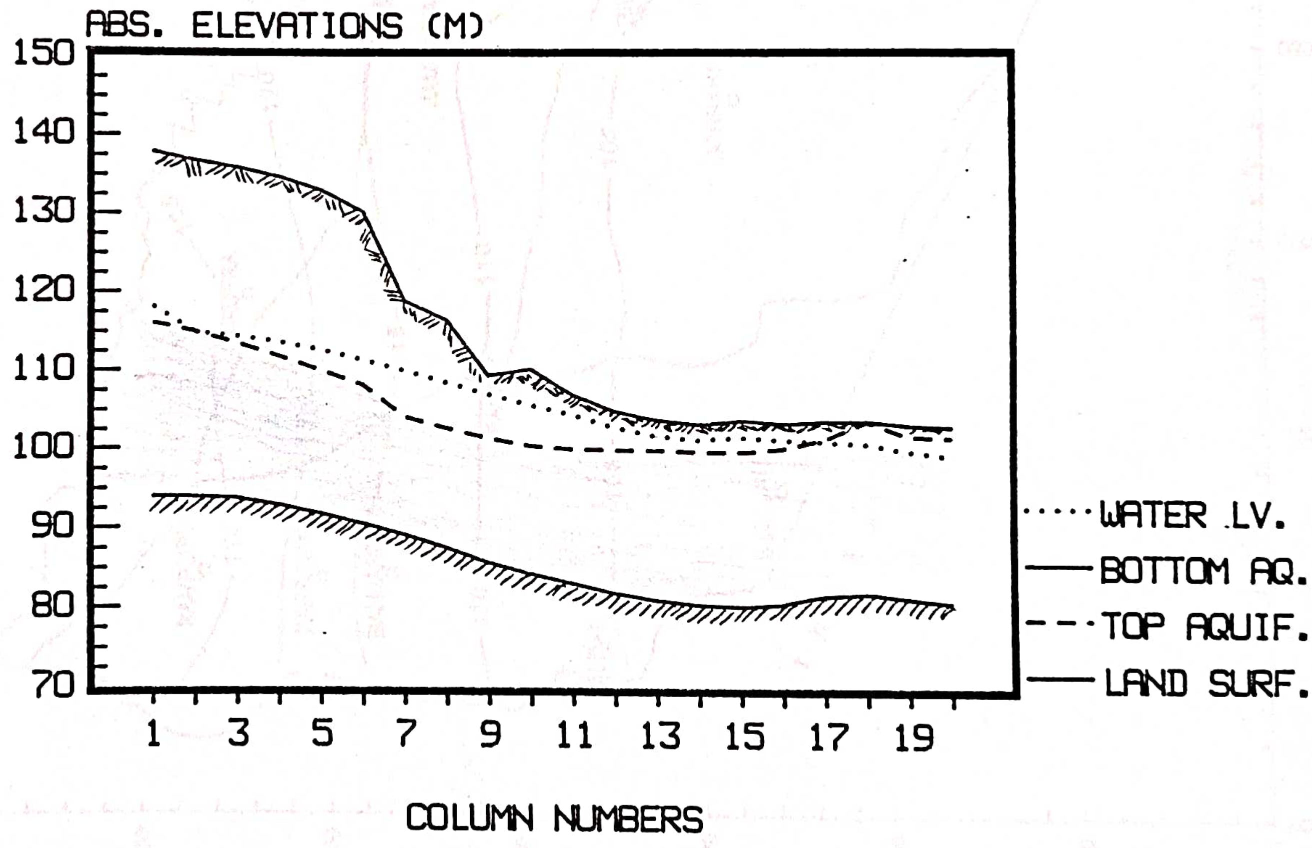
CROSS SECTION NORTH-SOUTH
ROW 13



CROSS SECTION NORTH-SOUTH
ROW 26



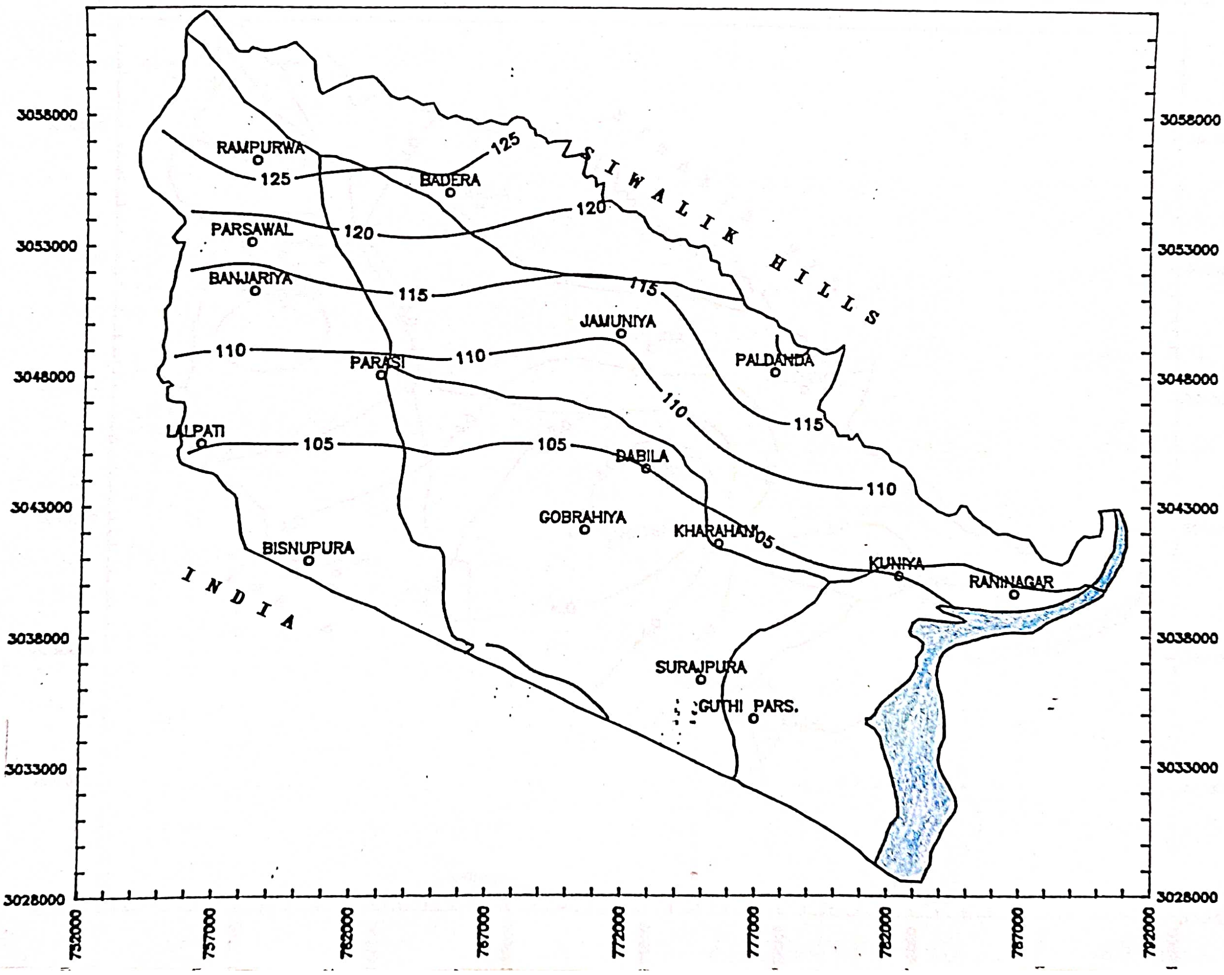
CROSS SECTION NORTH-SOUTH
ROW 32



APPENDIX 14 — Cont.

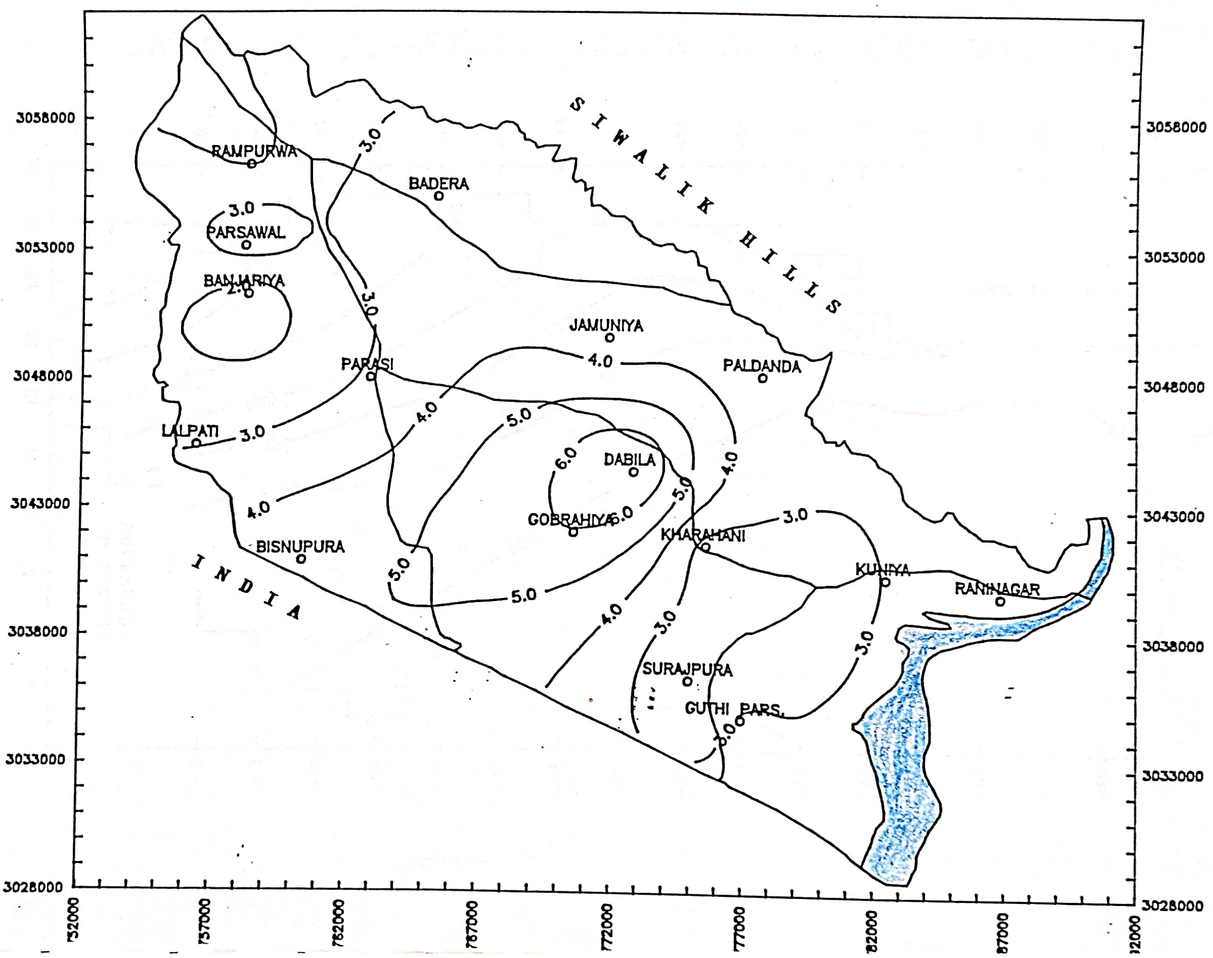
APPENDIX 15

NAWALPARASI (WEST) WATER LEVEL CONTOUR MAP MAY 1988



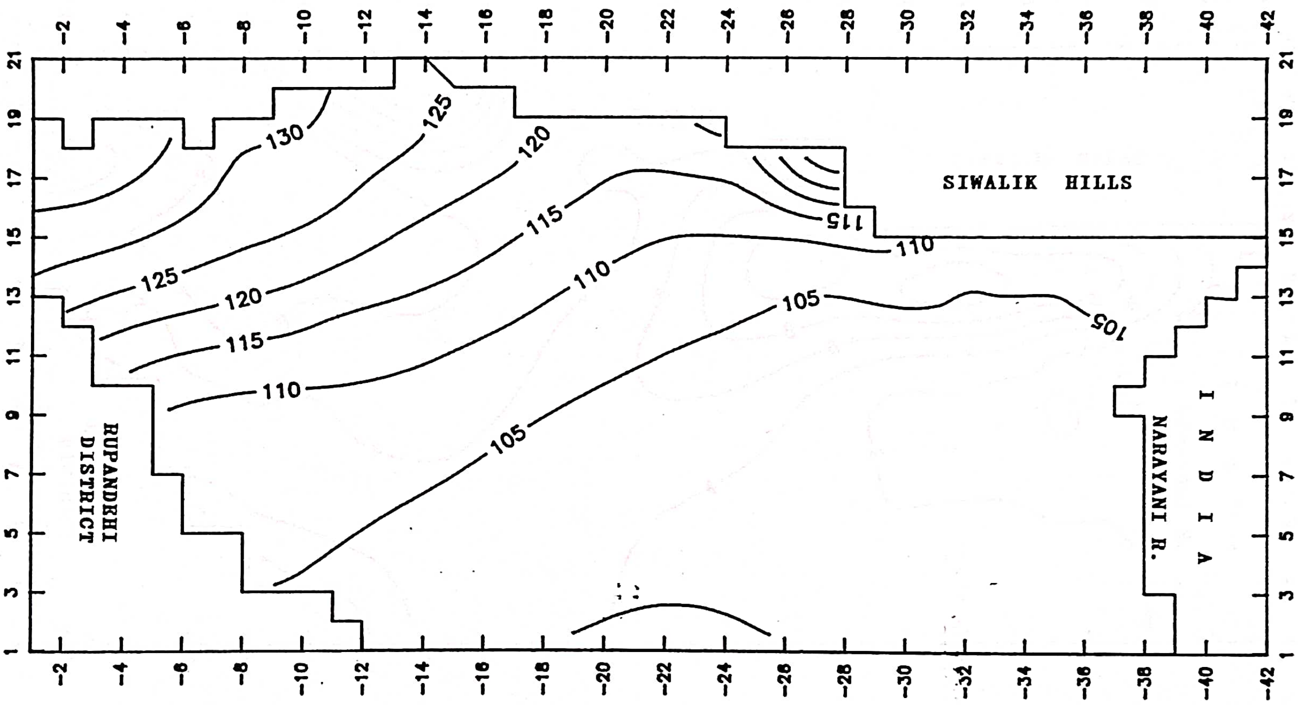
APPENDIX 16

NAWALPARASI (WEST) DEPTH TO WATER TABLE MAY 1988



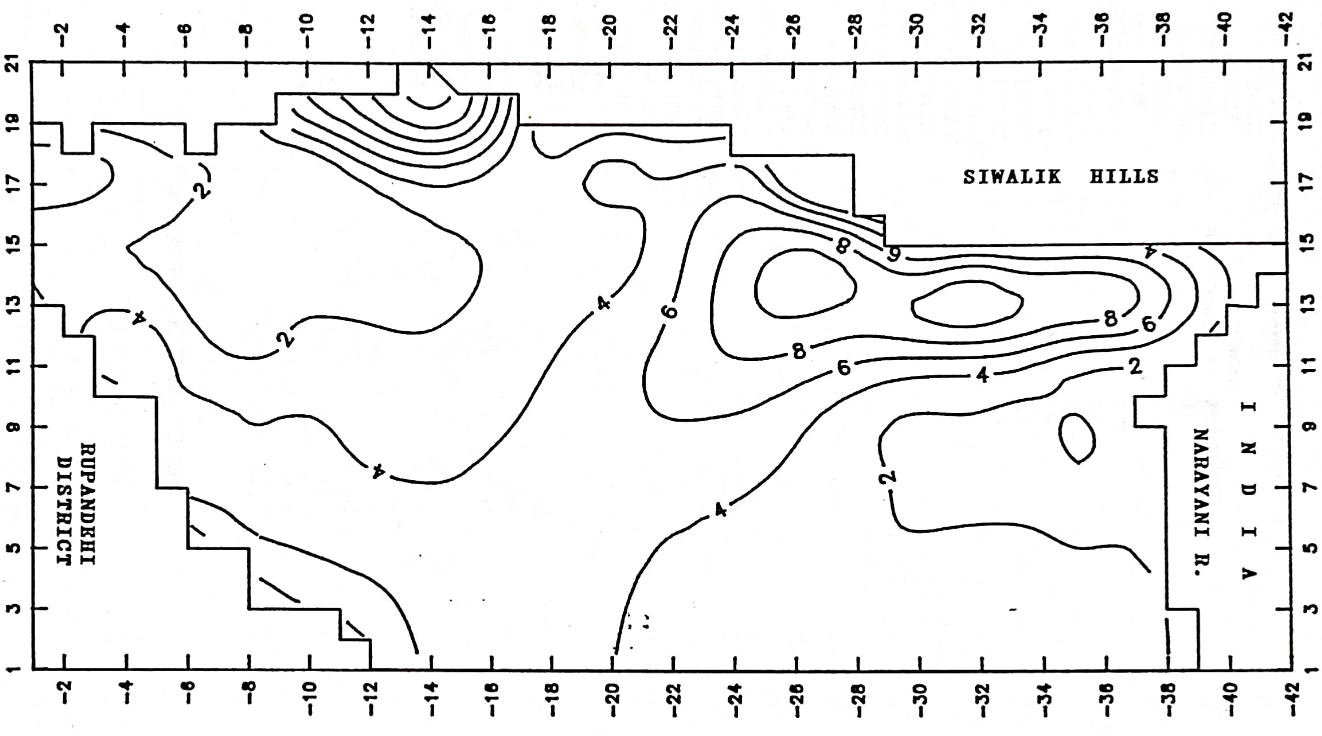
APPENDIX 17

FINAL STEADY-STATE WATER-LEVEL MAP MAY 1988



APPENDIX 18

DEPTH TO WATER TABLE FROM LAND SURFACE: MAY 1988



PERMEABILITY DATA INPUT FILE

```
0 1.0 2.5 5  7.5 12.5 20 30 40 60      values of K in m/day
    1             222222
    2            222222
    3          222222222
    4          221122222
    5       222221122222
    6     3333222112222
    7     33333221112222
    8  3333333321112222
    9  33333322311112222
   10  33333332211112222
   11 333333333322112222
   12 3333333333322112222
   13 33333333333222222222
   14 333333333332222222
   15 333333333332222222
   16 4443333333333322222
   17 4444444443333333222
   18 444444444334443332
   19 444444444444443332
   20 555555533444454332
   21 555555533555443111
   22 555555533454431111
   23 555555533443321111
   24 55555554444331114
   25 55555555544331111
   26 66666667765331111
   27 66666778876331111
   28 666677888774311
   29 66777888877441
   30 77778888877332
   31 77787788887722
   32 77777888888722
   33 77778888998841
   34 88888999999841
   35 99999999988841
   36 99999999988841
   37 99999999 88841
   38 99        9886
   39            886
   40             86
   41              8
1234512345678901234567890
```

Codes:

0 or blank	-	K=0 M/DAY
1	-	1
2	-	2.5
3	-	5
4	-	7.5
5	-	12.5
6	-	20
7	-	30
8	-	40
9	-	60

APPENDIX 19

RECHARGE DATA INPUT FILE

```
0.00 0.03 0.05 0.075 0.10 0.15 0.25 0.30 0.35 0.50
  1             444444
  2           0334444
  3          333344444
  4          113444444
  5       1    44444444
  6     331    1144444
  7     5533   44444444
  8   4453333333444444
  9   44533333334444444
 10   55533333334444444
 11  113333333332233444
 12 1113333333332233444
 13 44441111333322434444
 14 4444411133333334444
 15 3334411113333334444
 16 3334111133333334444
 17 333441111333333444
 18 444444111333333333
 19 444441111333333333
 20 444441113333333333
 21 444444444443333333
 22 444433335554444433
 23 444433335554444333
 24 44443333555444333
 25 11111444555444333
 26 11111111144443333
 27 11111111144444333
 28 111111111444444
 29 11111111144444
 30 11111111144444
 31 44444444444444
 32 45555444444444
 33 55555444444444
 33 55554444222444
 35 55555555222444
 36 55555555 22555
 37 55        5555
 38            555
 39             55
 40              5
 41
0.002 0.013 0.025 0.017 0.006 0.0004 0.00 0.0018 0.00 0.00 0.0008 0.0018
MAY   JUNE  JULY  AUG   SEP   OCT    NOV  DEC    JAN  FEB  MARCH  APRIL
```

Codes:

```
0 - Recharge 0.00
1 -          0.03
2 -          0.05
3 -          0.075
4 -          0.10
5 -          0.15
6 -          0.25
7 -          0.30
8 -          0.35
9 -          0.50
```

APPENDIX 20

EFFECTIVE POROSITY DATA INPUT FILE

```
0.1 0.05 0.08 0.1 0.125 0.15 0.175 0.20 0.25 1e21
  1              444444
  2             444444
  3           444444444
  4           444444444
  5        444444444444
  6      4444444444444
  7      22444444444444
  8    2222344444444444
  9    22244444444444444
 10    22244444444444444
 11   444444444444444444
 12  4444444444444444444
 13  44444444444444444444
 14  4444444444444444444
 15  4444444444444444444
 16  4444444444444444444
 17  444444444444444444
 18  444444444444444444
 19  444444444444444444
 20  444444444444444444
 21  444444422222444444
 22  444444222222444444
 23  444422222244444444
 24  44442222224444444
 25  44444444444444444
 26  44444444444444444
 27  44444444444444444
 28  444444444444444
 29  44444444444444
 30  11444444444444
 31  11114444444444
 32  11111444444444
 33  11111444444444
 34  11114444444444
 35  11444444444444
 36  44444444944444
 37  44999999 97774
 38  99         9774
 39              974
 40               94
 41                9
1234512345678901234567890
```

Codes:

0 or blank:	Effective porosity	0.1
1 -		0.05
2 -		0.08
3 -		0.10
4 -		0.125
5 -		0.15
6 -		0.175
7 -		0.20
8 -		0.25
9 -	1E21	Constant Head

APPENDIX 21

STORAGE COEFFICIENT DATA INPUT FILE

```
000.001 0.001 0.01 0.02 0.03 0.04 0.05 0.06 0.08 1e21
  1               444444
  2              446666
  3            444466666
  4            444466666
  5         466622466666
  6       4446662246666
  7       44466662455555
  8     4444444444455555
  9     44444444444555555
 10     44444444444444444
 11    444444444444444444
 12   4444444334444444444
 13   44444441144444444444
 14   4444444334444444444
 15   4444444444444444444
 16   4444444444444444444
 17   444444444444444444
 18   444444444444444444
 19   444444444444555554
 20   444444444444555554
 21   444444444444555554
 22   444444442222444444
 23   444444422222444444
 24   44444442222444444
 25   44444442222444444
 26   44444433322244444
 27   44444434422244444
 28   888884234222444
 29   88888444444444
 30   88888444444444
 31   44444444444444
 32   44444444444444
 33   44444444444444
 34   44444444777644
 35   44444444777644
 36   44444444977444
 37   44999999 94444
 38   99          9444
 39              944
 40               94
 41                9
1234512345678901234567890
```

Codes:

0 or blank:	Storage coeff.		0.001
1	–		0.001
2	–		0.01
3	–		0.02
4	–		0.03
5	–		0.04
6	–		0.05
7	–		0.06
8	–		0.08
9	–	1E21	.... Constant Head

APPENDIX 22

EVAPORATION DATA INPUT FILE

```
3.0  0.6  0.3
 1             110000
 2            111000
 3          111111000
 4          111111000
 5       111111111000
 6     11111111111000
 7     11111111111000
 8   1111111111111000
 9   11111111111110000
10   11111111111111000
11  111111111111111000
12 1111111111111111000
13 11111111111111111000
14 1111111111111111000
15 1111111111111111000
16 1111111111111110000
17 111111111111110000
18 111111111111111000
19 111111111111111000
20 111111111111111000
21 111111111111111000
22 111111111111110000
23 111111111111110000
24 11111111111111111
25 11111111111111111
26 11111111111111111
27 11111111111111111
28 111111111111111
29 11111111111111
30 11111111111111
31 11111111111111
32 11111111111111
33 11111111111111
34 11111111111111
35 11111111111111
36 11111111 11111
37 11        1111
38            111
39             11
40              1
41
0.0066  0.0052  0.0049  0.0049  0.0046  0.0041  0.004  0.0031  0.0031  0.0041  0.005  0.0
May     June    July    Aug     Sep     Oct     Nov    Dec     Jan     Feb     March  Ap
```

Codes:

0 – Zero evaporation
1 – Evaporation possible provided water level within 3.0 m from land surface

APPENDIX 23

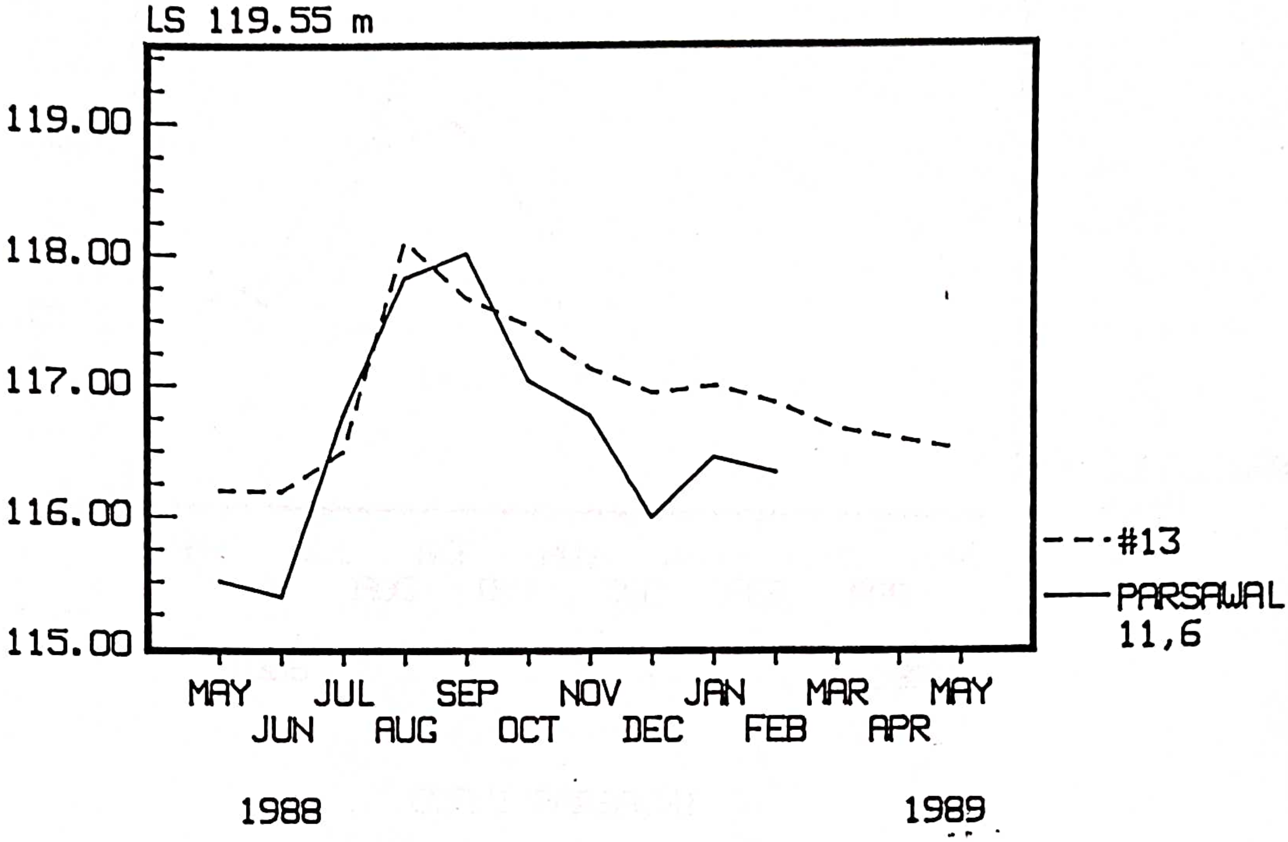
EVAPORATION LOSS — MAY 1988

APPENDIX 23 — Continued

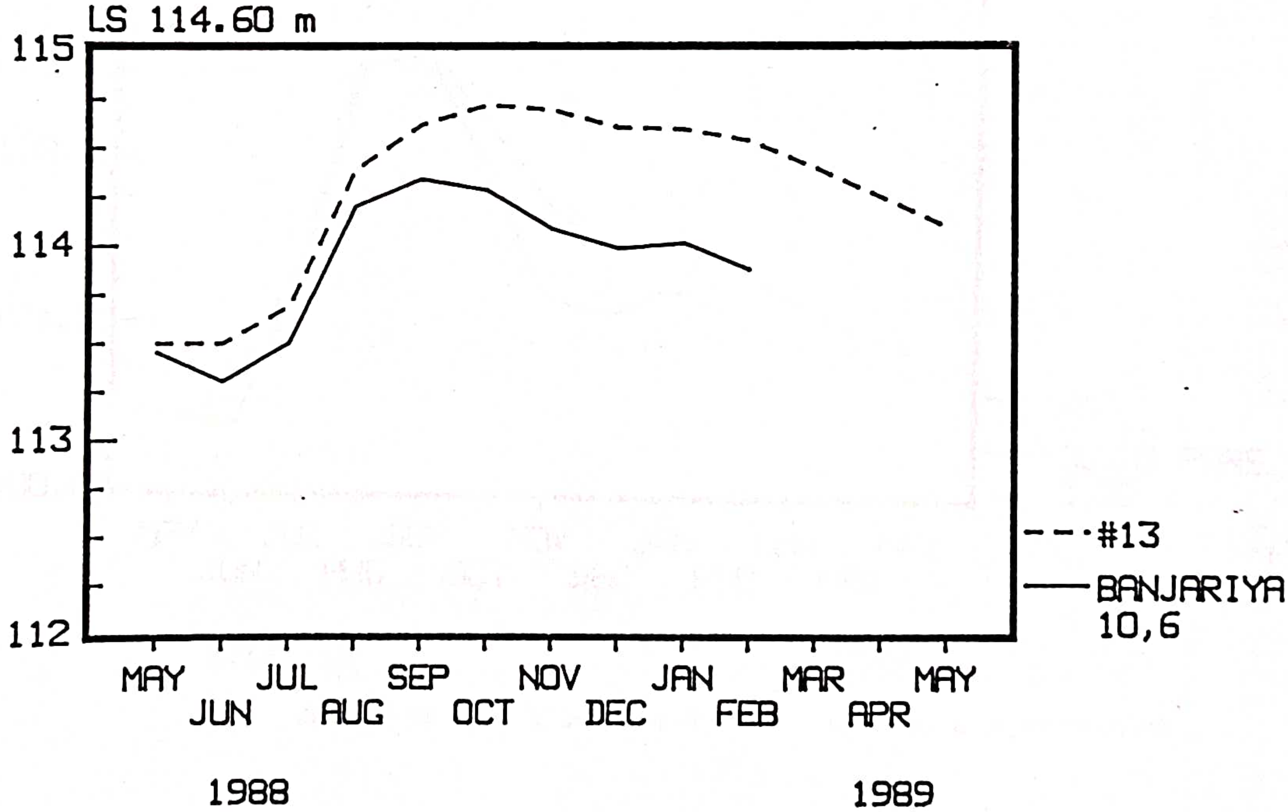
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	****	****	****	****	****	****	****	****	****	****	****	****	0.	0.	0.	0.	0.	0.	****	****
2	****	****	****	****	****	****	****	****	****	****	****	0.	0.	0.	0.	0.	0.	****	****	****
3	**	R U P	A N D	E H I	****	****	****	****	****	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****
4	****	****	****	****	****	****	****	****	****	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****
5	****	****	****	D I S	T R I	C T *****	495.	593.	466.	214.	158.	158.	158.	289.	0.	0.	0.	0.	****	****
6	****	****	****	****	390.	414.	526.	390.	439.	0.	0.	0.	0.	0.	0.	0.	0.	****	****	****
7	****	****	****	****	466.	495.	466.	289.	346.	558.	214.	168.	0.	0.	0.	0.	0.	0.	****	****
8	****	****	1492.	0.	241.	272.	367.	414.	289.	307.	256.	168.	0.	0.	0.	0.	0.	0.	****	****
9	****	****	0.	0.	0.	0.	0.	0.	158.	214.	179.	0.	0.	0.	0.	0.	0.	0.	0.	****
10	****	****	0.	0.	0.	0.	0.	0.	0.	0.	168.	149.	0.	0.	0.	0.	0.	0.	0.	****
11	****	0.	0.	0.	0.	0.	0.	0.	0.	0.	179.	179.	0.	0.	0.	0.	0.	0.	0.	****
12	0.	0.	0.	0.	0.	0.	0.	0.	158.	190.	190.	227.	0.	0.	0.	0.	0.	0.	0.	****
13	0.	0.	0.	0.	0.	0.	0.	0.	0.	190.	201.	256.	168.	149.	0.	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.	0.	0.	0.	0.	179.	190.	256.	0.	149.	0.	0.	0.	0.	0.	****
15	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	168.	214.	0.	0.	0.	0.	0.	0.	0.	****
16	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	149.	190.	0.	0.	0.	0.	0.	0.	0.	****
17	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****
18	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****
19	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****
20	1786.	190.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****
21	1682.	1682.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****
22	1492.	1584.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****
23	2014.	1682.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****
24	201.	168.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	149.	0.	****	****	****
25	190.	149.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****	****
26	158.	158.	158.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****	****
27	168.	168.	179.	168.	168.	149.	0.	0.	168.	0.	0.	0.	0.	0.	0.	0.	0.	****	****	****
28	149.	168.	179.	214.	227.	201.	201.	214.	214.	179.	0.	0.	0.	0.	0.	****	****	****	****	****
29	149.	179.	190.	241.	227.	241.	256.	414.	241.	241.	0.	0.	0.	0.	****	****	****	****	****	****
30	1492.	168.	179.	256.	241.	256.	256.	256.	256.	256.	0.	0.	0.	0.	****	****	****	****	****	****
31	0.	1492.	168.	201.	227.	256.	256.	241.	241.	227.	0.	0.	0.	0.	****	****	****	****	****	****
32	0.	0.	0.	1682.	241.	227.	256.	241.	241.	179.	0.	201.	0.	0.	****	****	****	****	****	****
33	0.	0.	0.	1584.	1786.	1786.	201.	241.	241.	214.	0.	0.	0.	0.	****	****	****	****	****	****
34	0.	0.	0.	0.	0.	1682.	0.	0.	227.	168.	149.	0.	0.	0.	****	****	****	****	****	****
35	0.	0.	0.	0.	0.	1584.	0.	0.	0.	0.	201.	0.	0.	0.	****	****	****	****	****	****
36	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	****	****	****	****	****	****
37	0.	0.	0.	0.	0.	0.	0.	0.	****	0.	0.	0.	0.	0.	****	****	****	****	****	****
38	0.	0.	****	N A R	A Y A	N I	****	R I V	E R	****	0.	0.	0.	0.	****	****	****	****	****	****
39	****	****	****	****	****	****	****	****	****	****	****	0.	0.	0.	****	****	****	****	****	****
40	****	****	****	****	****	****	****	****	****	****	****	****	0.	0.	****	****	****	****	****	****
41	****	****	****	****	****	****	****	****	****	****	****	****	****	0.	****	****	****	****	****	****
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

COMMENTS:
Evaporation is in [m3/day]
Time Step = 1
Time elapsed = 0.1000E+11 [day]
Steady-State Run ... May 1988

PARSAWAL

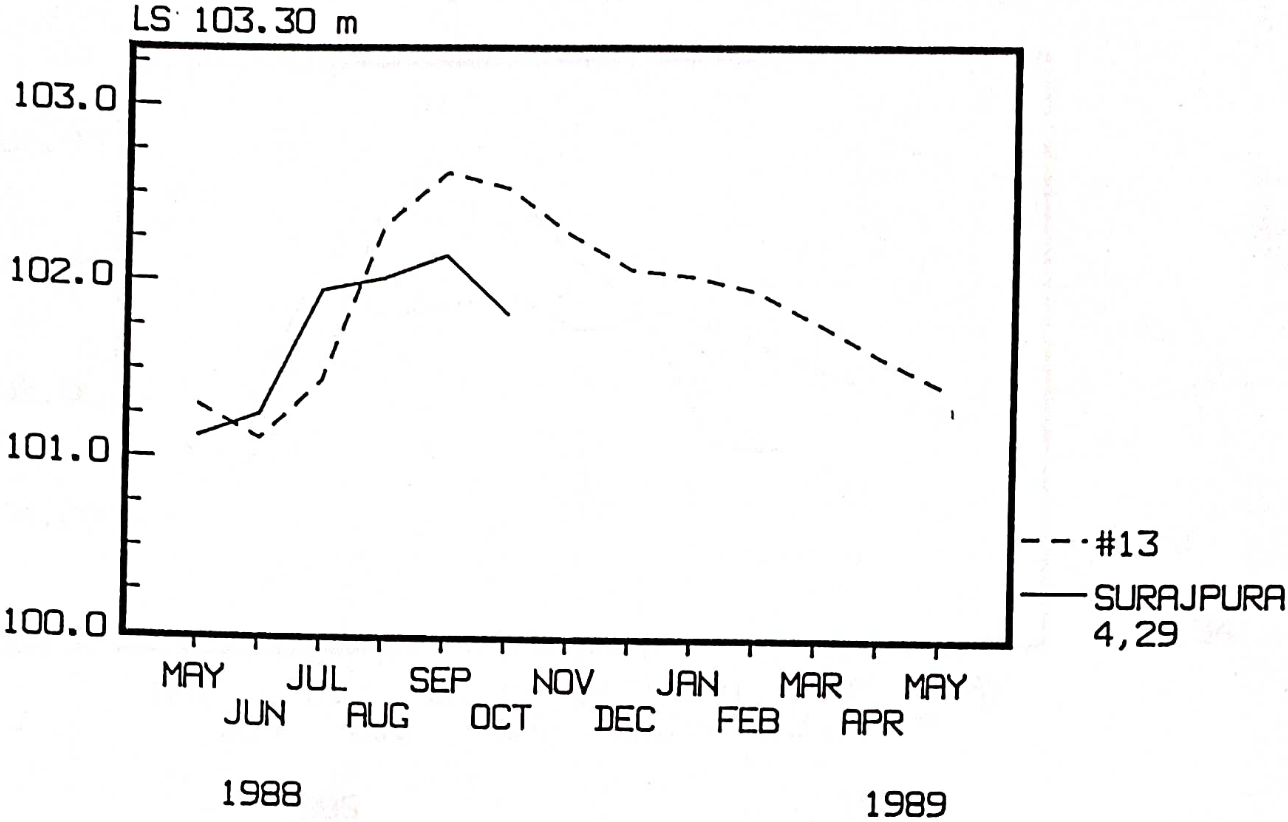


BANJARIYA

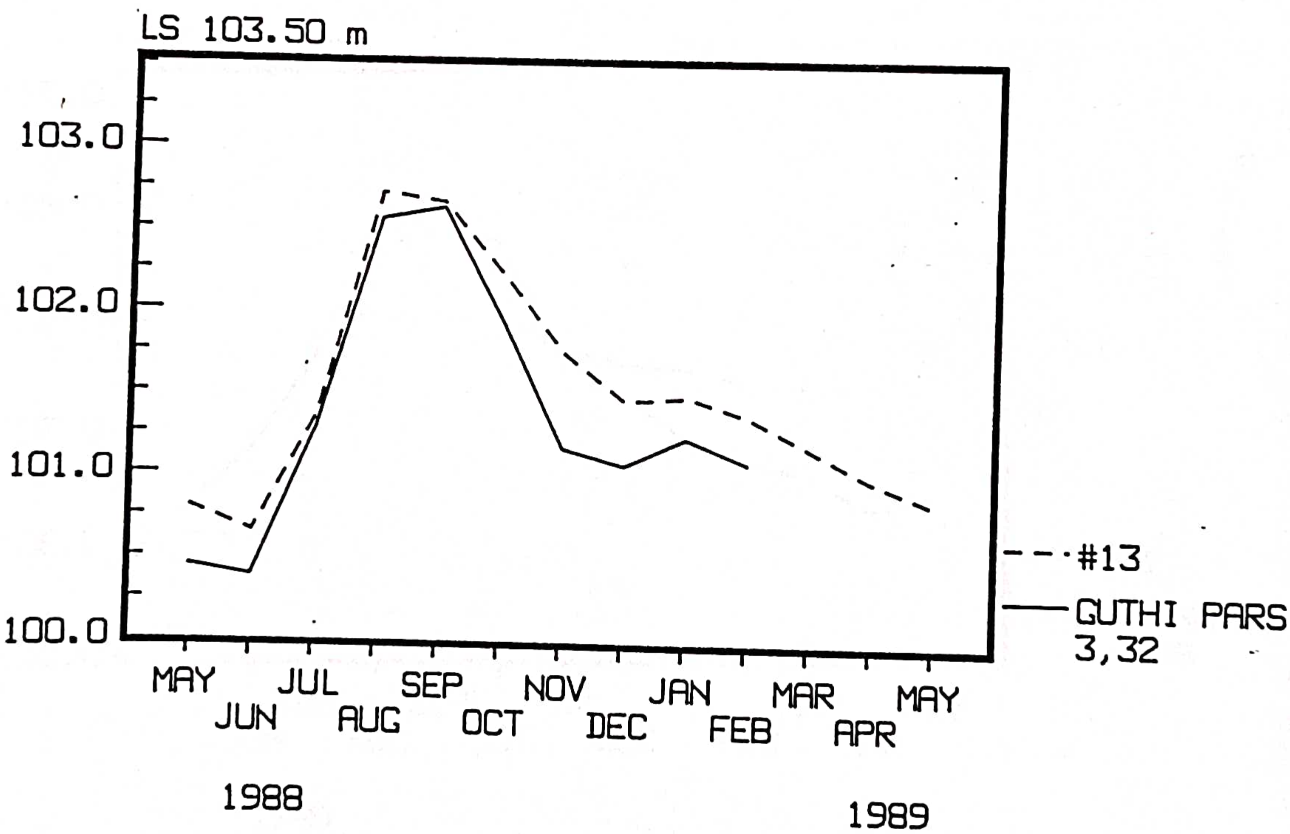


APPENDIX 24

SURAJPURA

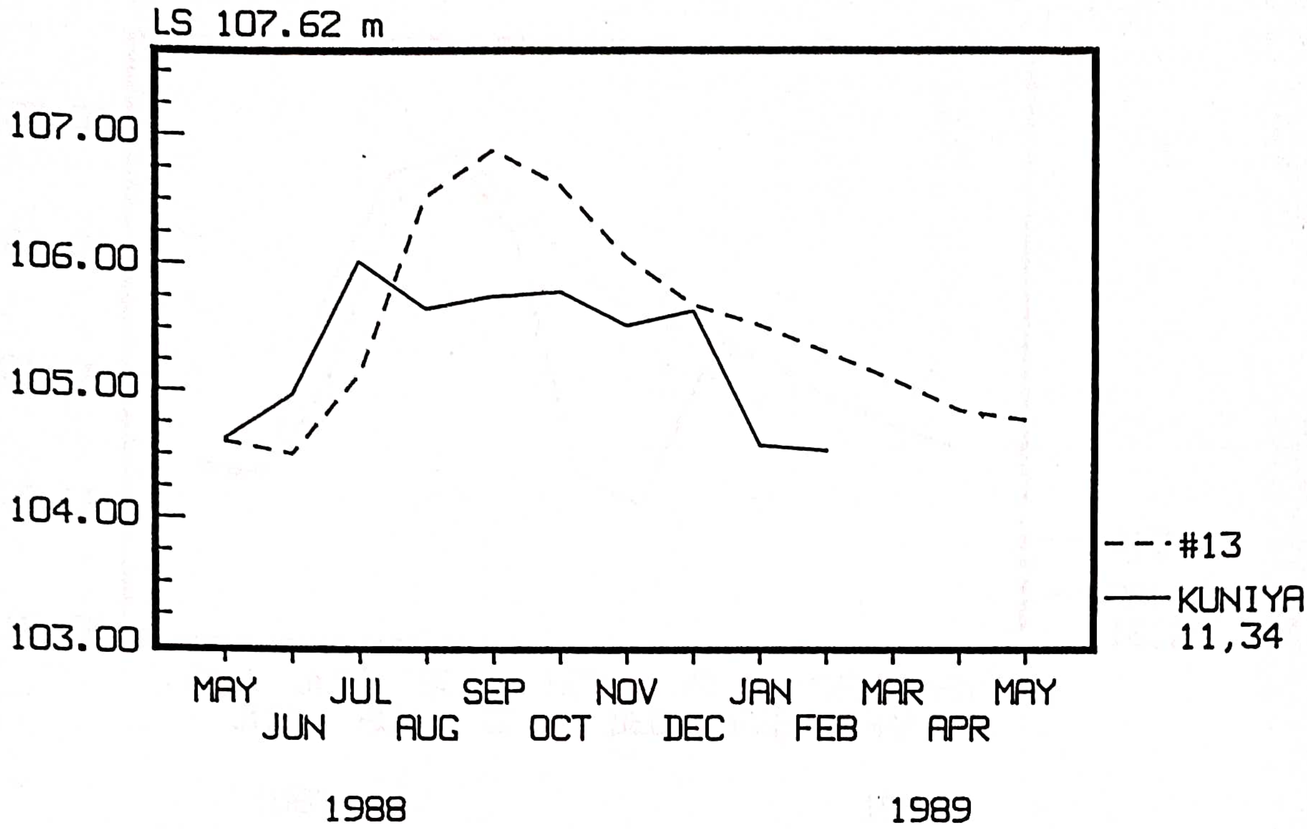


GUTHI PARSAUNI

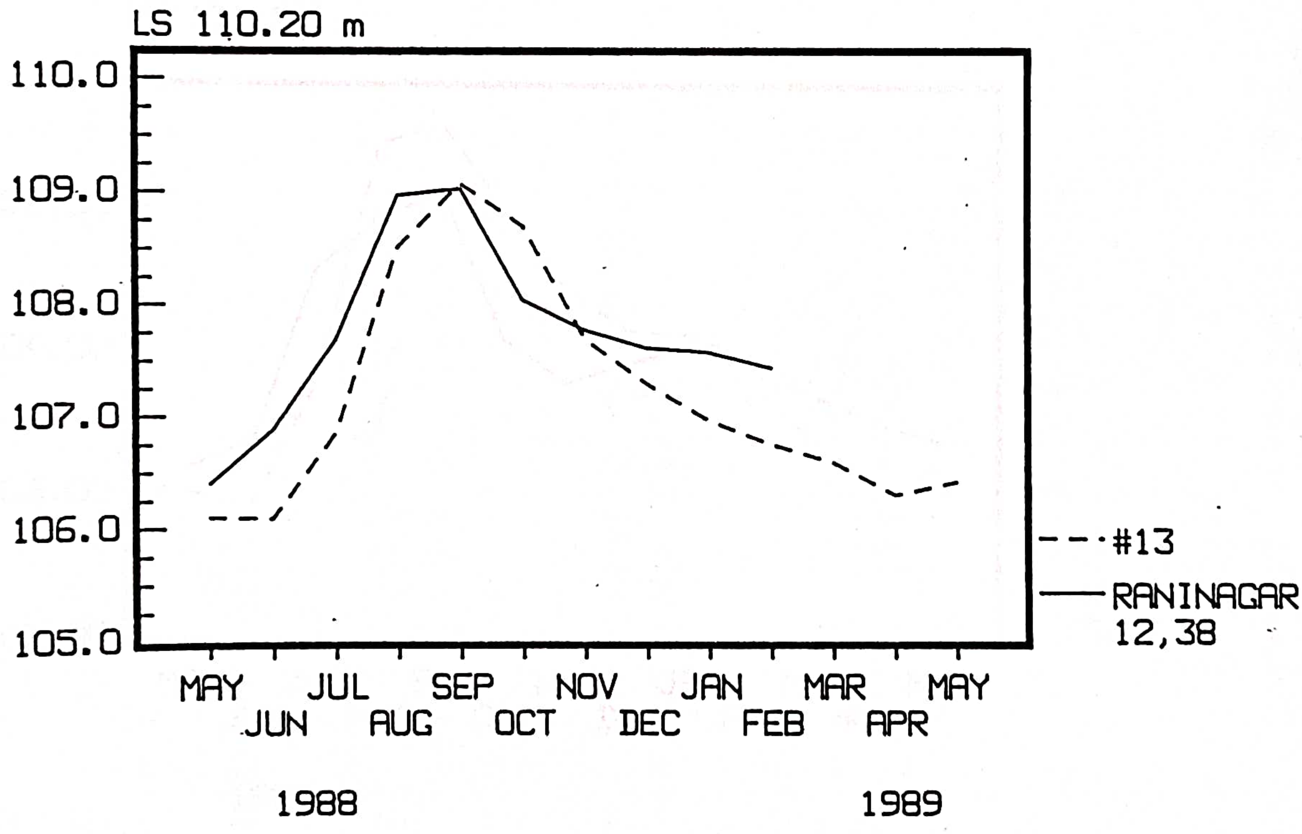


APPENDIX 24 — Continued

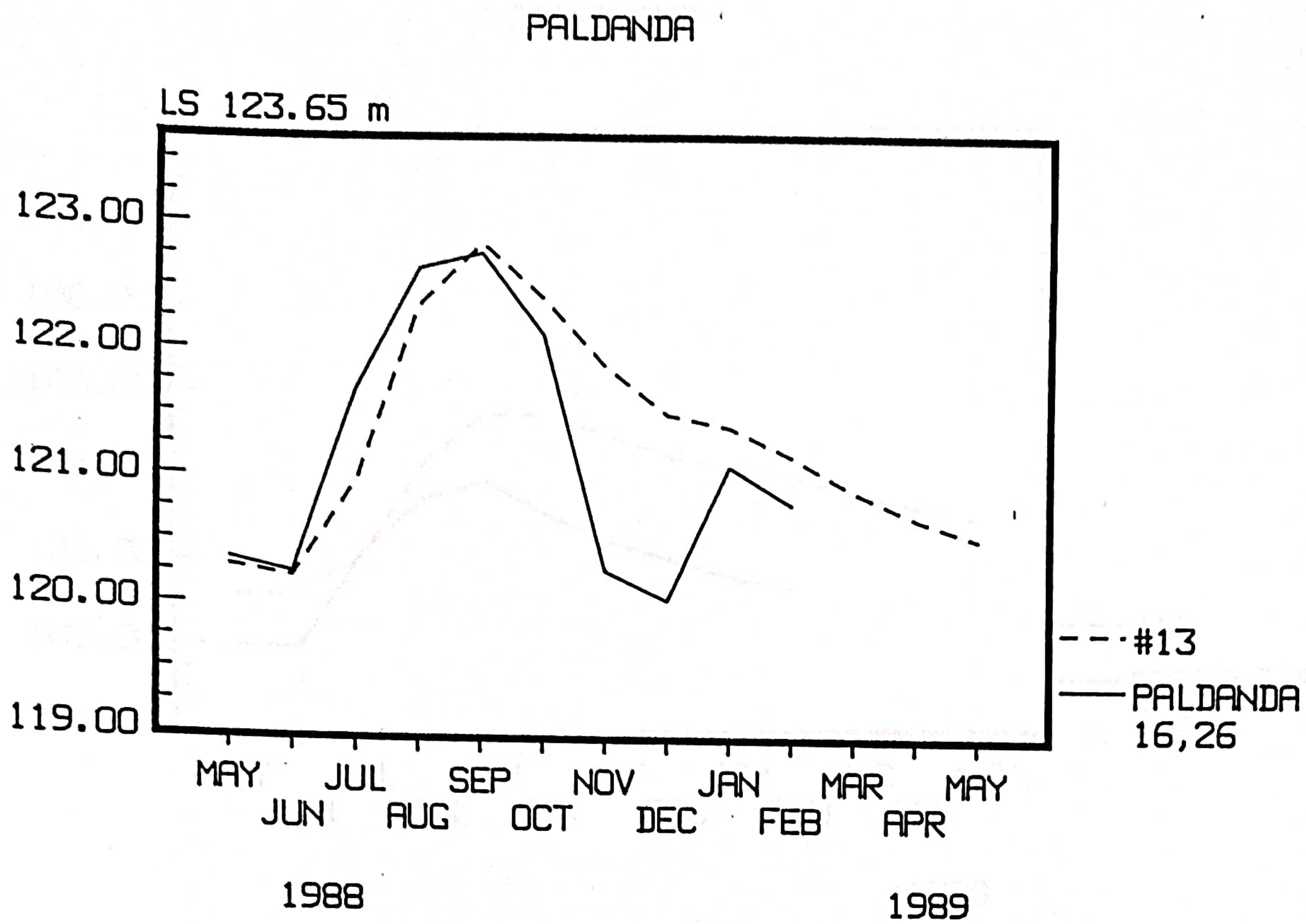
KUNIYA

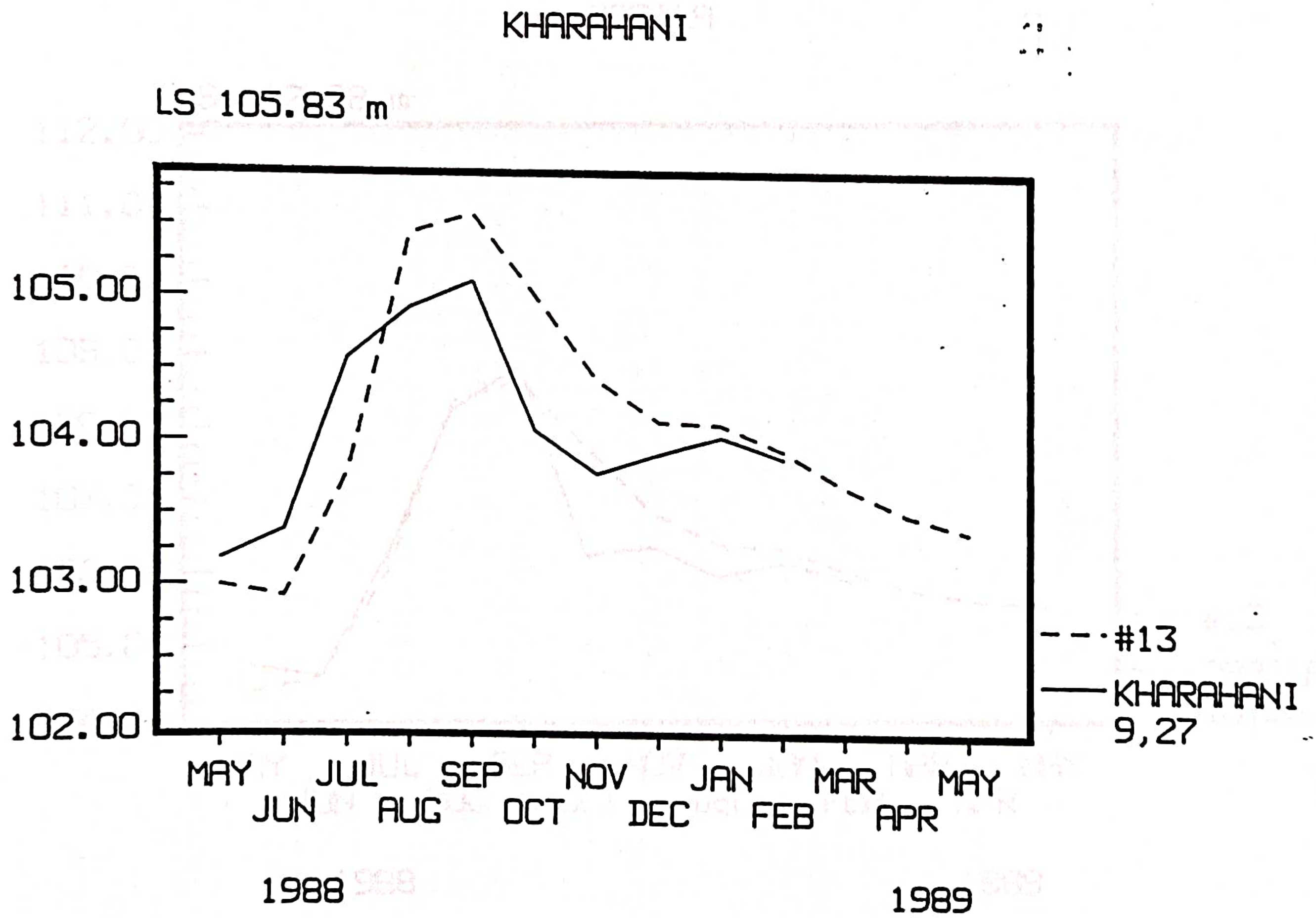


RANINAGAR



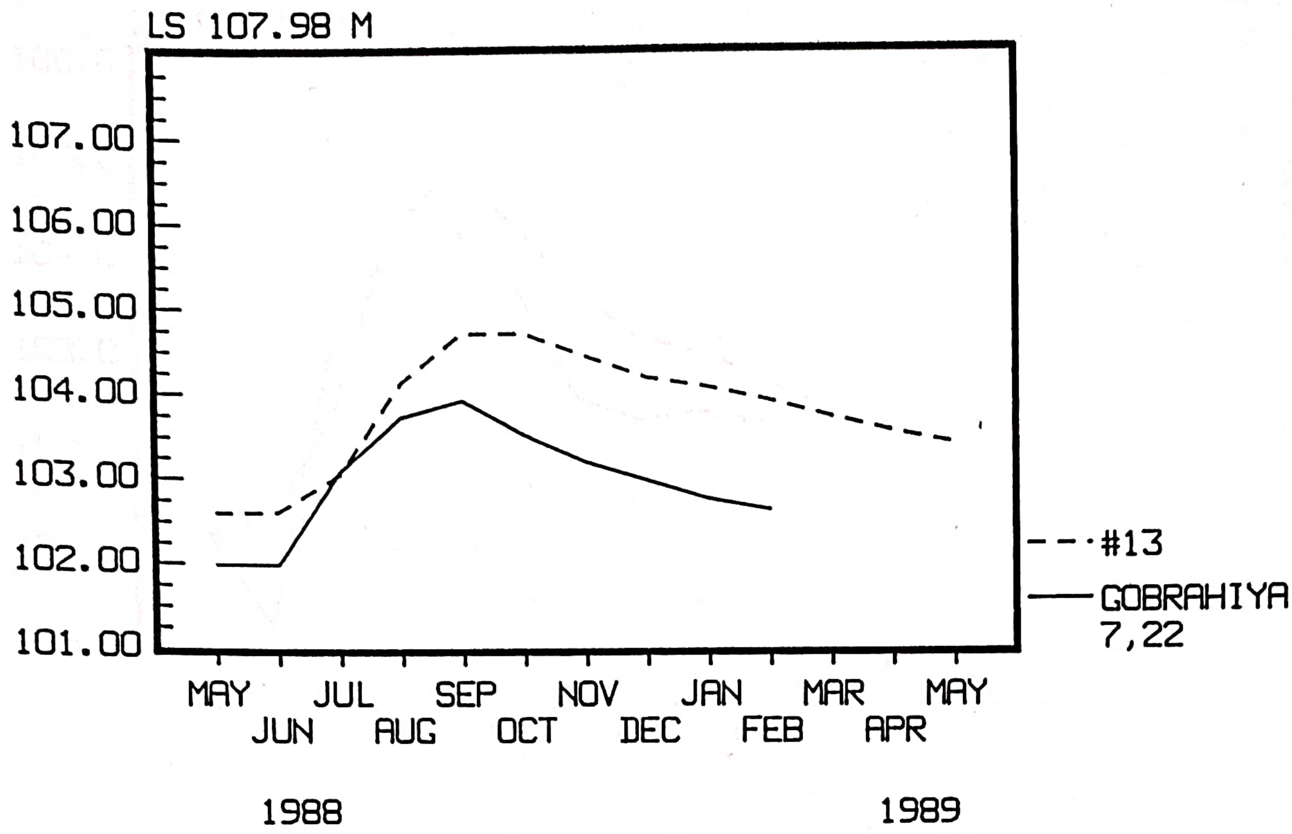
APPENDIX 24 — Continued



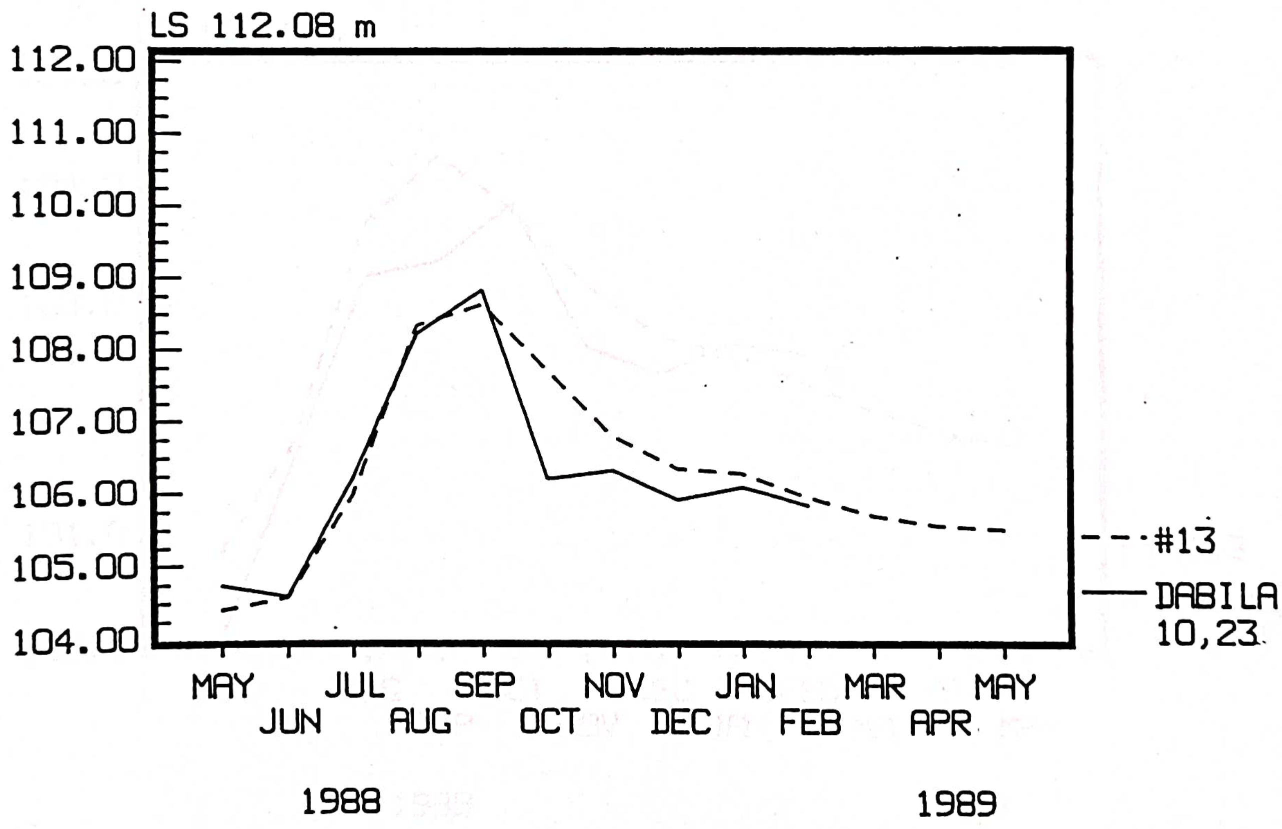


APPENDIX 24 — Continued

GOBRAHIYA

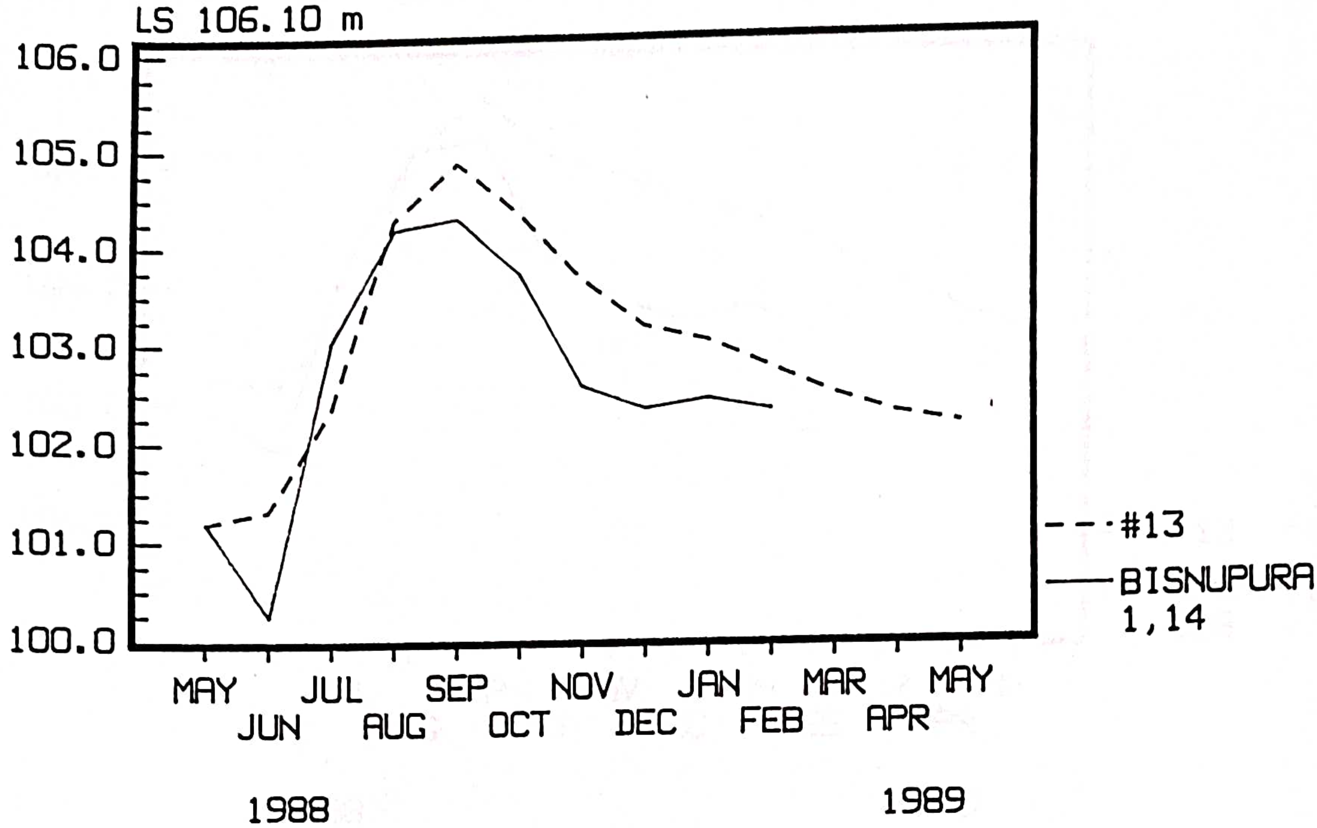


DABILA

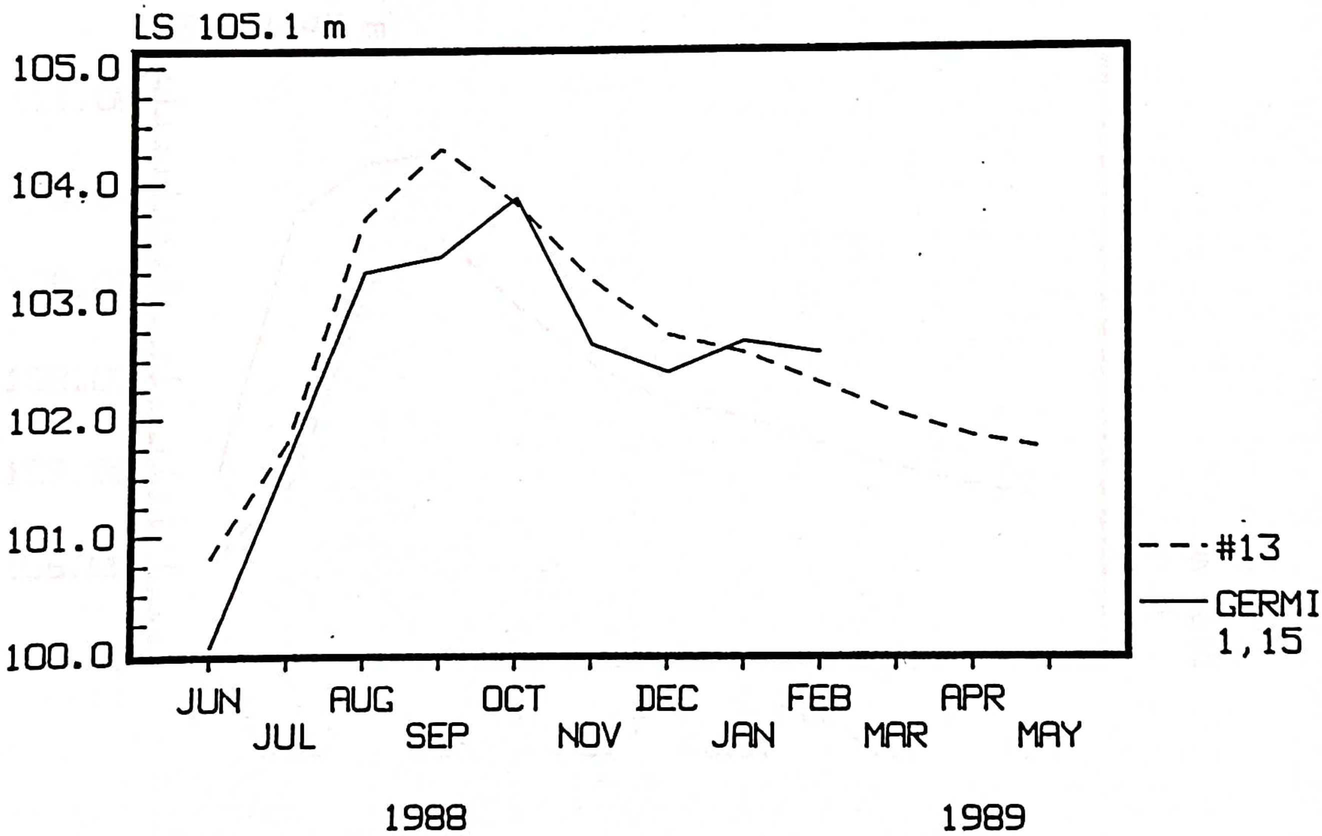


APPENDIX 24 — Continued

BISNUPURA

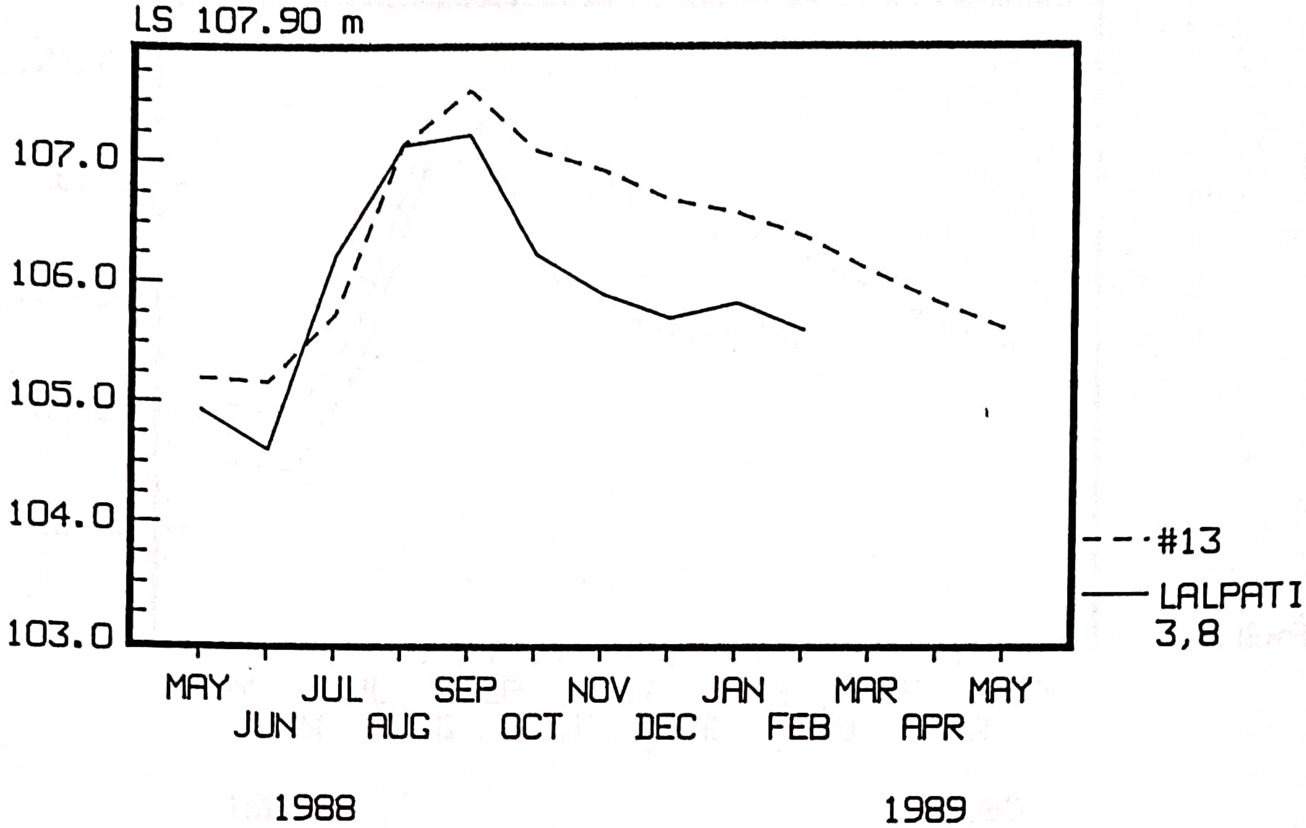


GERMI (HAND-PUMP WELL)

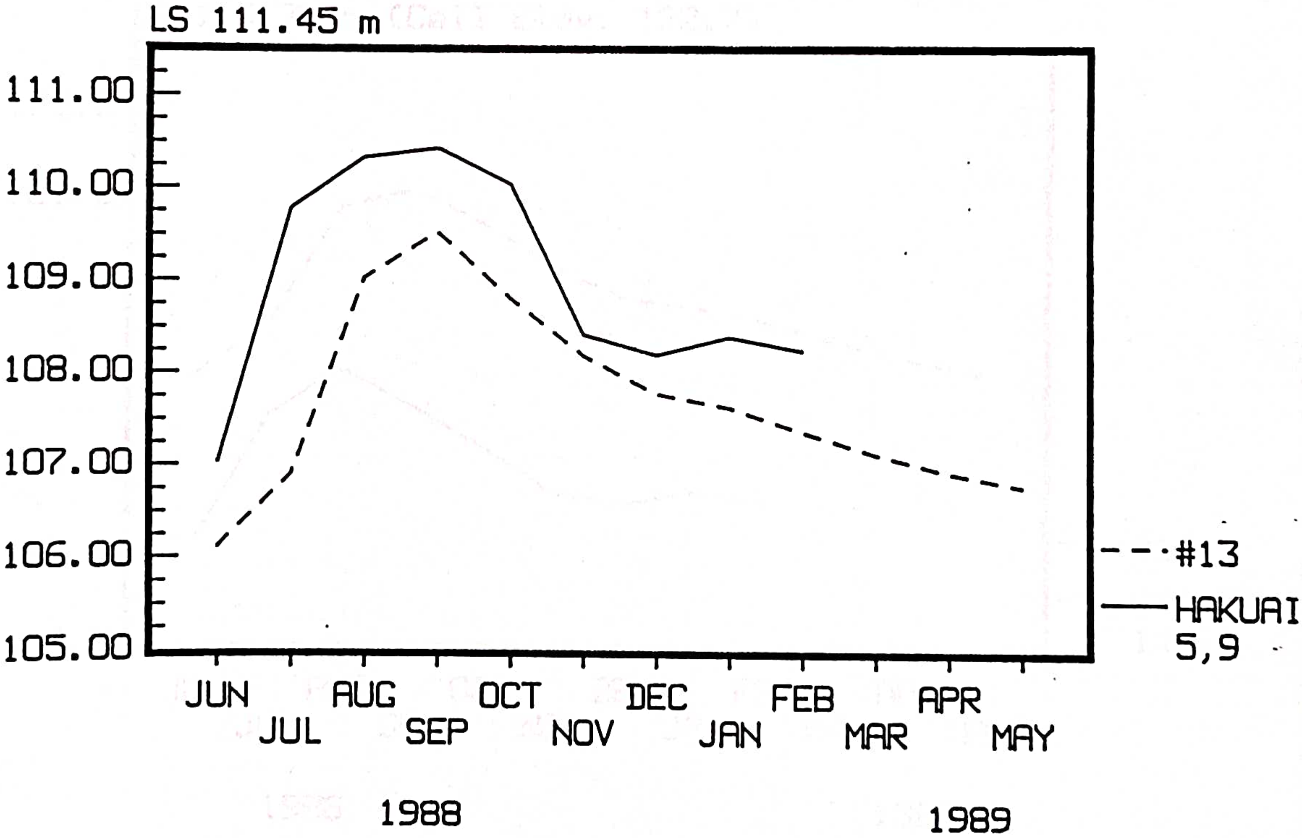


APPENDIX 24 —Continued

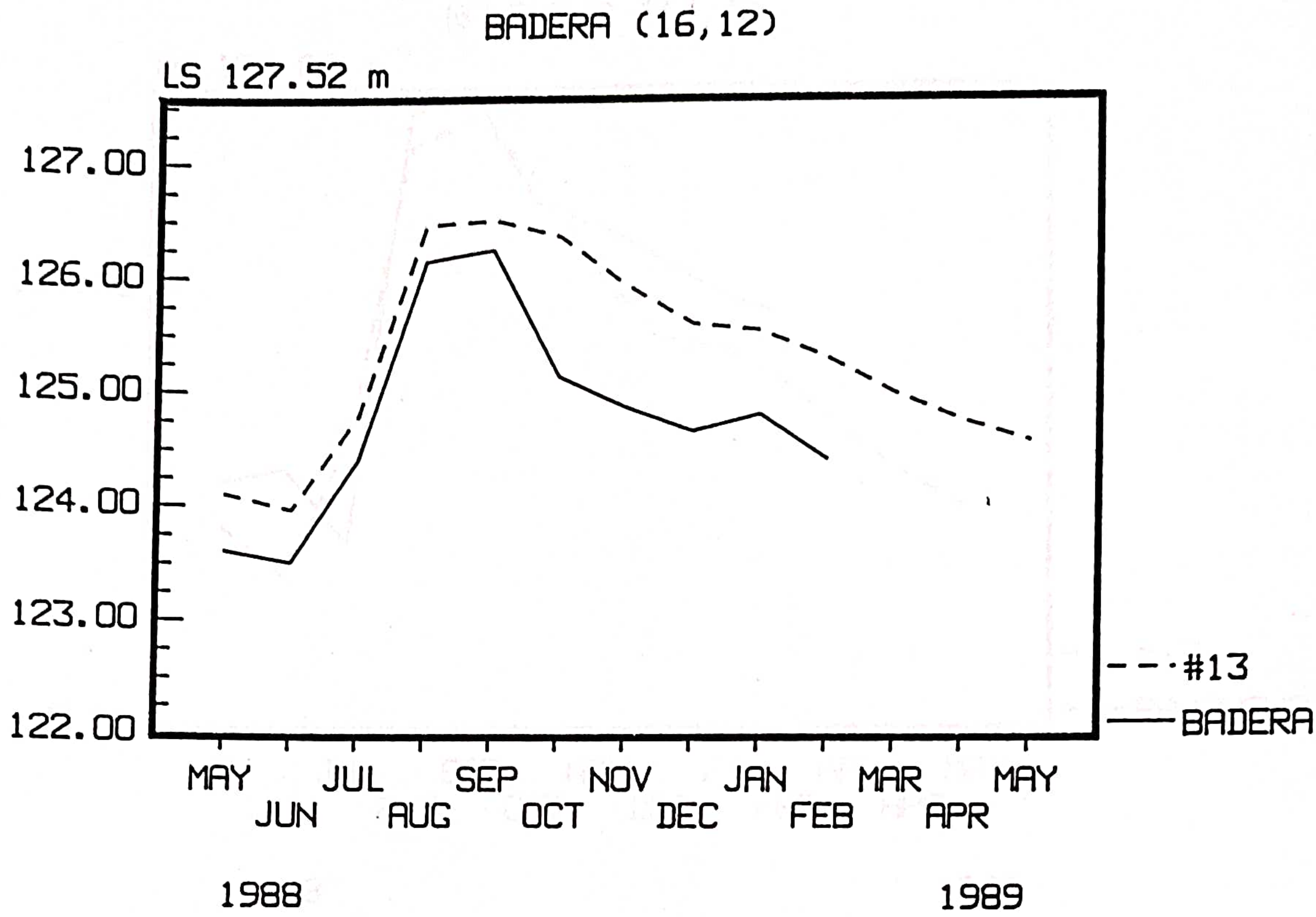
LALPATI

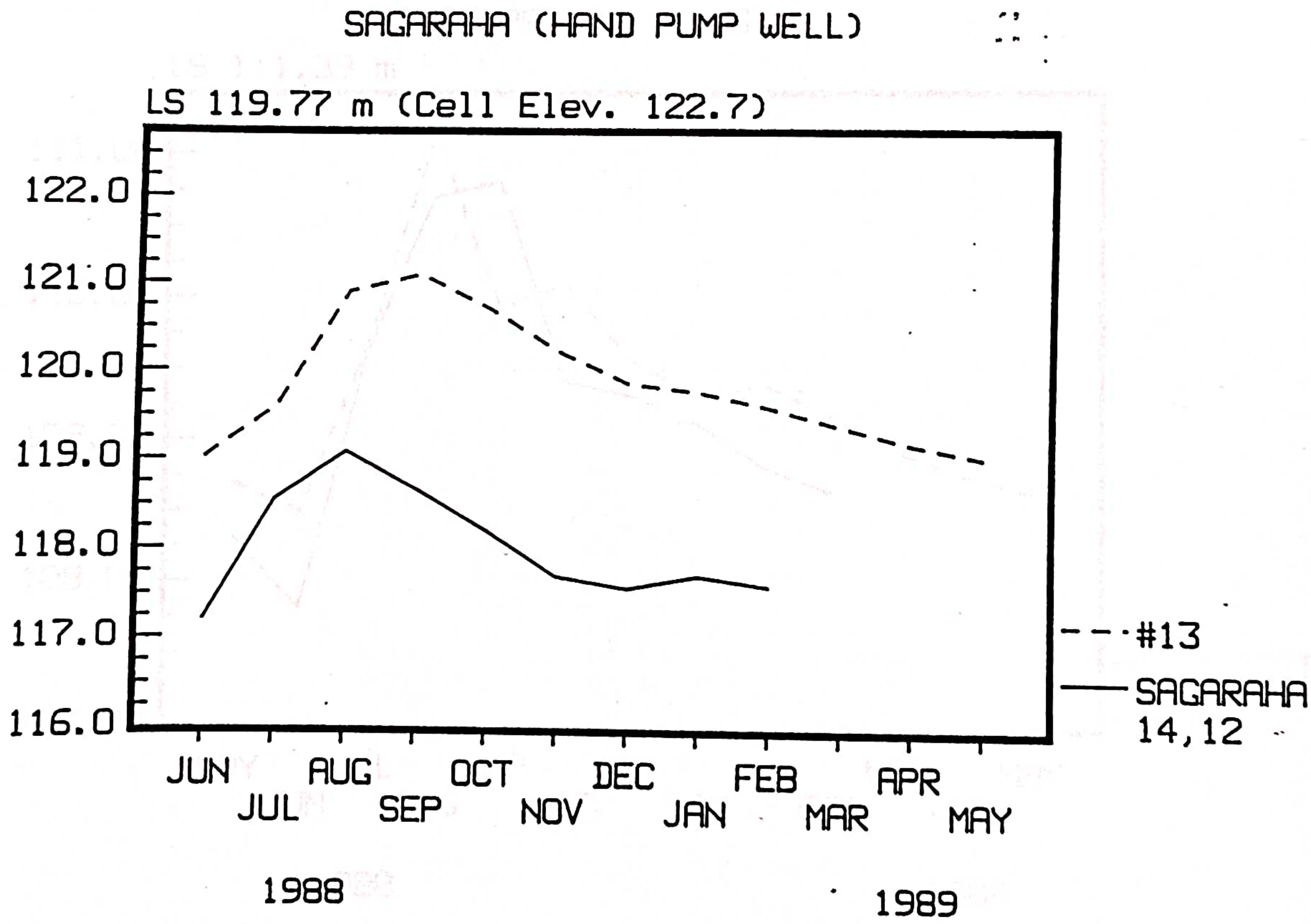


HAKUAI (HAND-PUMP WELL)

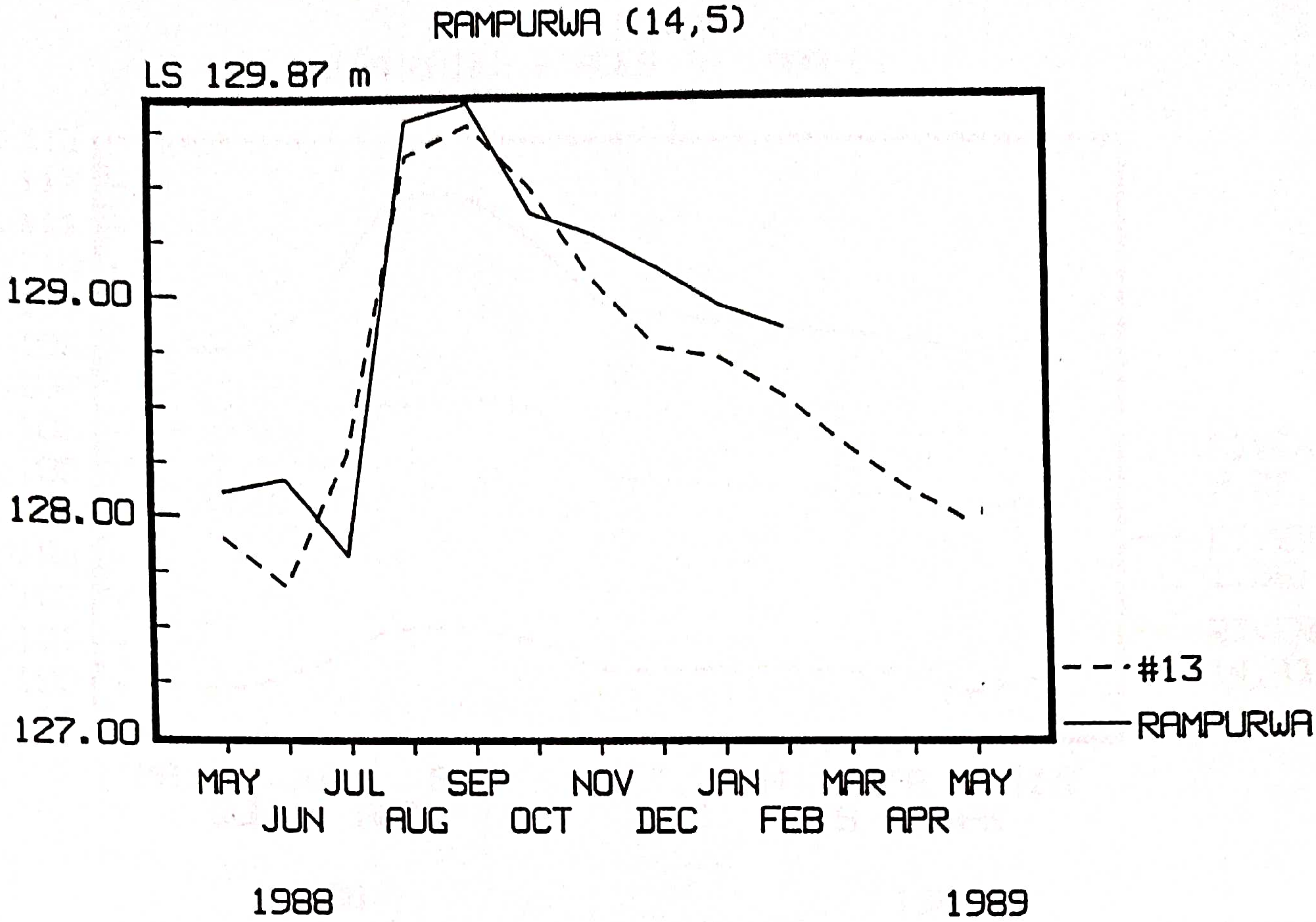


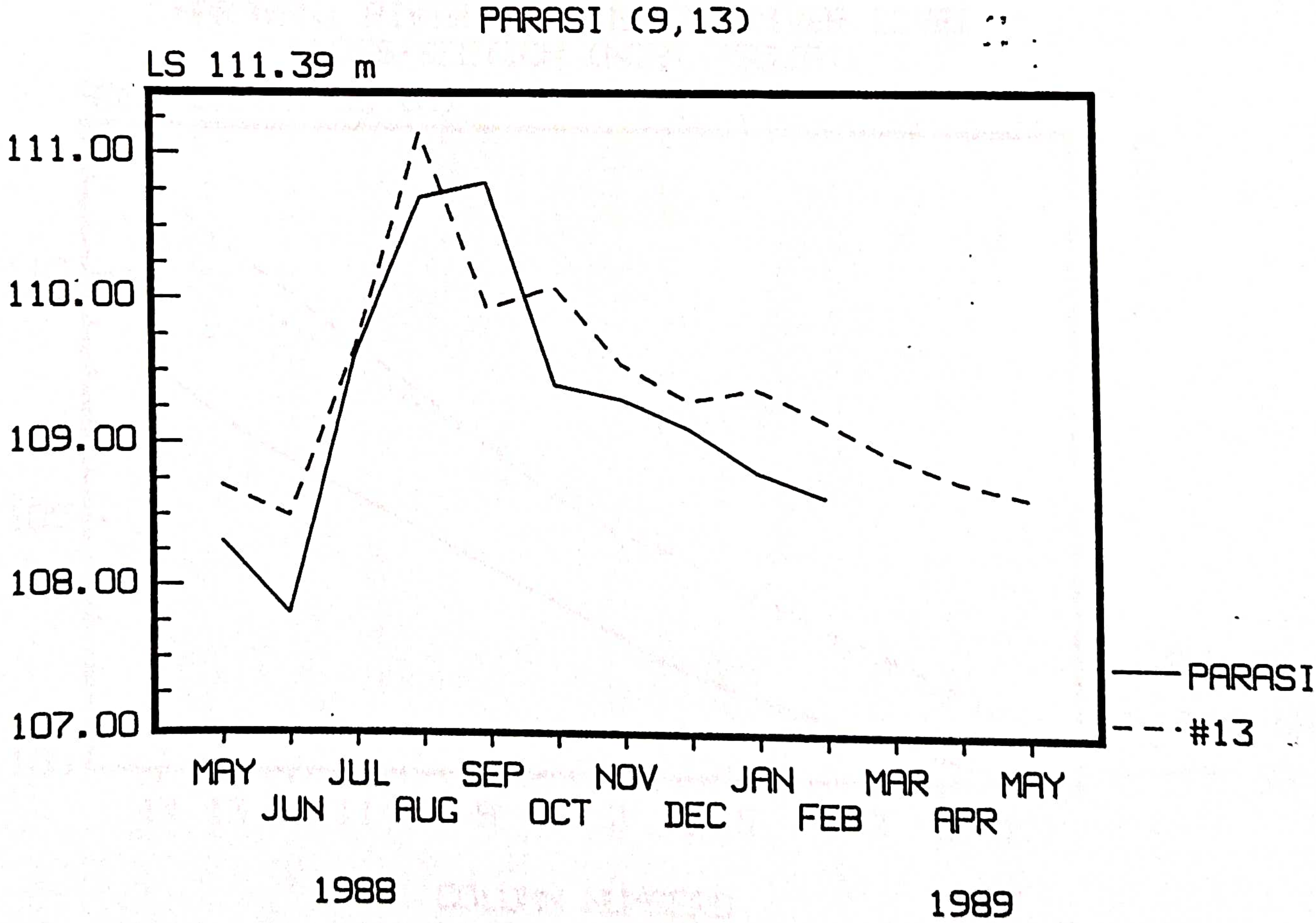
APPENDIX 24 — Continued





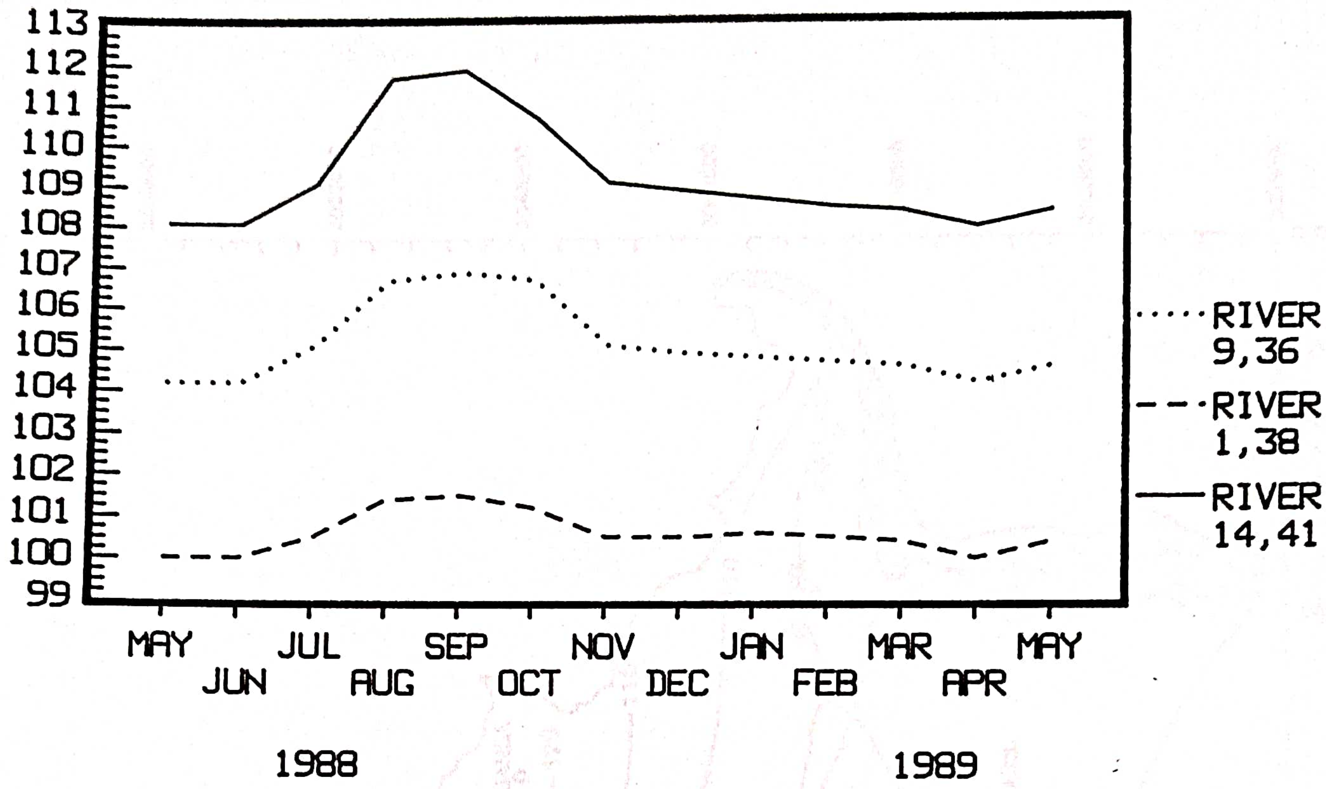
APPENDIX 24 — Continued



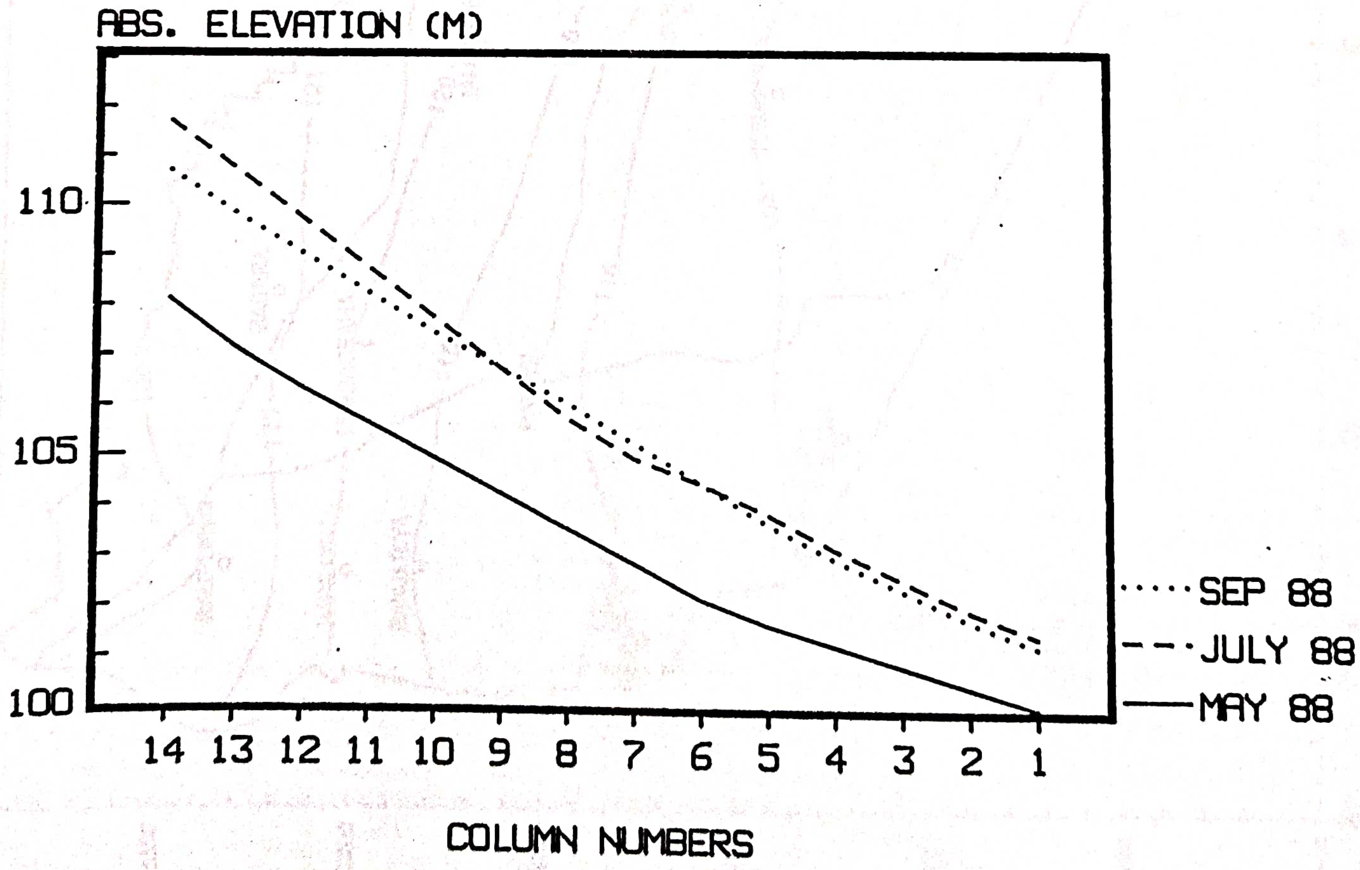


APPENDIX 24 — Continued

NARAYANI RIVER
SIMULATED STAGES IN 1988-89

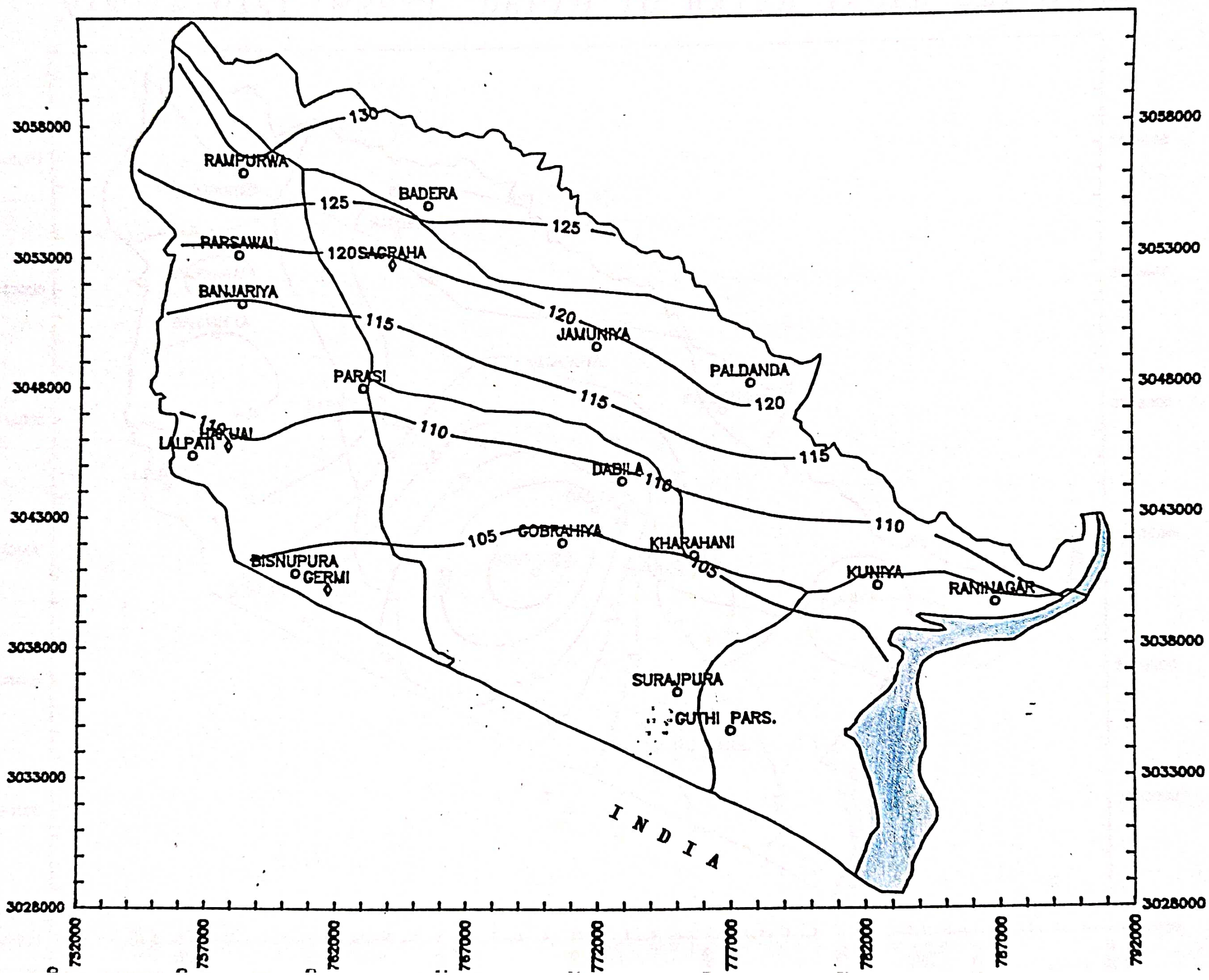


NARAYANI RIVER - SIMULATED RIVER LEVEL
CROSS-SECTION (NORTH-SOUTH)



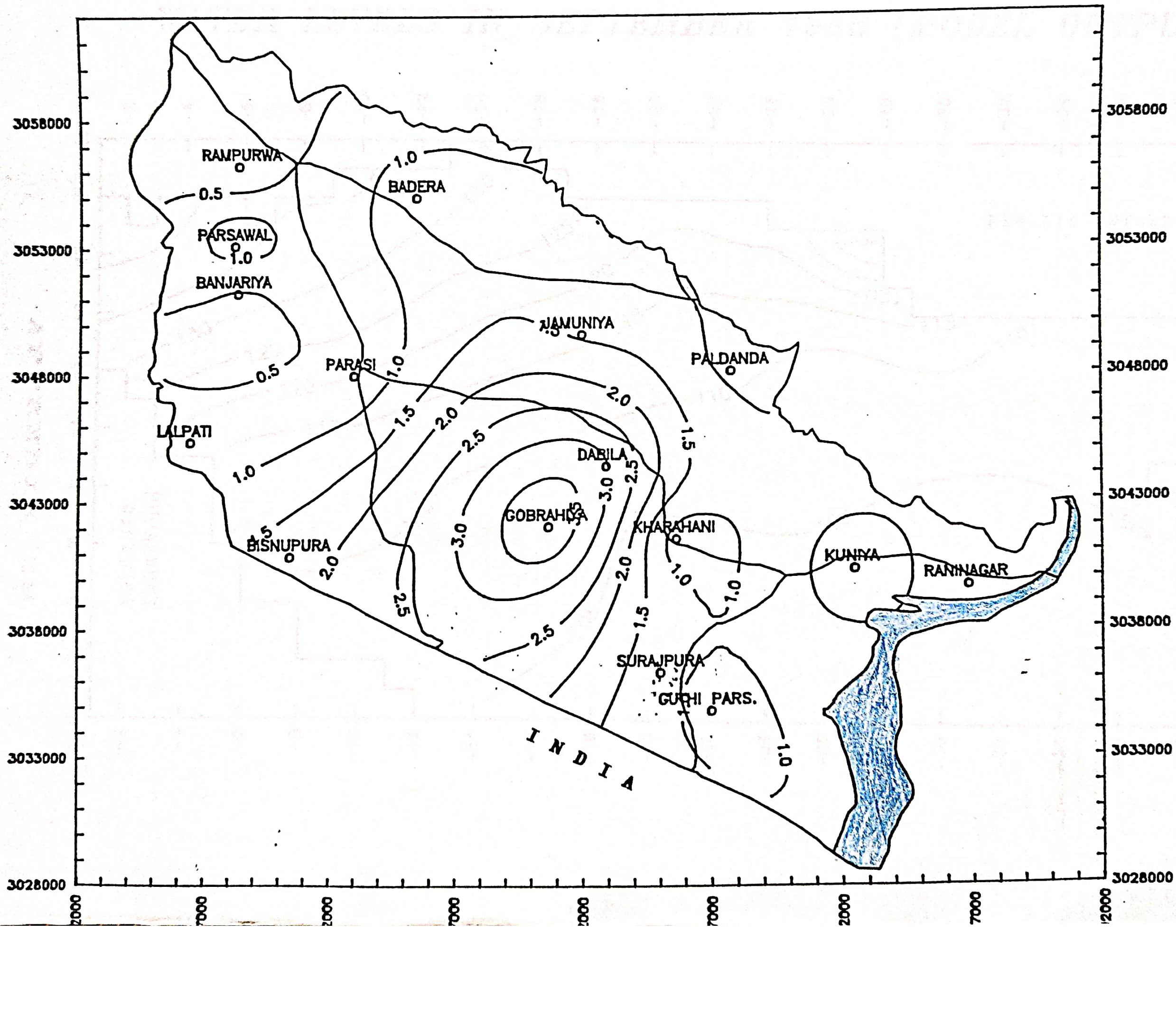
APPENDIX 26

NAWALPARASI (WEST) WATER LEVEL CONTOUR MAP SEP 1988



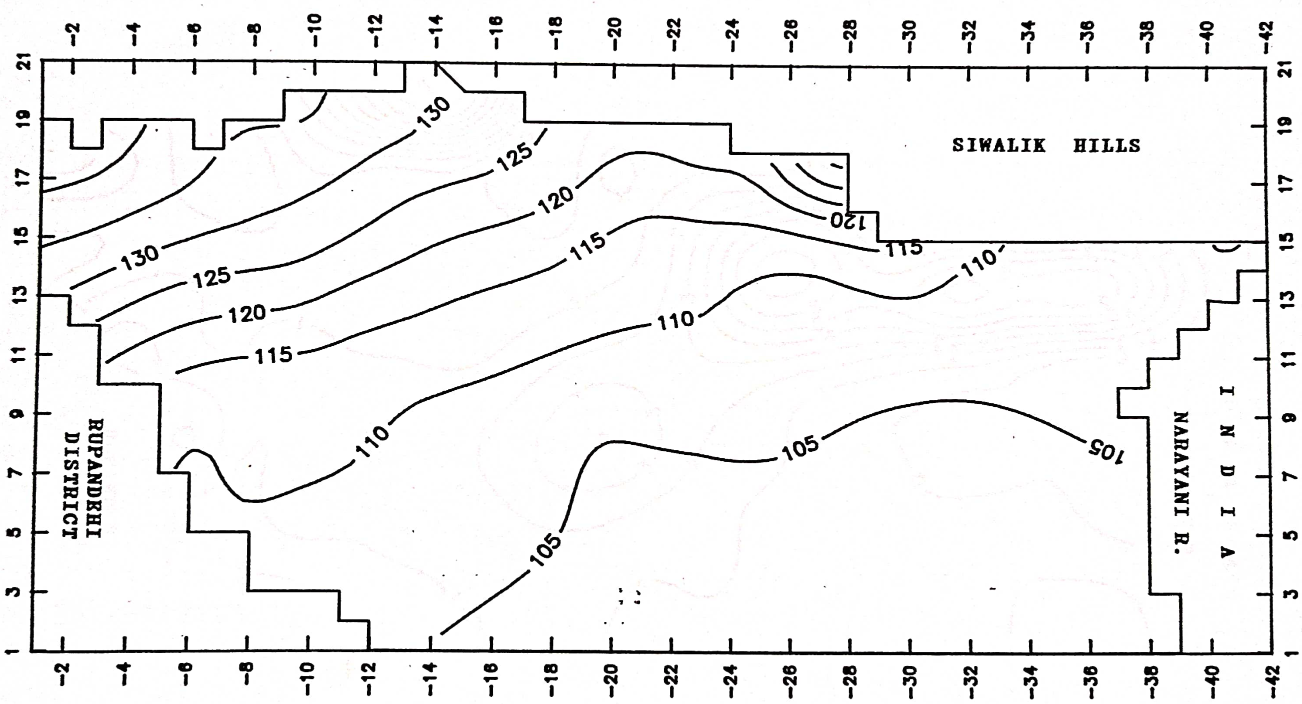
APPENDIX 27

NAWALPARASI (WEST) DEPTH TO WATER TABLE SEP 1988



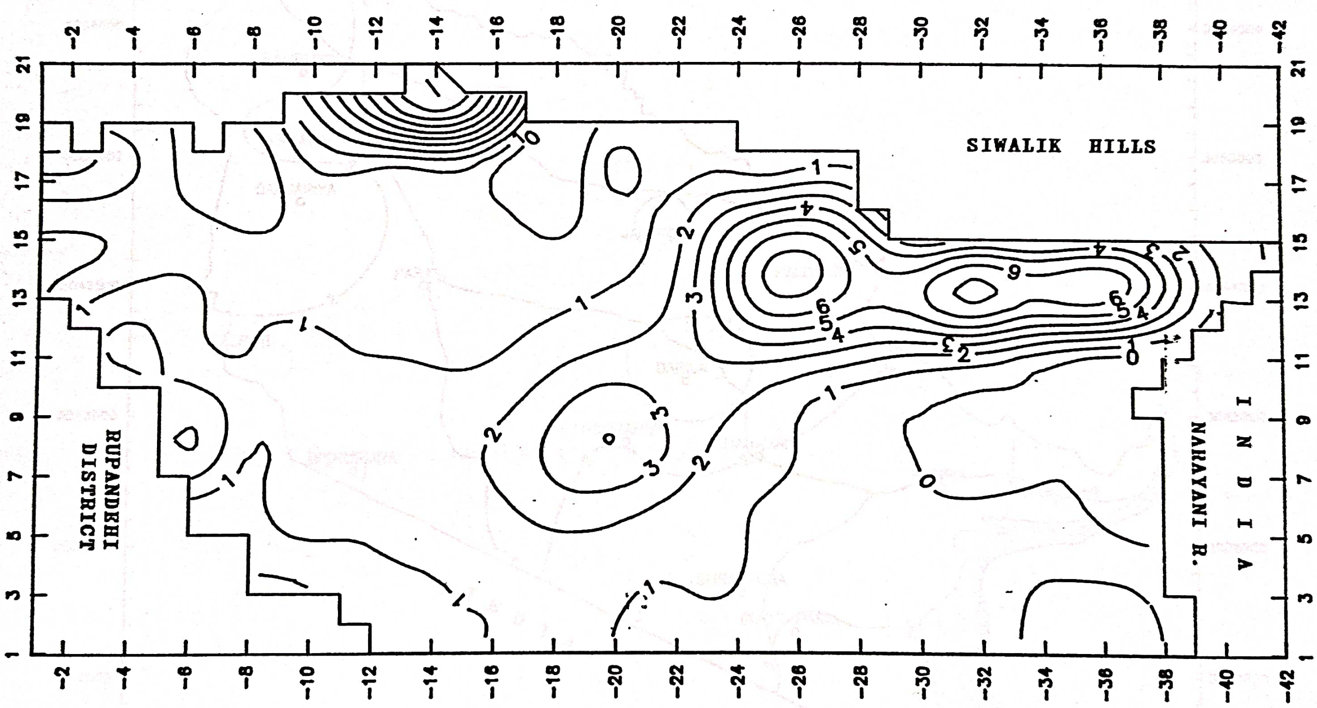
APPENDIX 28

WATER LEVELS IN SEPTEMBER 1988 (MODEL OUTPUT)



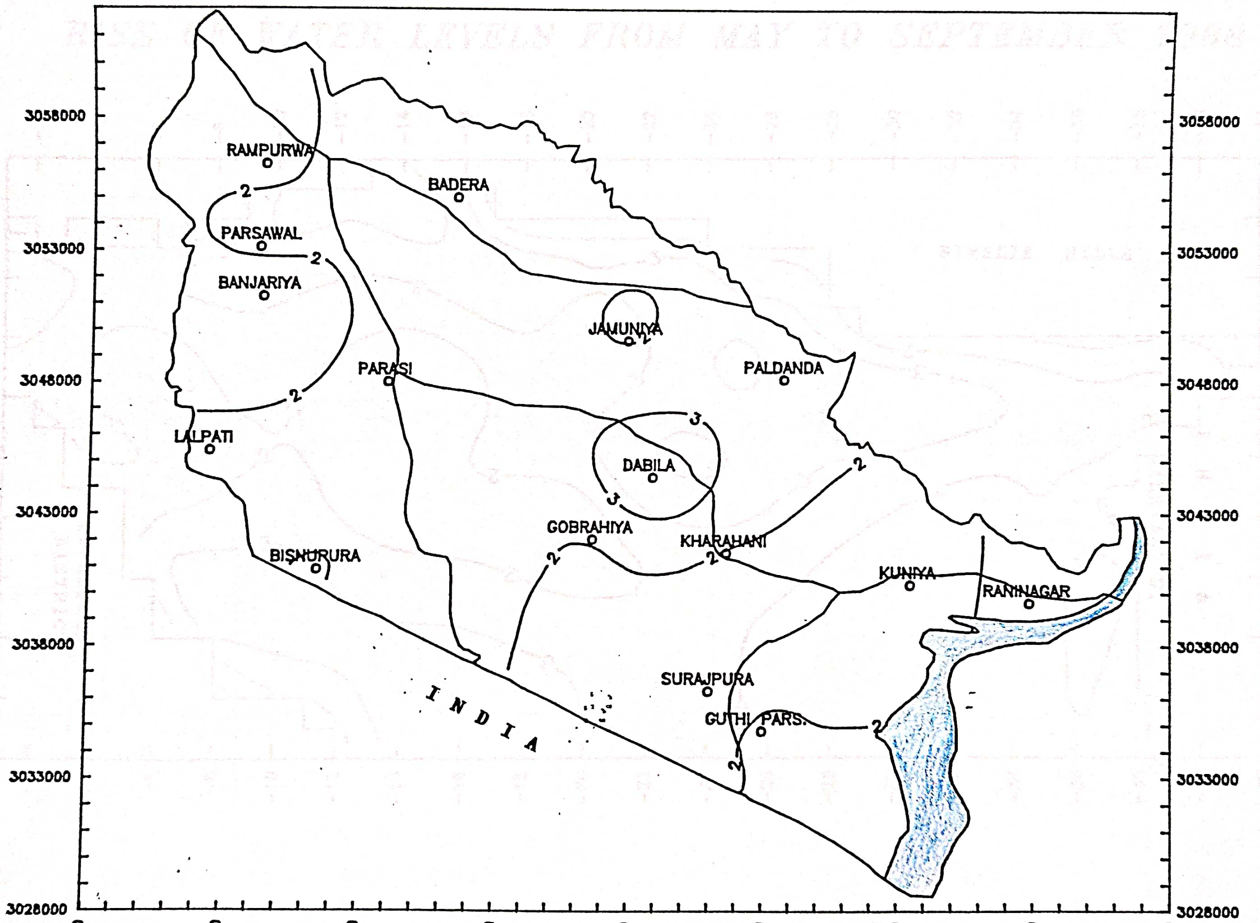
APPENDIX 29

DEPTH TO WATER TABLE IN SEPTEMBER 1988 (MODEL)



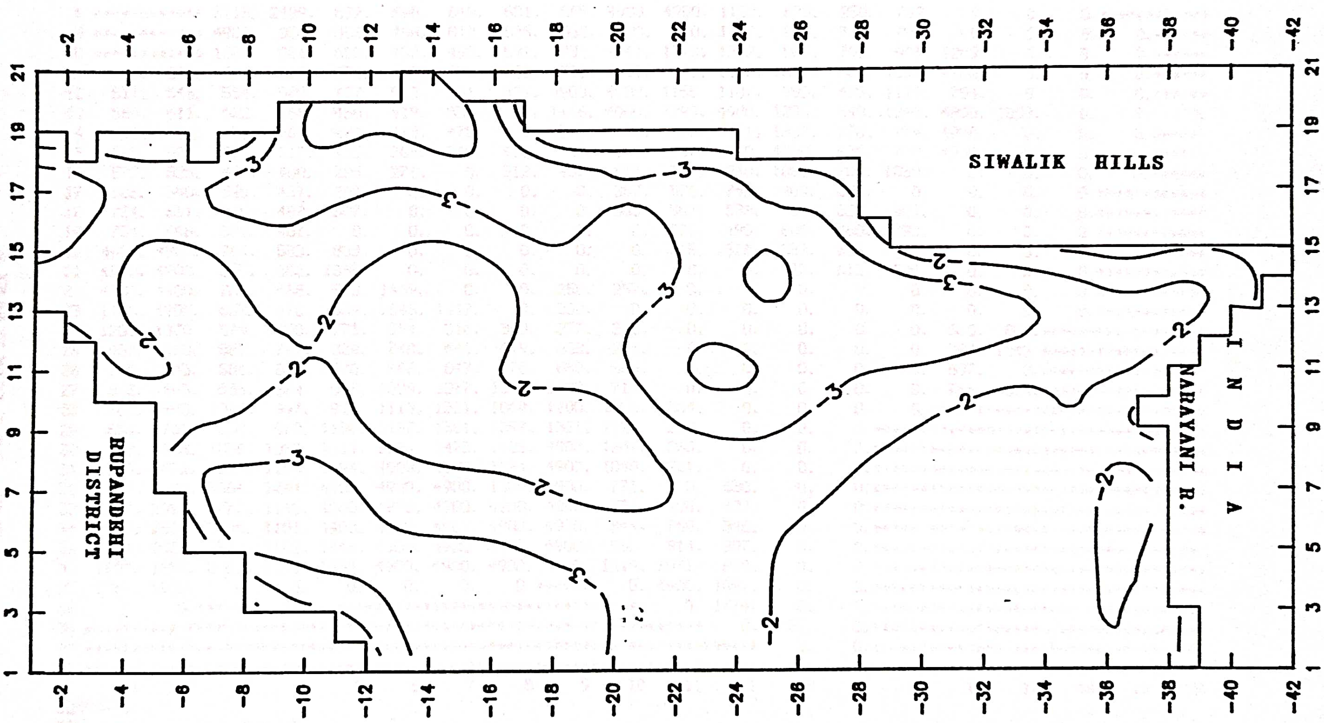
APPENDIX 30

NAWALPARASI (WEST) RISE OF WATER TABLE MAY - SEP 1988



APPENDIX 31

RISE OF WATER LEVELS FROM MAY TO SEPTEMBER 1988



APPENDIX 32

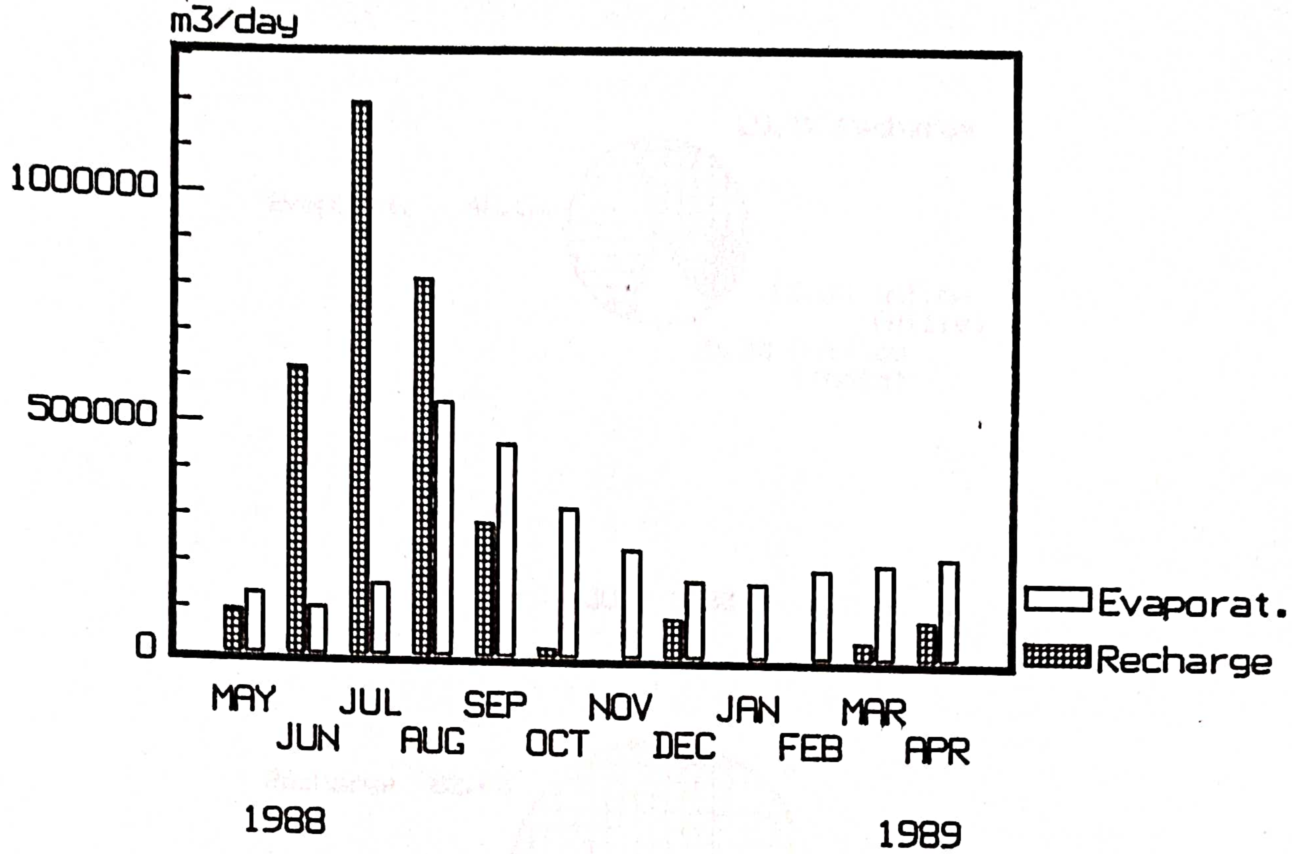
EVAPORATION LOSS — SEPTEMBER 1988

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	******	******	******	******	******	******	******	******	******	******	******	******	1303.	1168.	0.	0.	0.	0.	******	******
2	******	******	******	******	******	******	******	******	******	******	******	418.	898.	888.	0.	0.	0.	******	******	******
3	******	******	******	******	******	******	******	******	******	0.	0.	0.	878.	759.	1137.	0.	0.	0.	******	******
4	******	******	******	******	******	******	******	******	******	381.	381.	291.	4900.	820.	1028.	0.	0.	0.	******	******
5	******	******	******	******	******	******	0.	0.	0.	427.	879.	1236.	4900.	1247.	794.	0.	0.	0.	******	******
6	******	******	******	******	486.	350.	255.	0.	419.	288.	600.	838.	4900.	873.	774.	0.	0.	******	******	******
7	******	******	******	******	985.	755.	592.	357.	419.	949.	1157.	4900.	1038.	873.	1287.	0.	0.	0.	******	******
8	******	******	3113.	2499.	832.	698.	649.	601.	565.	4900.	4900.	1152.	625.	250.	762.	0.	0.	0.	******	******
9	******	******	4900.	959.	356.	466.	513.	535.	682.	4900.	770.	1097.	873.	524.	921.	0.	0.	0.	0.	******
10	******	******	1285.	981.	603.	452.	490.	591.	731.	1361.	1323.	1332.	985.	791.	901.	1269.	0.	0.	0.	******
11	******	679.	691.	687.	576.	490.	604.	681.	781.	1308.	921.	1023.	1009.	669.	1092.	4900.	0.	0.	0.	******
12	517.	546.	554.	580.	497.	513.	551.	884.	4900.	4900.	1155.	1187.	990.	498.	1113.	794.	0.	0.	0.	******
13	566.	611.	622.	568.	450.	419.	530.	803.	1416.	4900.	1399.	4900.	1235.	540.	1246.	4900.	1099.	0.	0.	0.
14	495.	594.	633.	567.	473.	413.	470.	622.	582.	4900.	1420.	1431.	1307.	720.	794.	4900.	0.	0.	0.	******
15	565.	605.	565.	517.	455.	363.	348.	458.	610.	898.	1067.	1280.	4900.	625.	797.	4900.	0.	0.	0.	******
16	577.	525.	487.	400.	295.	271.	0.	312.	437.	565.	741.	940.	1063.	706.	1030.	0.	0.	0.	0.	******
17	605.	590.	545.	431.	287.	0.	0.	0.	0.	387.	576.	740.	909.	629.	0.	0.	0.	0.	******	******
18	724.	661.	576.	497.	307.	0.	0.	0.	0.	305.	501.	578.	708.	851.	901.	0.	0.	0.	******	******
19	754.	698.	578.	407.	0.	0.	0.	0.	0.	0.	371.	490.	600.	760.	790.	0.	0.	0.	******	******
20	4900.	4900.	764.	533.	883.	0.	0.	0.	0.	0.	315.	378.	532.	735.	729.	0.	0.	0.	******	******
21	4900.	4900.	845.	602.	1335.	0.	0.	0.	0.	0.	0.	0.	422.	612.	500.	0.	0.	0.	******	******
22	4900.	4900.	707.	468.	523.	1469.	0.	0.	256.	257.	0.	0.	0.	0.	0.	0.	0.	0.	******	******
23	1416.	4900.	657.	378.	604.	1645.	1417.	0.	330.	0.	0.	0.	0.	0.	0.	0.	0.	0.	******	******
24	1206.	1370.	579.	500.	771.	554.	516.	350.	377.	260.	0.	0.	0.	0.	0.	500.	801.	******	******	******
25	937.	1010.	887.	797.	829.	740.	641.	619.	603.	281.	0.	0.	0.	0.	0.	398.	1249.	******	******	******
26	794.	843.	884.	860.	870.	866.	847.	976.	688.	309.	0.	0.	0.	0.	0.	697.	0.	******	******	******
27	843.	845.	838.	874.	903.	1009.	1077.	1064.	1192.	715.	0.	0.	0.	0.	0.	785.	624.	******	******	******
28	782.	845.	1064.	997.	916.	1113.	1321.	1068.	1200.	1025.	364.	0.	0.	0.	0.	******	******	******	******	******
29	655.	761.	954.	978.	1136.	1137.	1381.	1397.	1381.	1129.	270.	0.	0.	0.	******	******	******	******	******	******
30	778.	858.	1056.	1088.	1219.	1184.	1423.	1425.	4900.	1241.	265.	0.	0.	0.	******	******	******	******	******	******
31	1040.	1032.	1015.	1150.	1394.	4900.	4900.	1224.	4900.	1040.	261.	0.	0.	0.	******	******	******	******	******	******
32	779.	893.	3064.	1244.	4900.	4900.	4900.	1380.	4900.	771.	0.	538.	0.	0.	******	******	******	******	******	******
33	2367.	2987.	2777.	1140.	4900.	4900.	4900.	4900.	4900.	771.	498.	438.	0.	0.	******	******	******	******	******	******
34	1920.	2524.	2736.	1101.	4900.	4900.	4900.	4900.	4900.	844.	768.	346.	0.	0.	******	******	******	******	******	******
35	1794.	2056.	2382.	3162.	1444.	4900.	4900.	4900.	4900.	933.	814.	307.	0.	0.	******	******	******	******	******	******
36	1591.	1852.	2302.	3154.	1438.	4900.	4900.	4900.	0.	1319.	1071.	880.	0.	0.	******	******	******	******	******	******
37	1787.	1938.	0.	0.	0.	0.	0.	0.	******	0.	4900.	1091.	0.	0.	******	******	******	******	******	******
38	0.	0.	******	******	******	******	******	******	******	******	0.	1774.	0.	0.	******	******	******	******	******	******
39	******	******	******	******	******	******	******	******	******	******	******	0.	1265.	0.	******	******	******	******	******	******
40	******	******	******	******	******	******	******	******	******	******	******	******	0.	0.	******	******	******	******	******	******
41	******	******	******	******	******	******	******	******	******	******	******	******	******	0.	******	******	******	******	******	******

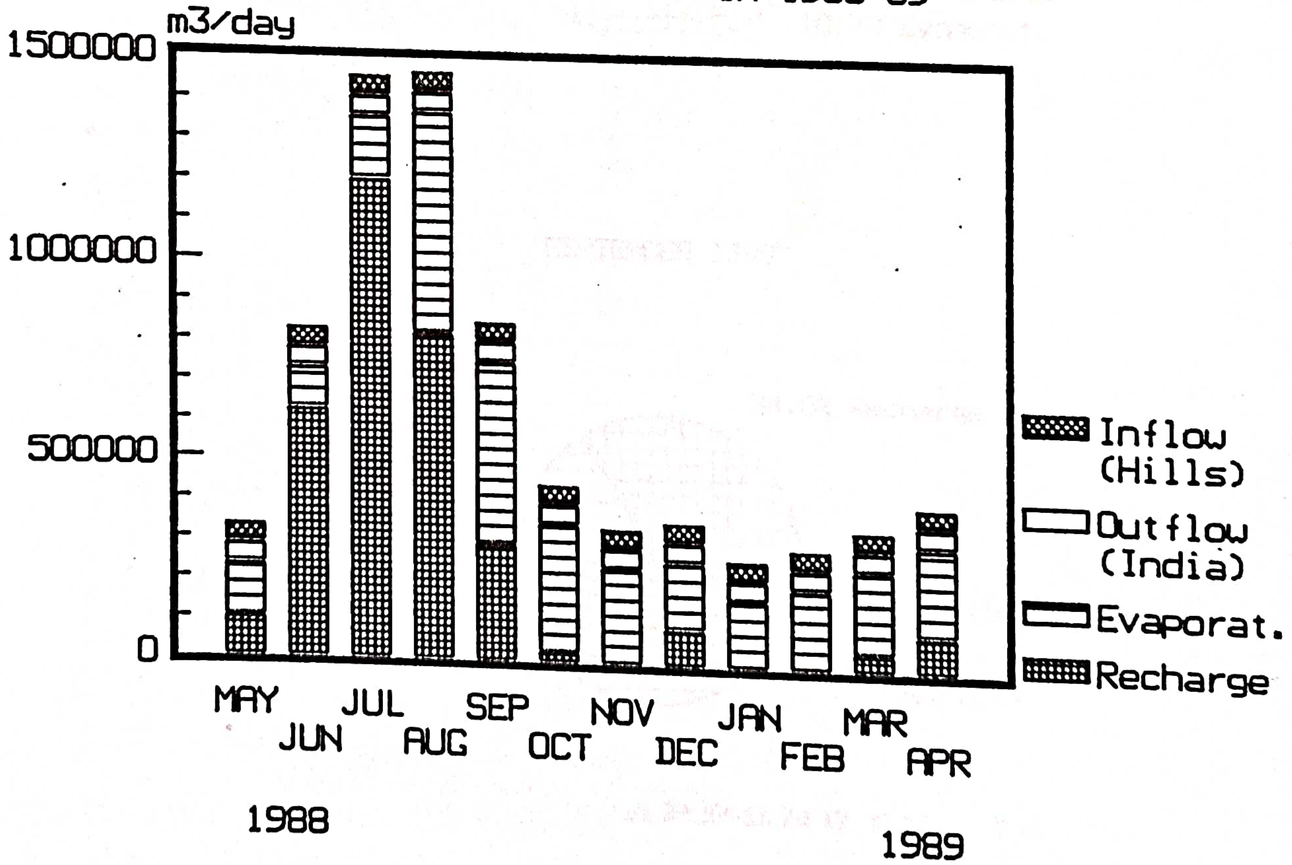
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

COMMENTS:
Evaporation is in [m3/day]
Time Step = 4
Time elapsed = 0,1200E+03 [day]
Evaporation Losses in September 1988 ... Maximum Water Levels

Nawalparasi (West) Model
Monthly Water Balance in 1988-89

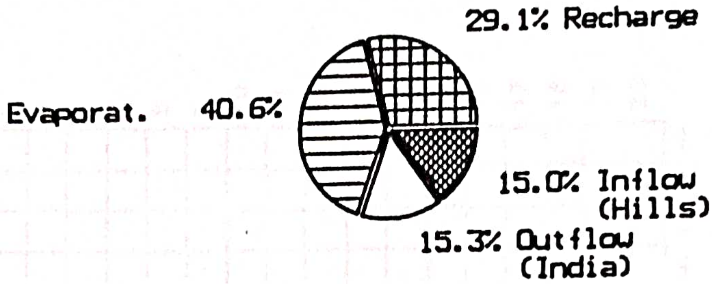


Nawalparasi (West) Model
Monthly Water Balance in 1988-89

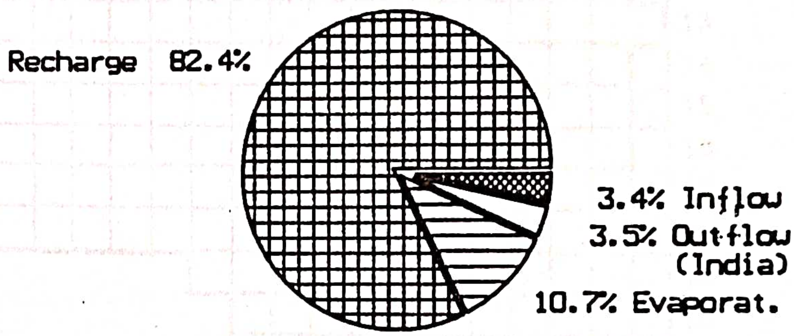


APPENDIX 33

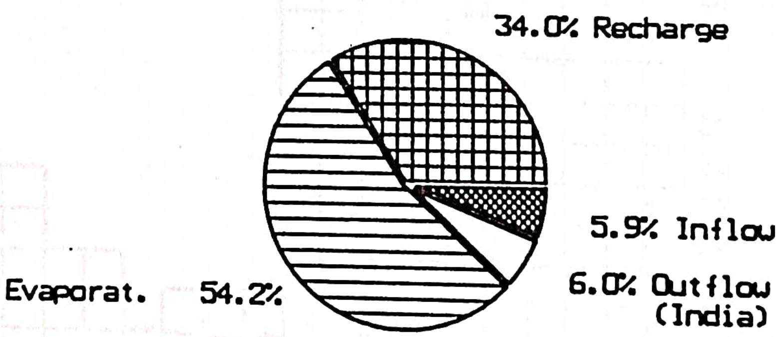
MAY 1988



JULY 1988

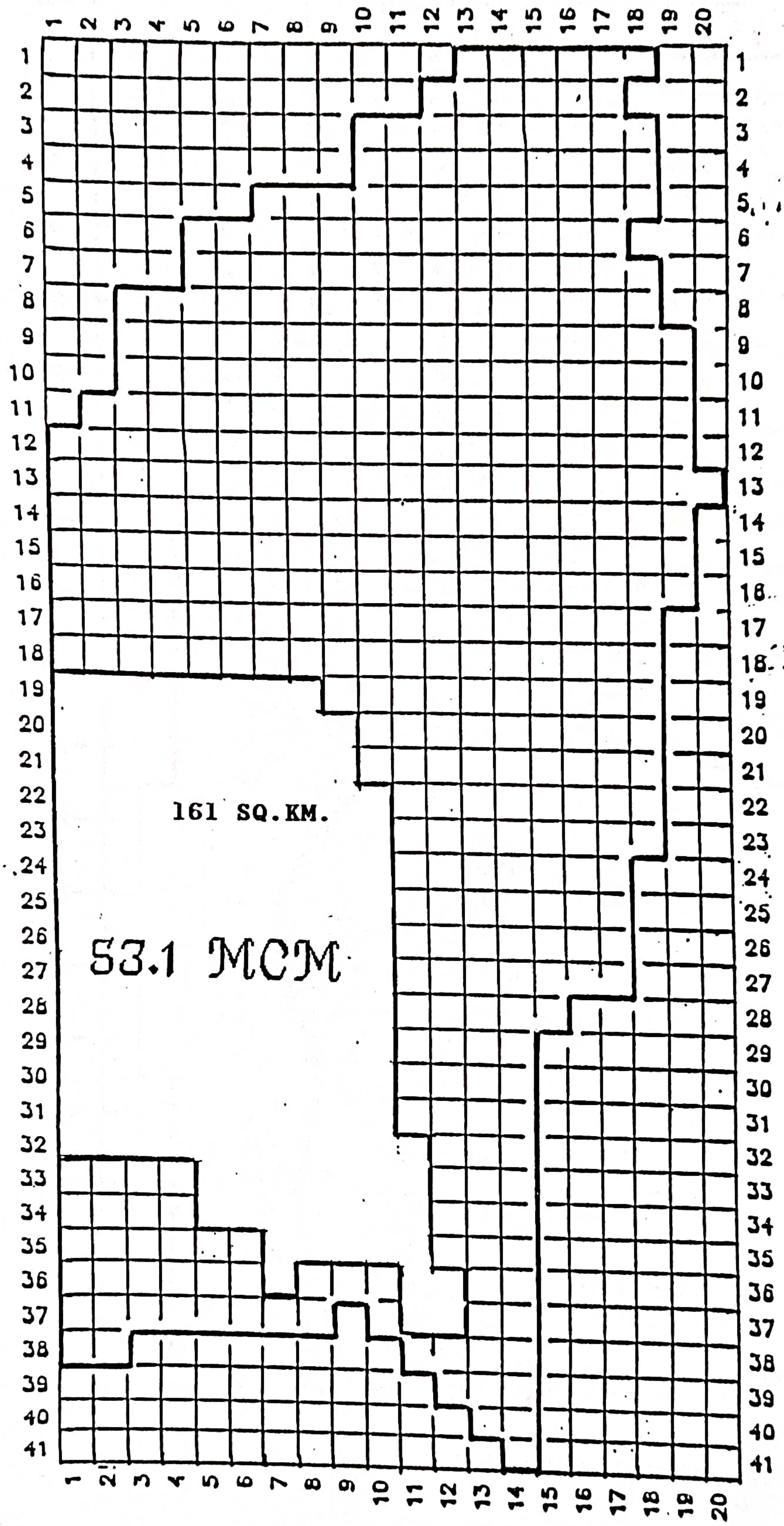


SEPTEMBER 1988



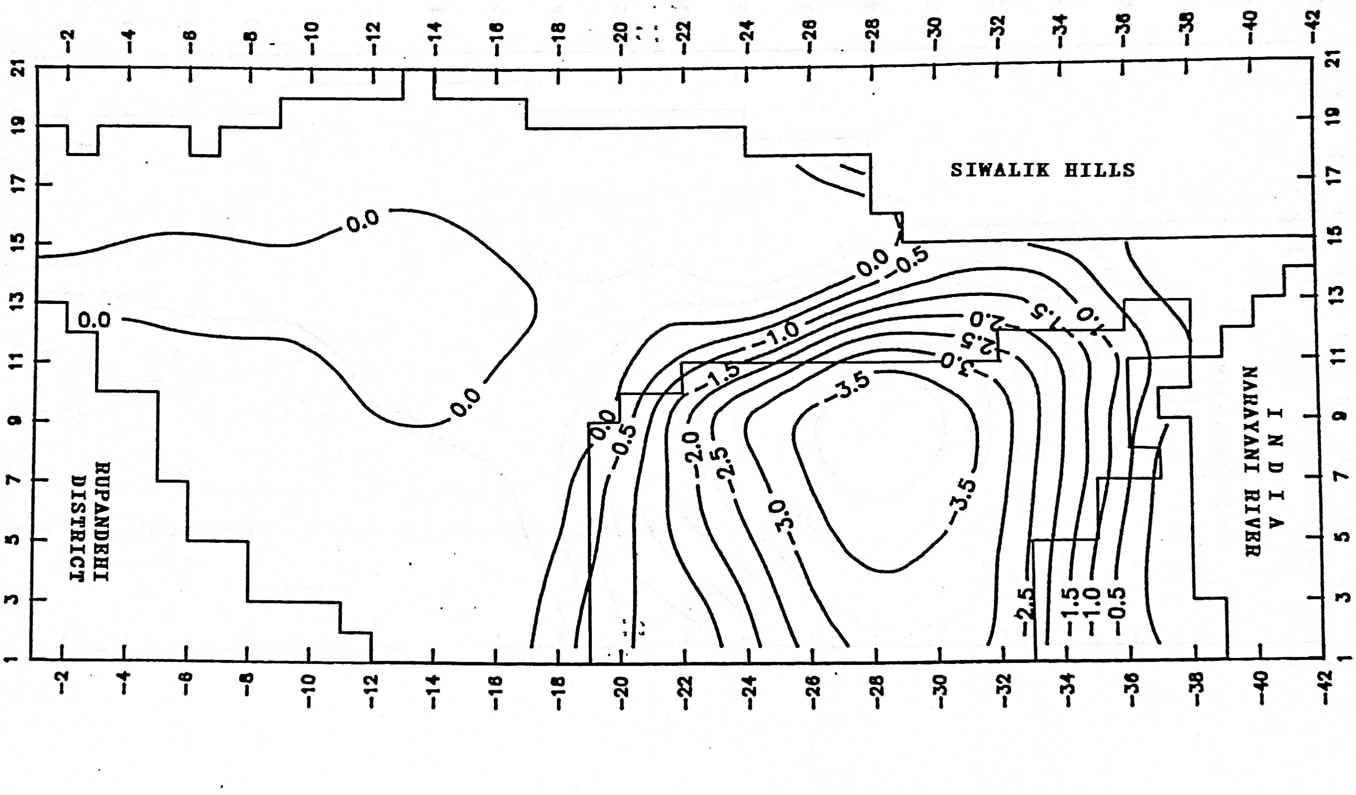
APPENDIX 34

FUTURE DEVELOPMENT SCHEME No. 1
DISTRIBUTION OF PUMPING CELLS



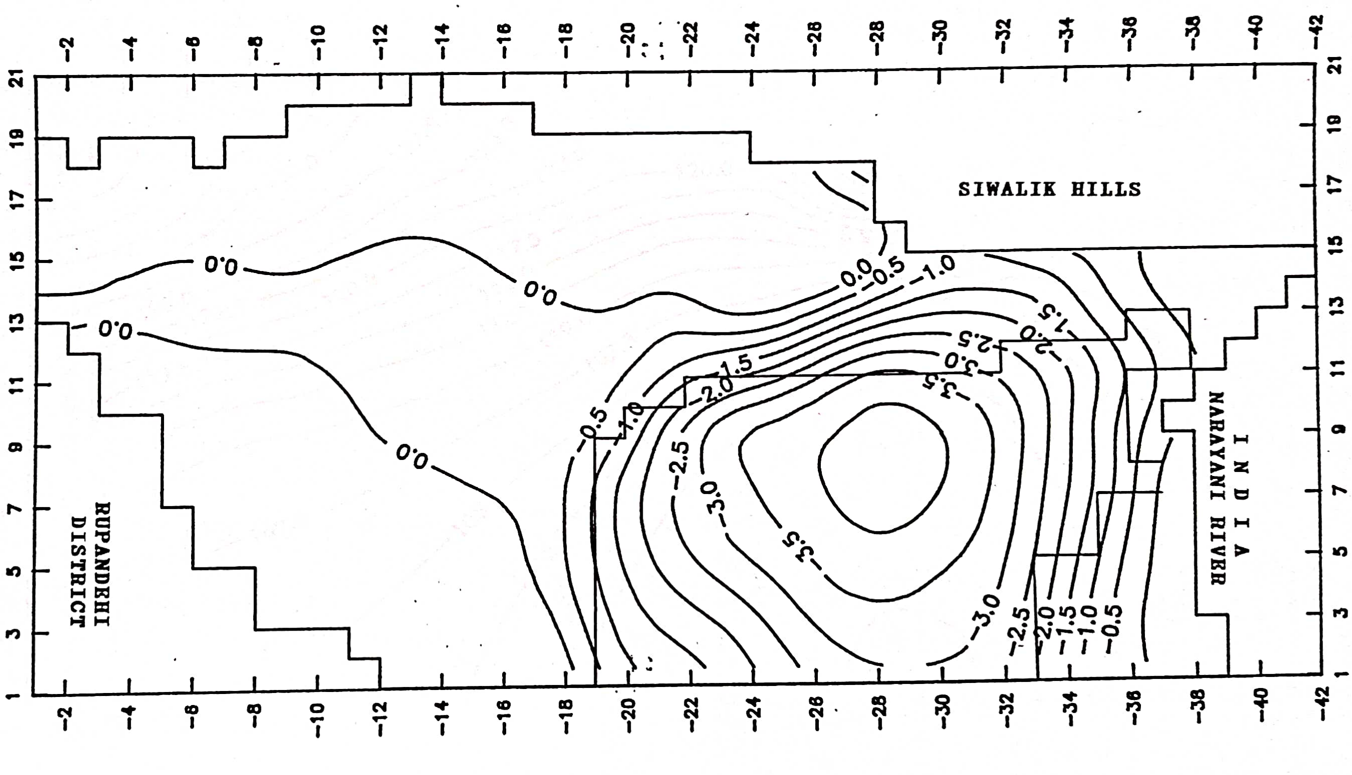
APPENDIX 36

FUTURE DEVELOPMENT '1: DRAWDOWNS AFTER 1 YEAR

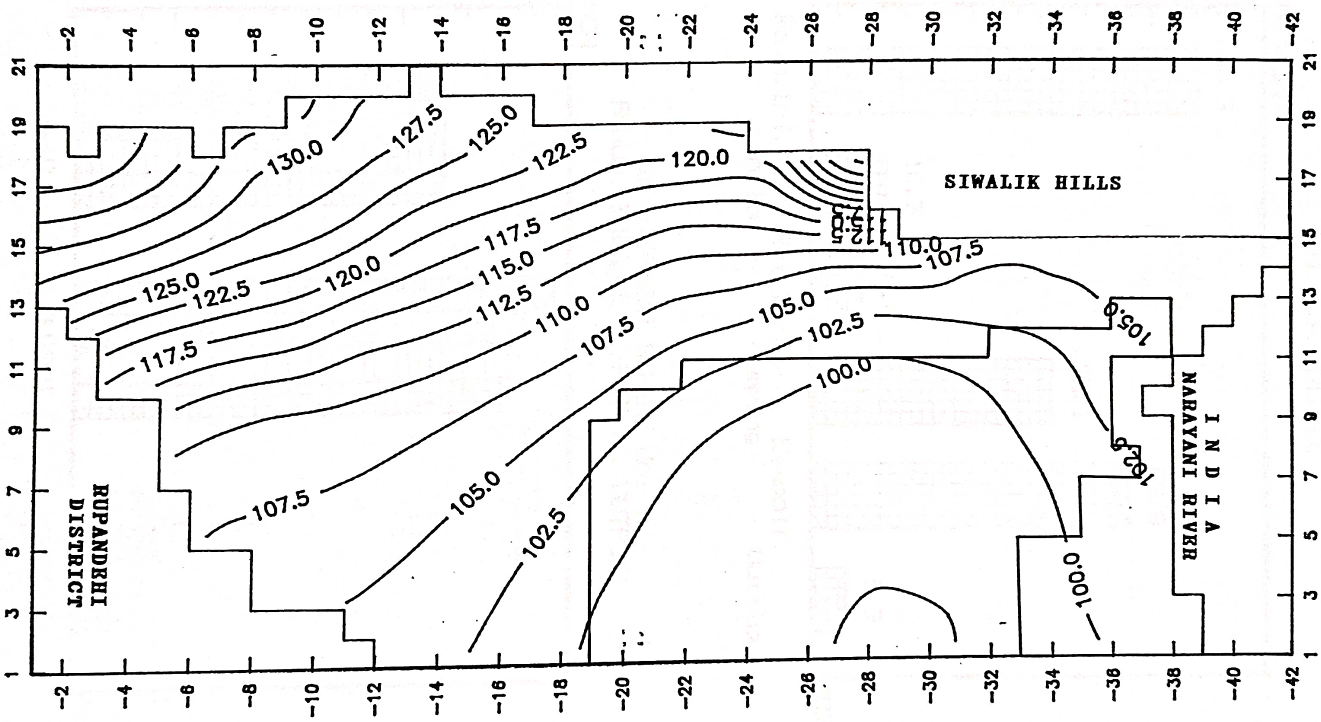


APPENDIX 37

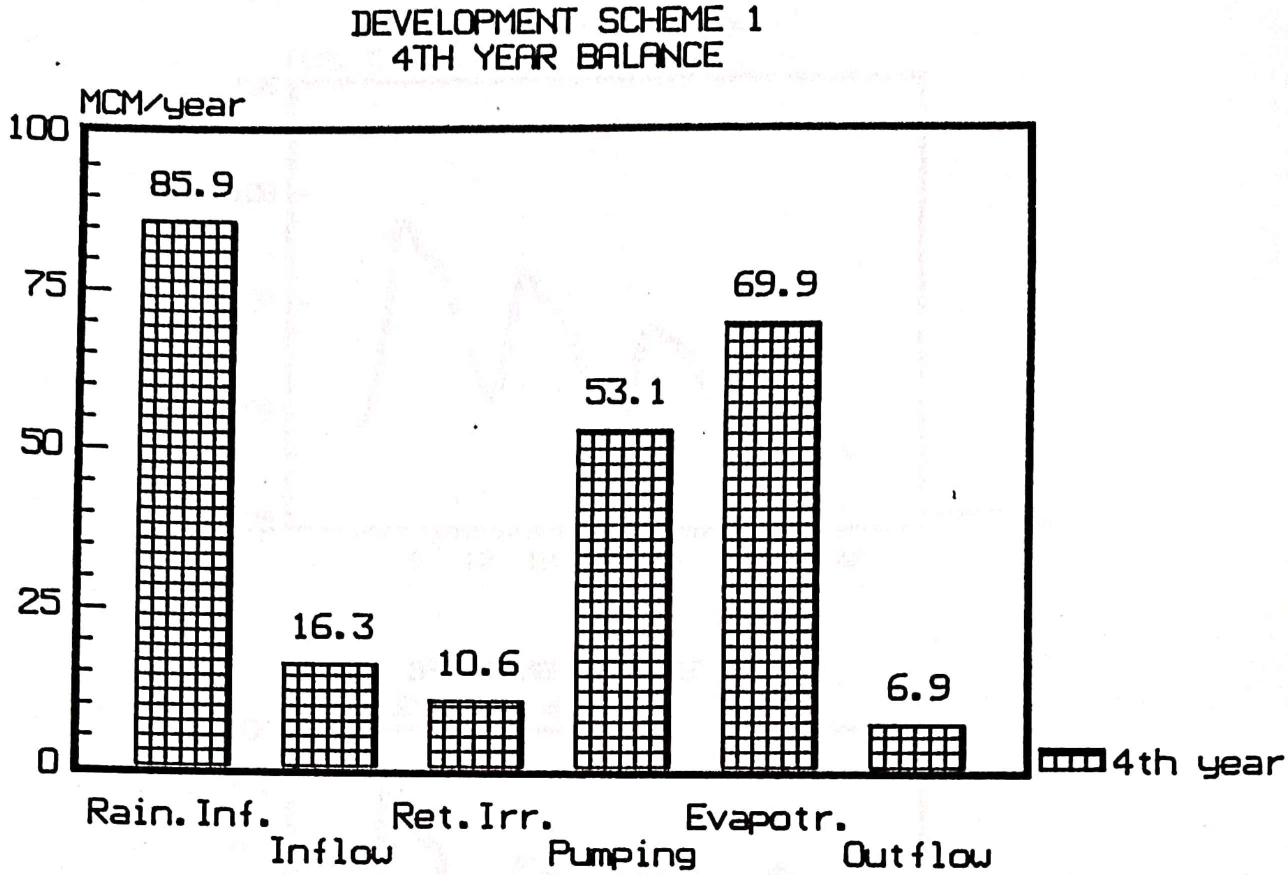
FUTURE DEVELOPMENT '1: DRAWDOWNS AFTER 4 YEARS

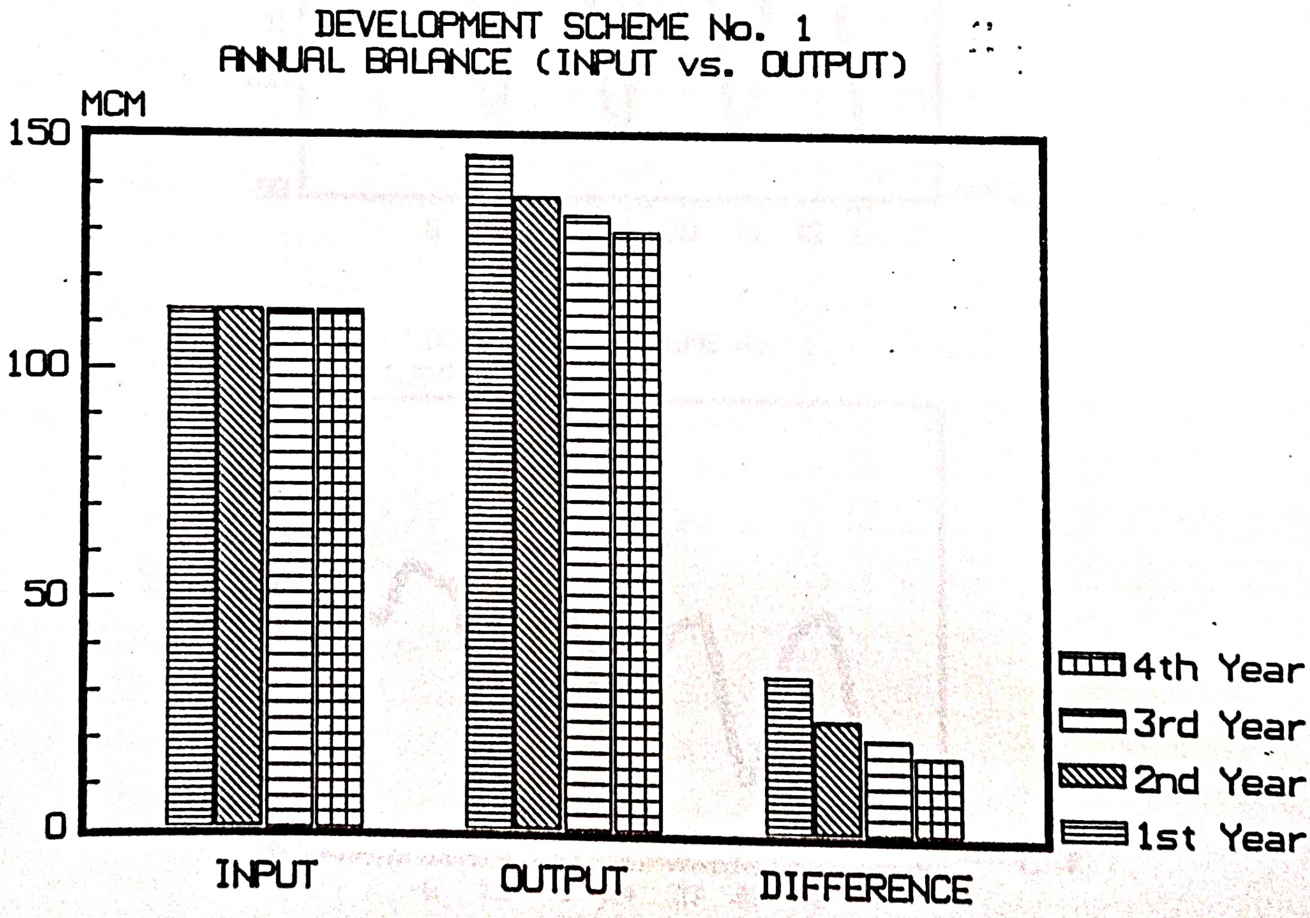


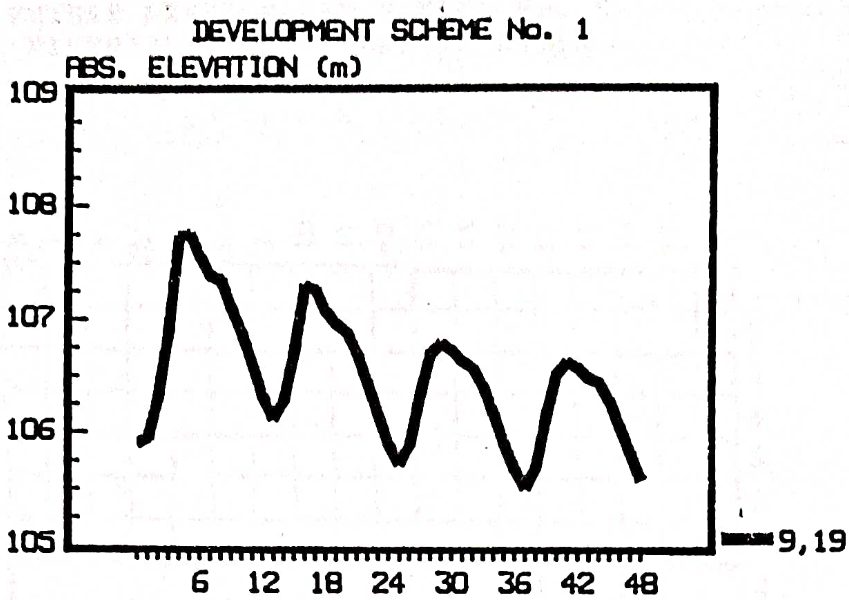
FUTURE DEVELOPMENT '1: WATER LEVELS AFTER 4 YRS

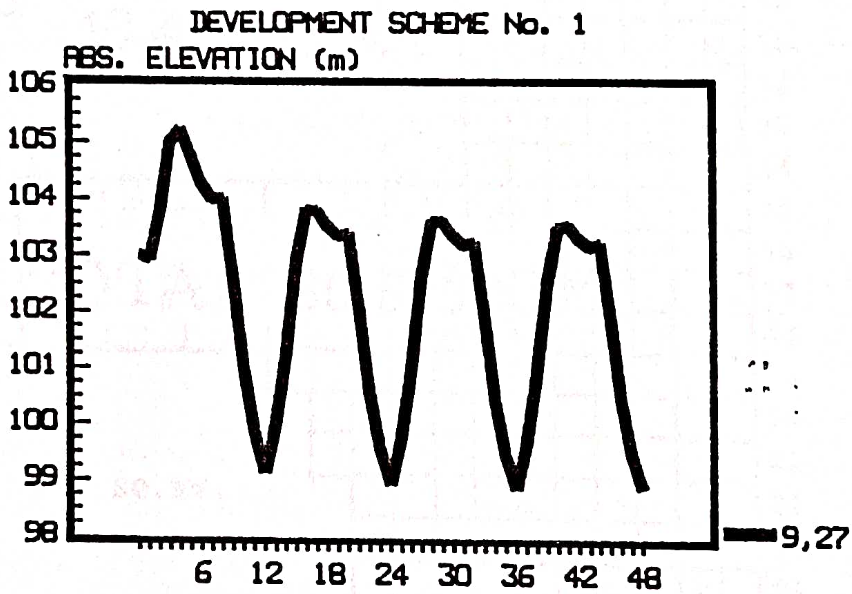


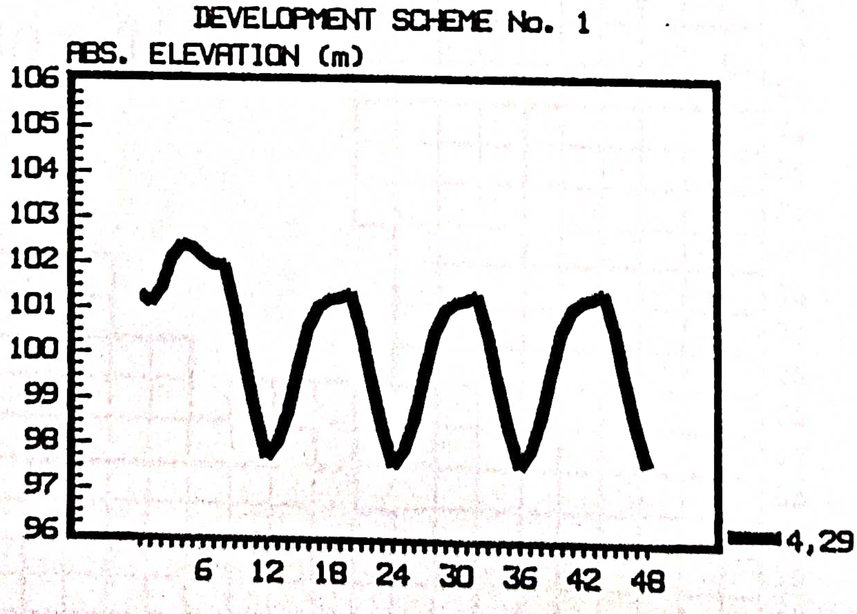
APPENDIX 38


DEVELOPMENT SCHEME 1
4TH YEAR BALANCE
MCM/year
100
75
50
25
0
85.9
16.3
10.6
53.1
69.9
6.9
Rain.Inf.
Inflow
Ret.Irr.
Pumping
Evapotr.
Outflow
4th year


DEVELOPMENT SCHEME No. 1
ANNUAL BALANCE (INPUT vs. OUTPUT)
MCM
150
100
50
0
INPUT
OUTPUT
DIFFERENCE
4th Year
3rd Year
2nd Year
1st Year

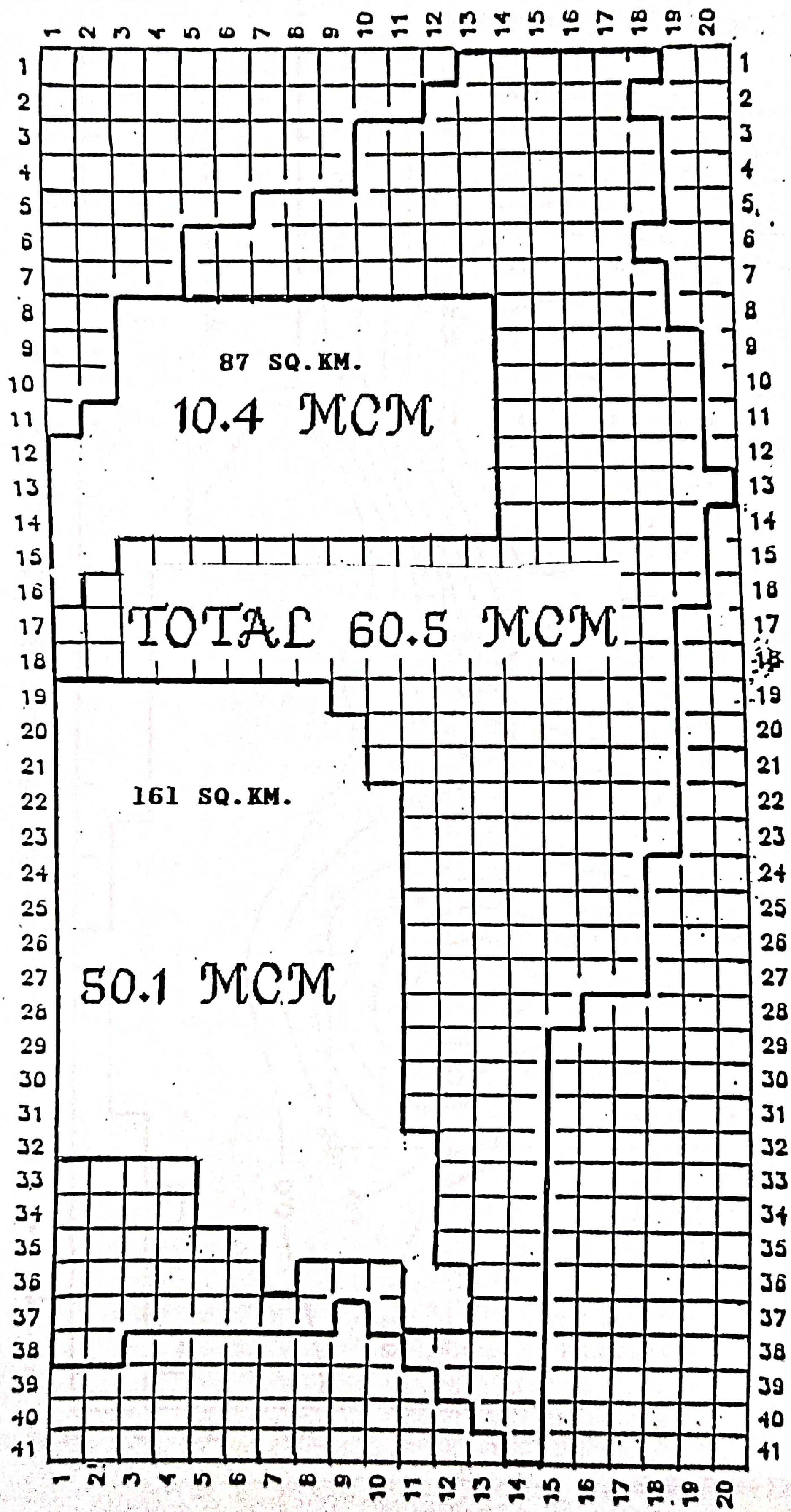

DEVELOPMENT SCHEME No. 1
ABS. ELEVATION (m)
109
108
107
106
105
6 12 18 24 30 36 42 48
9,19


DEVELOPMENT SCHEME No. 1
ABS. ELEVATION (m)
106
105
104
103
102
101
100
99
98
6 12 18 24 30 36 42 48
9,27

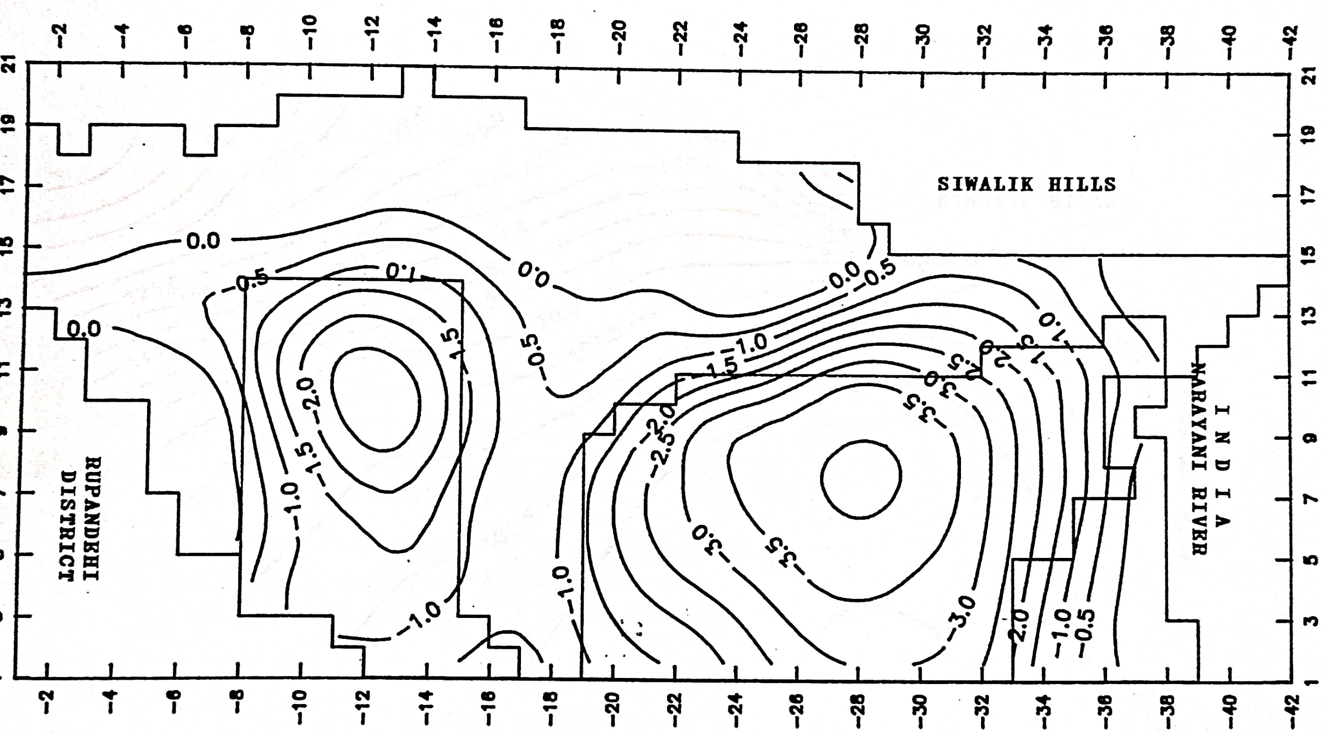

DEVELOPMENT SCHEME No. 1
ABS. ELEVATION (m)
106
105
104
103
102
101
100
99
98
97
96
6 12 18 24 30 36 42 48
4,29

APPENDIX 40

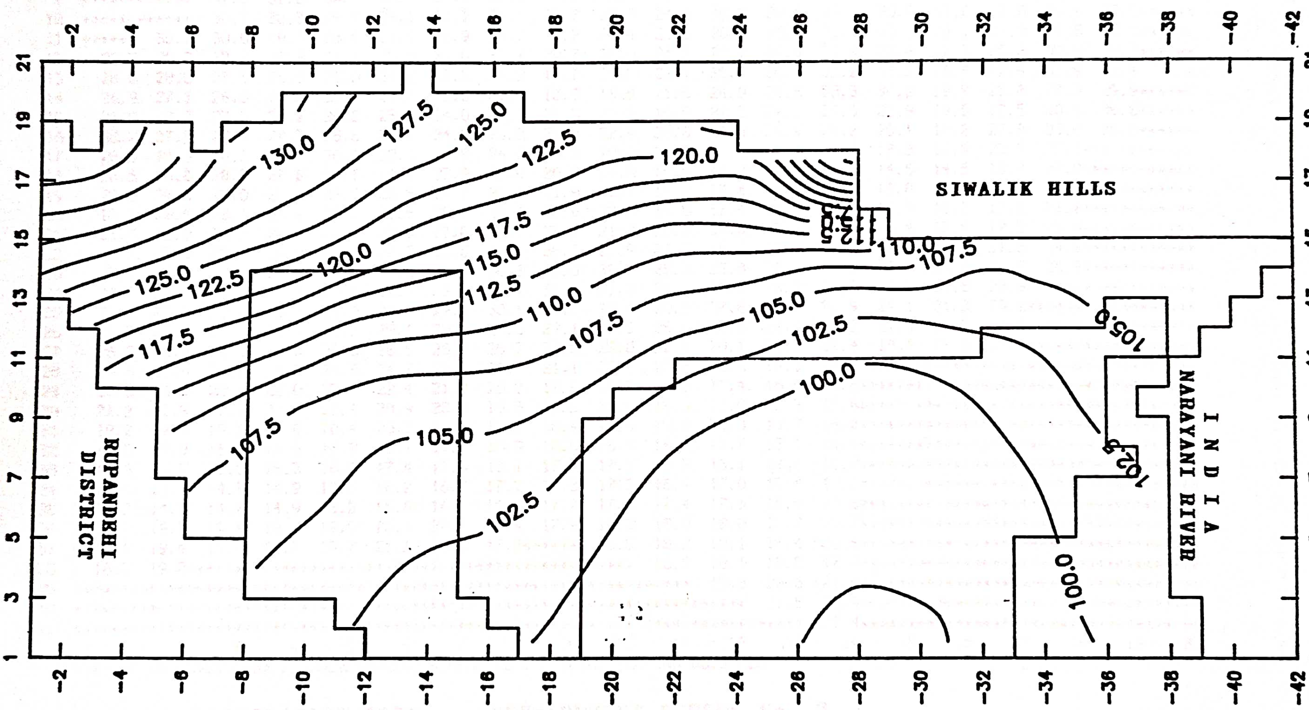
FUTURE DEVELOPMENT SCHEME No. 2
DISTRIBUTION OF PUMPING CELLS



FUTURE DEVELOPMENT '2: DECLINE OF LEVELS AFTER 4 YEARS



FUTURE DEVELOPMENT '2: WATER LEVELS AFTER 4 YRS



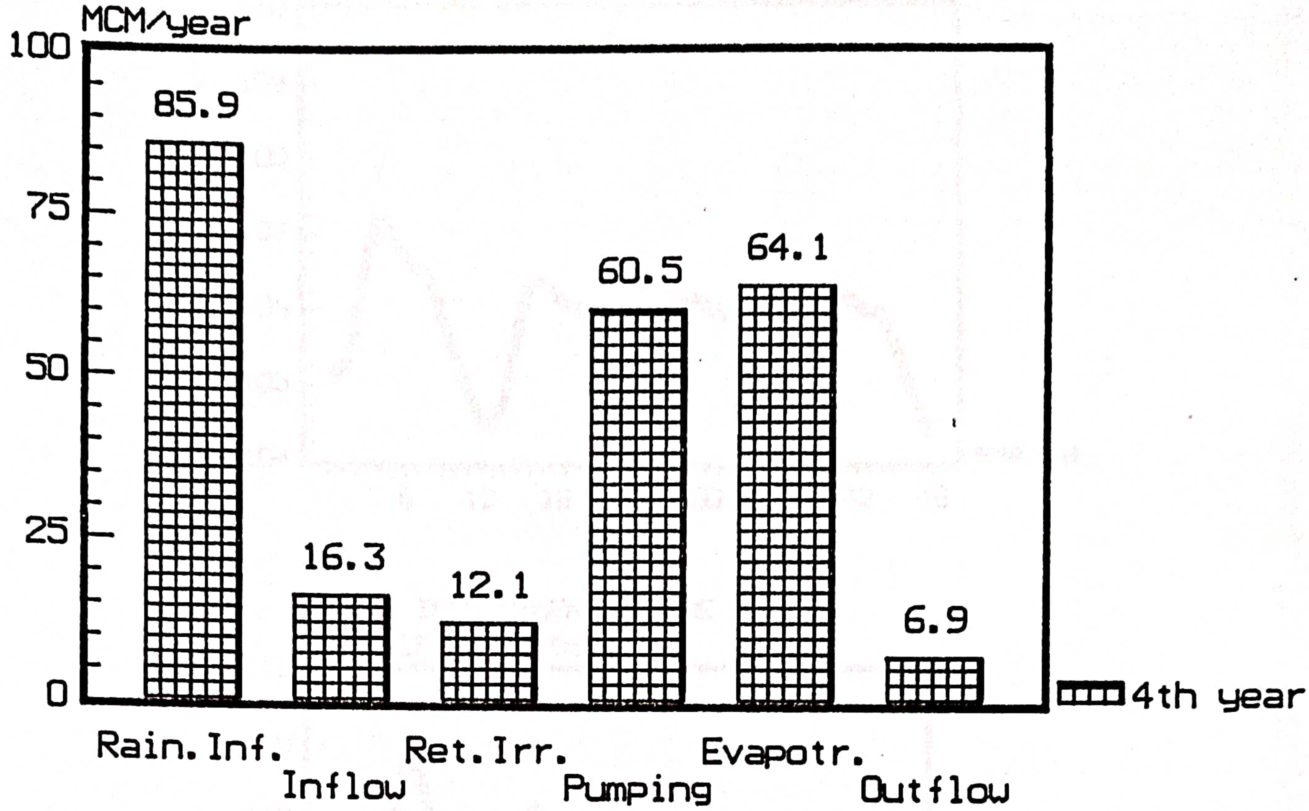
APPENDIX 44

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	******	******	******	******	******	******	******	******	******	******	******	******	25.6	25.4	25.8	26.4	27.1	25.7	******	******
2	******	******	******	******	******	******	******	******	******	******	******	26.2	25.4	25.2	25.7	26.5	25.7	******	******	******
3	******	******	******	******	******	******	******	******	******	26.4	26.2	26.1	25.2	24.9	25.5	26.7	26.7	27.5	******	******
4	******	******	******	******	******	******	******	******	******	25.9	28.4	26.4	24.9	24.3	25.4	26.6	28.0	28.7	******	******
5	******	******	******	******	******	******	28.7	26.7	25.0	25.0	30.0	27.9	25.4	22.2	25.1	28.6	29.5	30.1	******	******
6	******	******	******	******	31.5	31.3	29.5	26.6	22.9	21.5	34.7	31.6	27.3	24.5	27.2	30.5	31.2	******	******	******
7	******	******	******	******	31.8	31.9	30.9	27.8	20.8	24.0	21.1	33.5	34.3	31.6	32.1	32.6	31.9	31.5	******	******
8	******	******	31.4	31.3	31.5	31.6	31.8	31.9	21.7	13.4	21.1	38.5	44.6	40.8	37.2	34.3	32.9	30.8	******	******
9	******	******	31.3	31.2	30.9	30.7	30.5	28.3	23.5	21.4	28.3	34.6	40.2	41.5	37.3	35.1	32.9	30.9	28.3	******
10	******	******	30.7	30.3	29.7	29.1	28.1	26.3	23.8	22.3	24.4	25.8	29.8	33.7	35.0	33.8	32.0	29.6	27.5	******
11	******	30.3	30.0	29.3	28.5	27.4	25.9	24.2	22.2	21.4	21.3	20.7	25.3	31.4	33.3	33.1	31.2	28.5	30.2	******
12	29.7	29.3	28.7	28.3	27.1	25.8	24.0	22.4	20.7	20.0	21.2	23.7	27.9	31.9	33.4	32.9	30.3	32.9	32.2	******
13	28.6	28.0	27.5	26.8	25.8	24.2	22.5	21.2	17.7	19.5	22.1	25.7	30.3	35.2	33.6	26.4	22.4	31.9	32.4	41.1
14	26.9	27.1	26.8	26.2	26.1	24.7	23.0	21.1	18.9	18.9	21.6	24.9	28.8	33.3	30.2	19.9	25.8	27.3	29.9	******
15	26.8	27.2	27.3	27.1	26.2	25.3	24.0	23.0	21.3	20.2	19.9	22.3	24.1	25.8	23.9	19.5	27.5	30.9	36.6	******
16	28.2	27.9	27.6	27.3	25.8	25.2	24.2	23.2	22.8	22.4	20.8	19.8	20.9	21.2	20.1	18.2	27.3	33.0	36.8	******
17	28.3	28.3	28.2	27.7	26.8	25.9	24.9	24.3	20.5	20.8	20.9	19.6	17.9	17.8	17.3	16.9	23.9	27.1	******	******
18	28.6	28.8	28.3	27.8	26.1	24.4	23.9	22.0	20.3	19.8	19.6	18.2	16.5	14.5	14.5	14.5	18.7	23.9	******	******
19	29.0	28.6	28.0	27.4	26.9	25.8	24.7	23.1	21.9	21.1	19.8	17.4	14.9	13.9	12.8	13.4	17.6	24.1	******	******
20	28.6	28.5	28.1	28.1	27.5	26.5	25.5	24.4	22.9	20.3	19.8	17.4	14.0	8.5	10.3	12.2	17.5	21.6	******	******
21	28.8	28.9	28.7	28.7	28.3	27.9	27.0	25.7	25.1	21.7	20.9	18.0	17.8	15.5	15.4	15.8	19.8	23.4	******	******
22	28.7	29.0	28.4	29.2	29.1	27.7	29.5	28.2	28.2	23.9	21.8	18.4	21.1	26.7	27.3	23.1	21.8	24.9	******	******
23	27.4	27.9	28.4	28.8	29.4	29.2	29.5	30.2	30.0	32.0	25.3	22.8	26.9	34.3	32.6	25.8	24.7	26.9	******	******
24	27.2	27.7	28.3	28.4	29.0	29.3	29.8	30.4	31.6	31.3	28.7	27.8	28.8	32.9	30.3	24.8	23.9	******	******	******
25	27.3	27.9	28.6	28.5	29.0	29.7	29.6	30.1	30.6	29.4	30.1	27.6	26.0	26.9	26.1	21.3	20.2	******	******	******
26	26.7	27.5	27.4	28.2	28.7	29.1	29.3	29.0	29.1	26.5	26.6	24.6	24.6	24.2	21.5	12.0	14.6	******	******	******
27	26.0	25.9	26.5	26.6	26.6	26.5	26.2	25.7	24.5	25.0	22.5	20.1	22.8	21.4	18.1	13.8	14.4	******	******	******
28	24.3	25.3	25.0	24.8	24.6	24.3	23.6	22.4	21.1	20.5	20.5	18.5	19.3	17.6	15.4	******	******	******	******	******
29	23.0	23.9	23.4	22.0	22.7	22.4	21.7	20.2	17.9	16.7	17.8	17.4	16.9	15.8	******	******	******	******	******	******
30	21.2	21.9	22.2	21.7	21.4	20.9	20.5	19.8	17.5	15.7	15.9	16.0	16.3	14.6	******	******	******	******	******	******
31	19.2	19.4	19.8	20.6	20.4	20.3	19.9	19.7	18.4	16.5	15.8	15.3	15.7	14.2	******	******	******	******	******	******
32	17.5	17.0	16.4	16.9	18.3	19.1	19.2	18.9	18.0	16.9	16.1	15.7	15.1	14.9	******	******	******	******	******	******
33	16.6	15.9	15.0	15.3	16.5	17.4	17.6	18.1	17.6	17.1	16.3	16.1	17.3	18.0	******	******	******	******	******	******
34	15.6	15.1	14.7	14.9	15.5	16.2	16.7	17.2	17.3	17.3	16.4	17.0	17.4	19.5	******	******	******	******	******	******
35	15.2	14.9	14.7	14.9	15.2	15.6	16.1	16.6	17.7	17.6	17.4	17.8	18.0	20.6	******	******	******	******	******	******
36	19.7	19.5	19.4	19.6	19.9	20.4	20.8	16.4	17.9	18.3	18.0	18.0	18.2	20.7	******	******	******	******	******	******
37	19.1	19.4	19.5	19.7	19.7	21.1	21.6	17.2	******	18.5	18.2	18.1	18.4	20.5	******	******	******	******	******	******
38	18.9	19.0	******	******	******	******	******	******	******	******	18.2	18.1	18.0	17.9	******	******	******	******	******	******
39	******	******	******	******	******	******	******	******	******	******	******	19.8	20.6	21.4	******	******	******	******	******	******
40	******	******	******	******	******	******	******	******	******	******	******	******	21.5	20.9	******	******	******	******	******	******
41	******	******	******	******	******	******	******	******	******	******	******	******	******	22.4	******	******	******	******	******	******
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

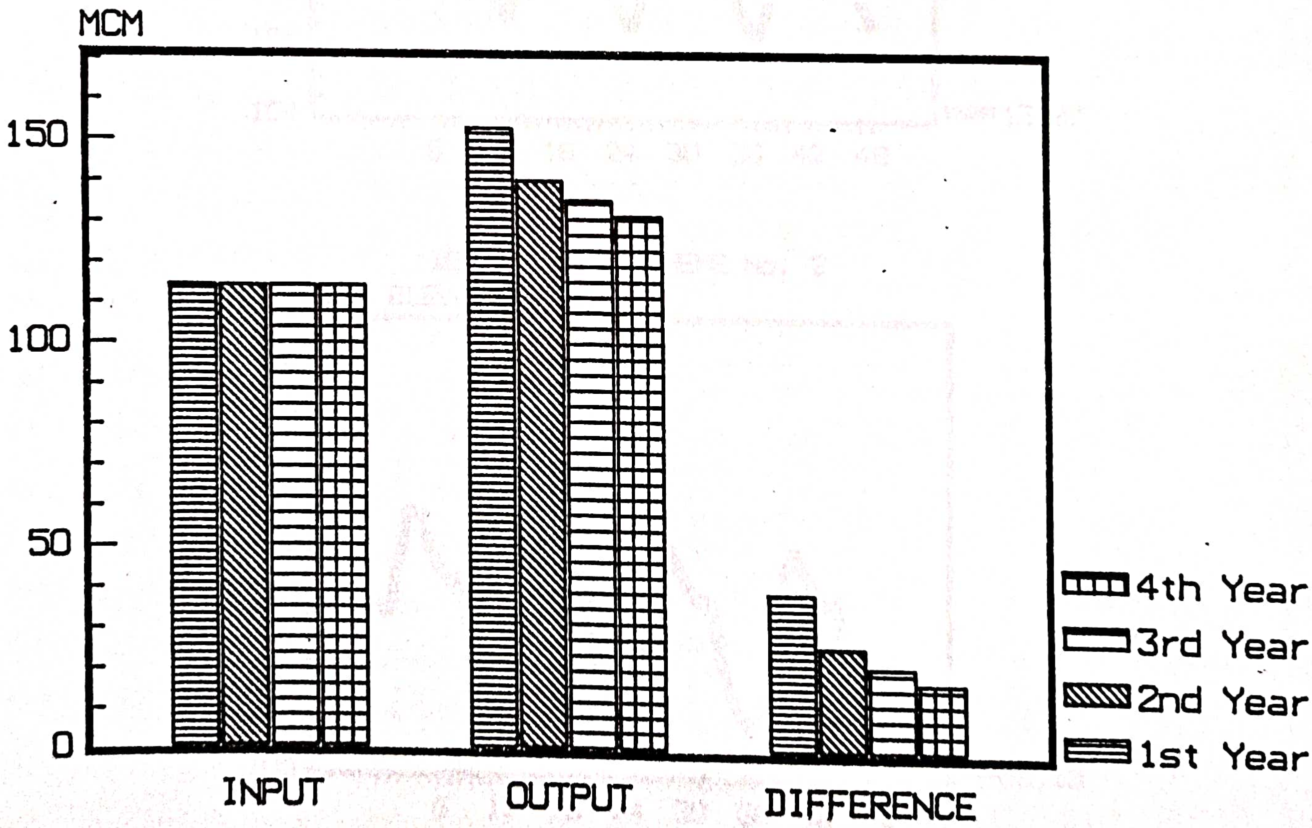
SATURATED THICKNESS (M) ... DEVELOPMENT SCHEME #2 ... TOTAL PUMPING 60.5 MCM

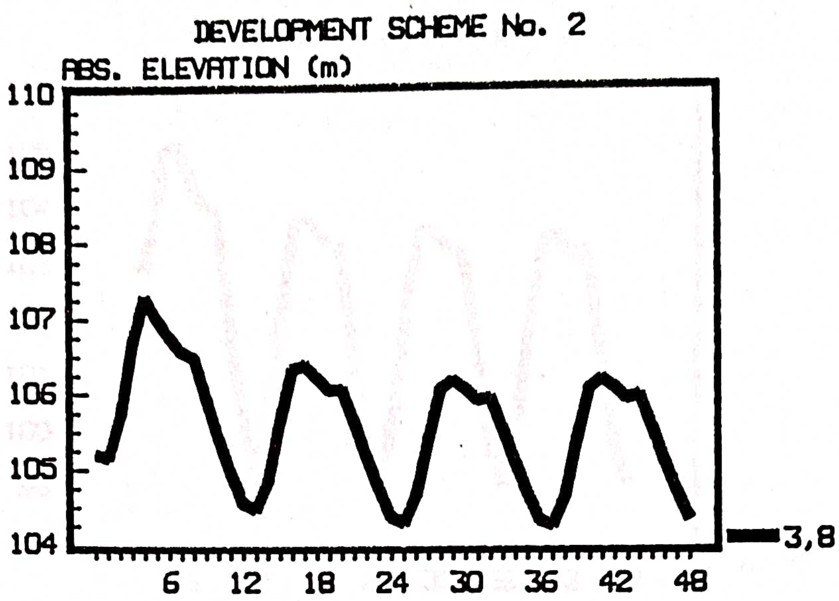
EVAPORATION LOSS ... DEVELOPMENT SCHEME No. 2

DEVELOPMENT SCHEME 2
4TH YEAR BALANCE

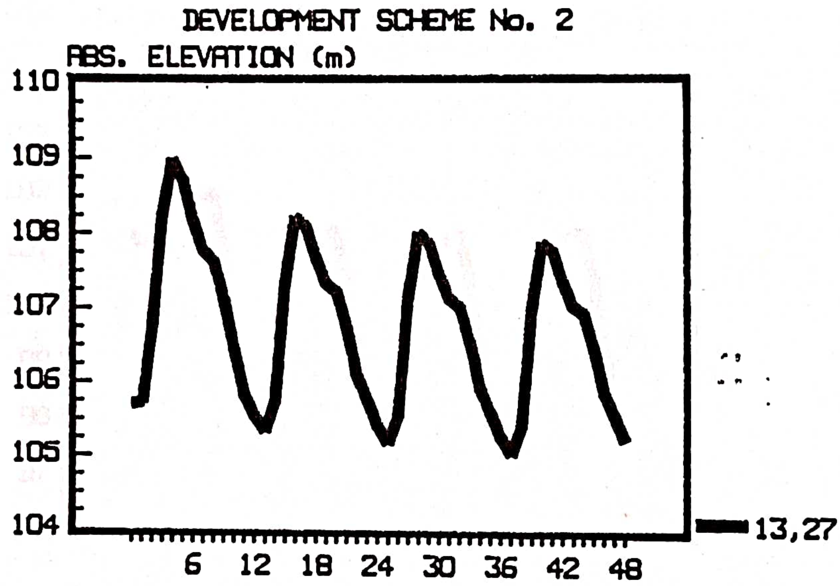


DEVELOPMENT SCHEME No. 2
ANNUAL BALANCE (INPUT vs. OUTPUT)

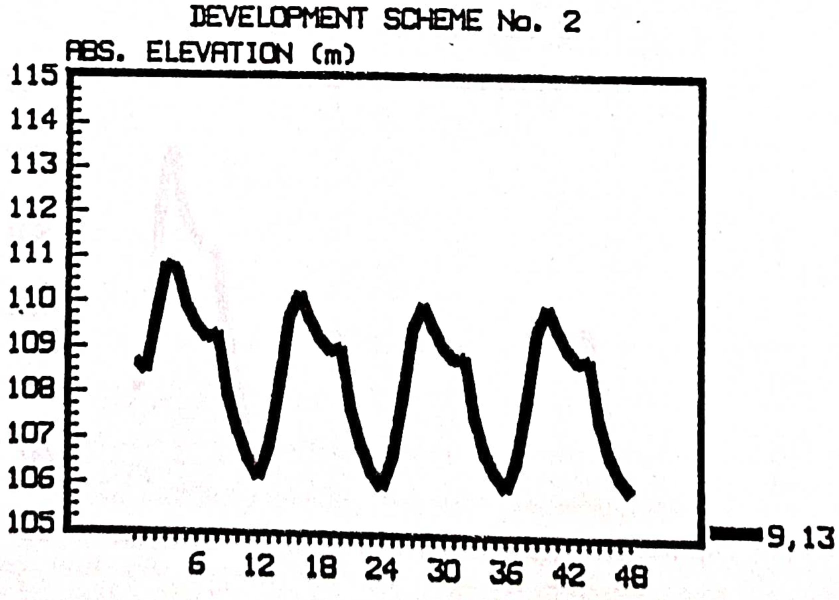




DEVELOPMENT SCHEME No. 2
ABS. ELEVATION (m)
110
109
108
107
106
105
104
6
12
18
24
30
36
42
48
3,8

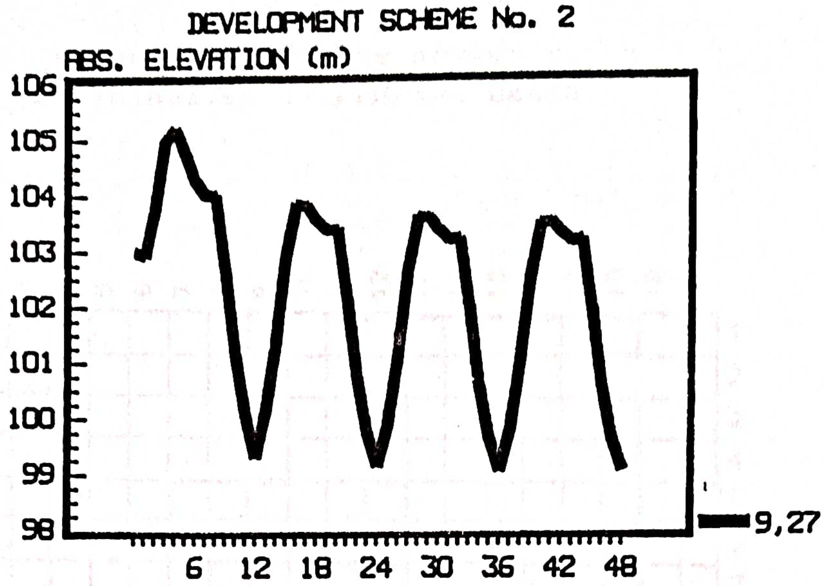


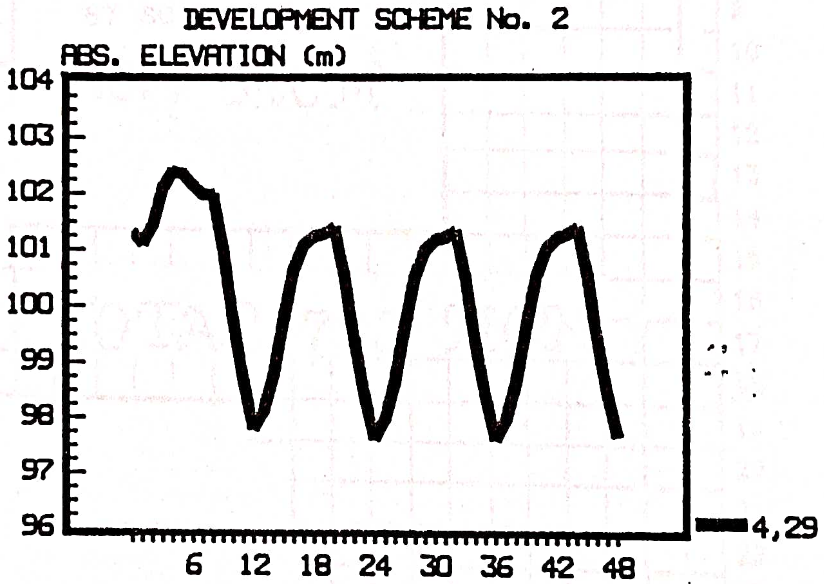
DEVELOPMENT SCHEME No. 2
ABS. ELEVATION (m)
110
109
108
107
106
105
104
6
12
18
24
30
36
42
48
13,27

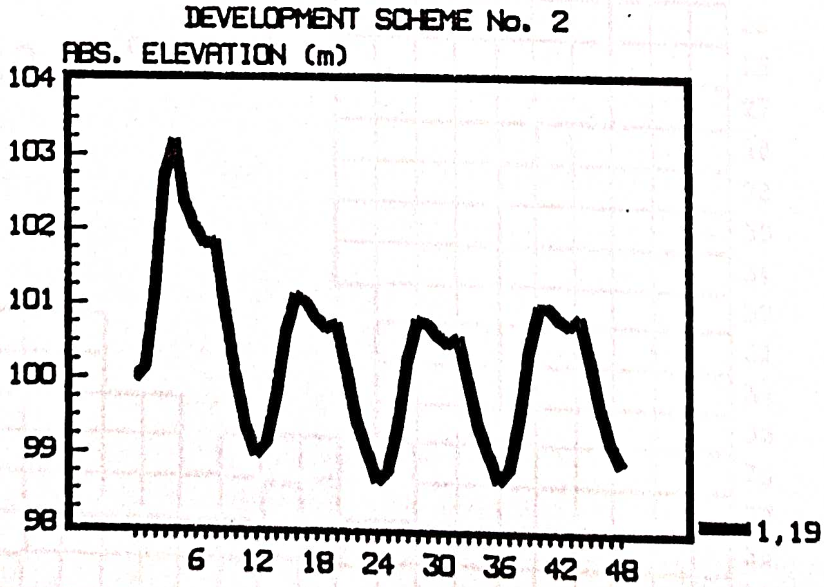


DEVELOPMENT SCHEME No. 2
ABS. ELEVATION (m)
115
114
113
112
111
110
109
108
107
106
105
6
12
18
24
30
36
42
48
9,13

APPENDIX 46

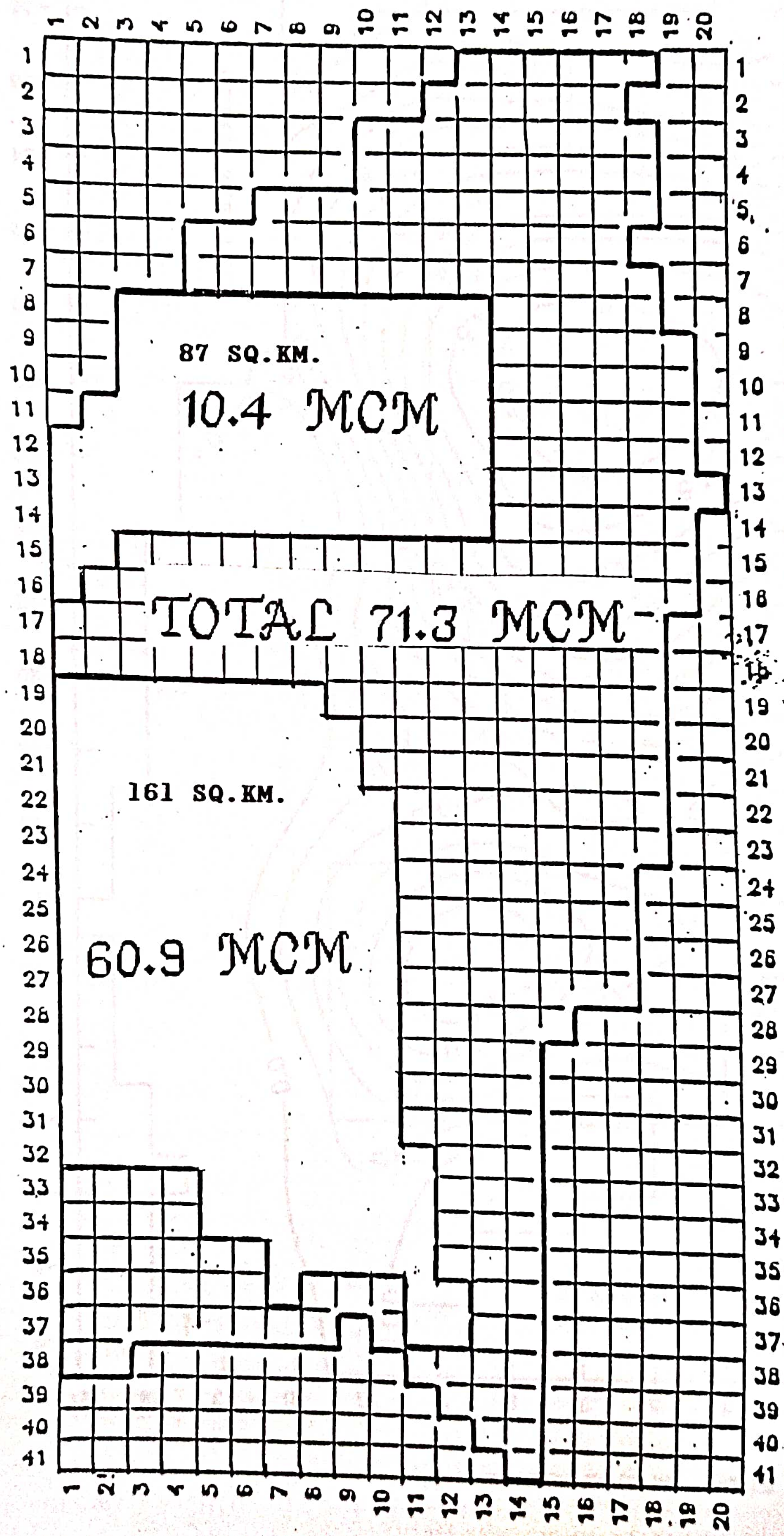




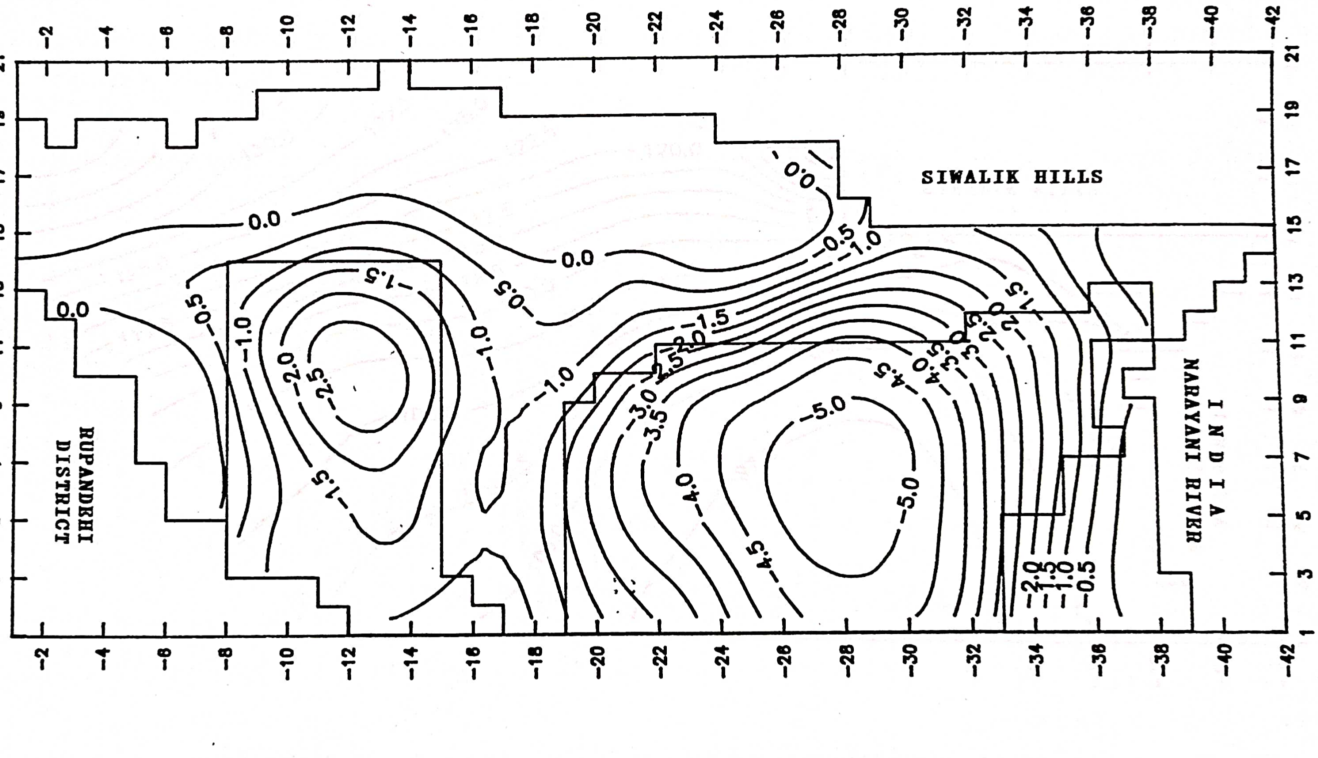


APPENDIX 46 — CONTINUED

FUTURE DEVELOPMENT SCHEME No. 3
DISTRIBUTION OF PUMPING CELLS

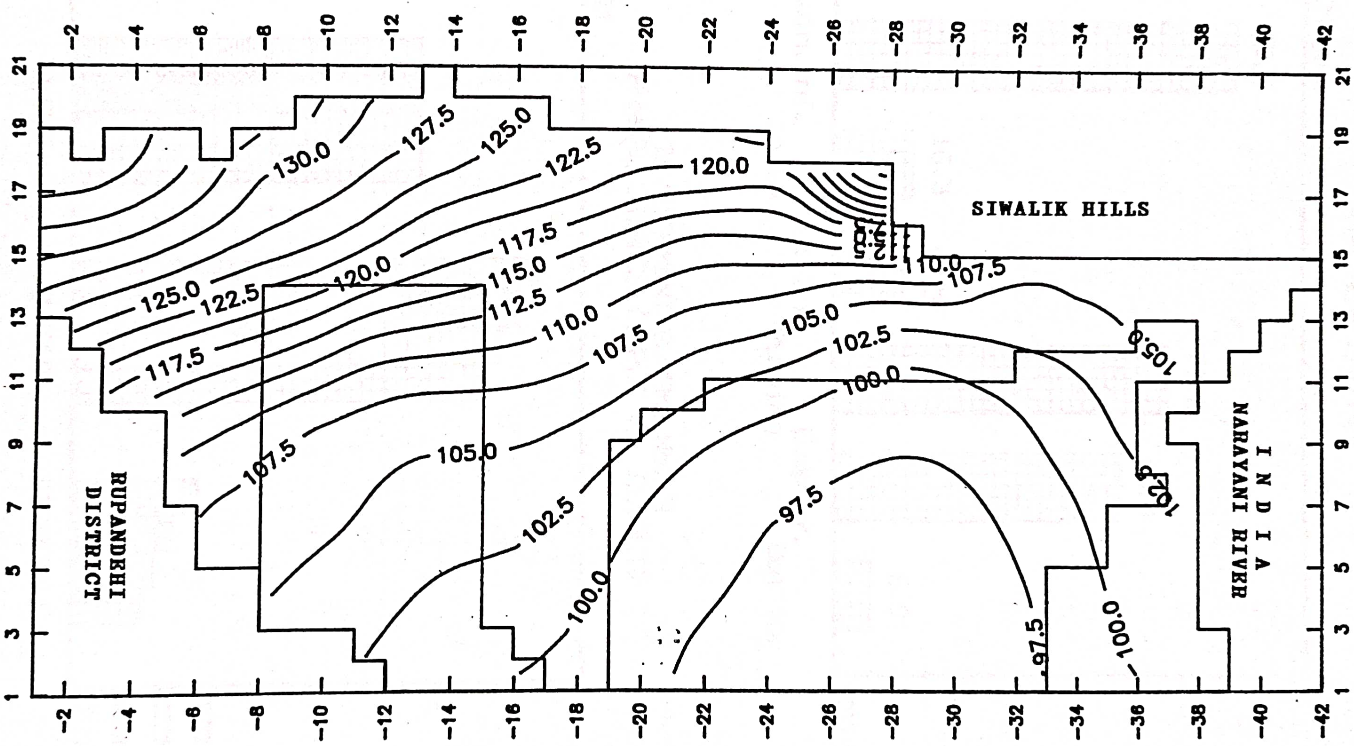


FUTURE DEVELOPMENT '3: DECLINE OF LEVELS AFTER 4 YEARS

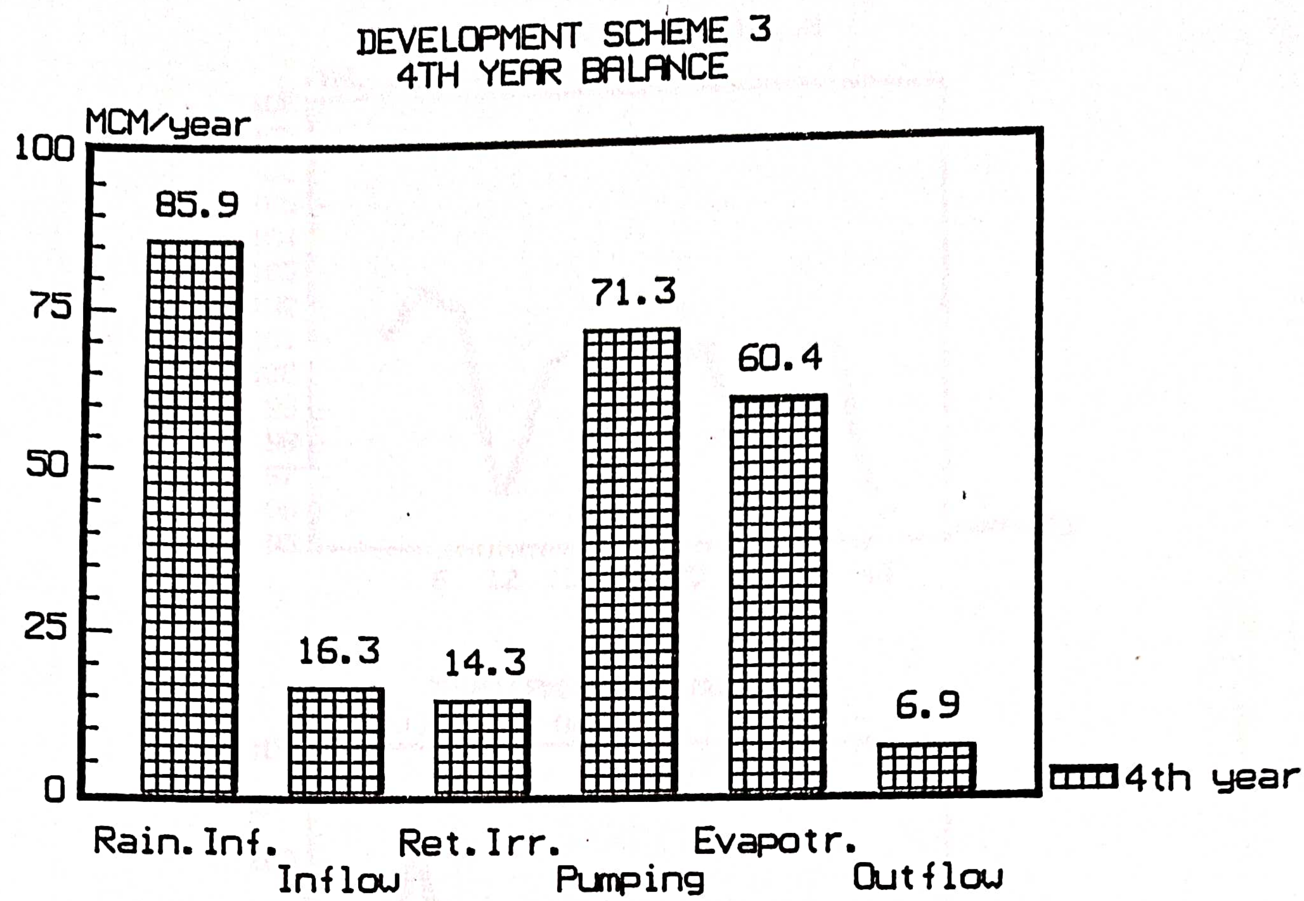


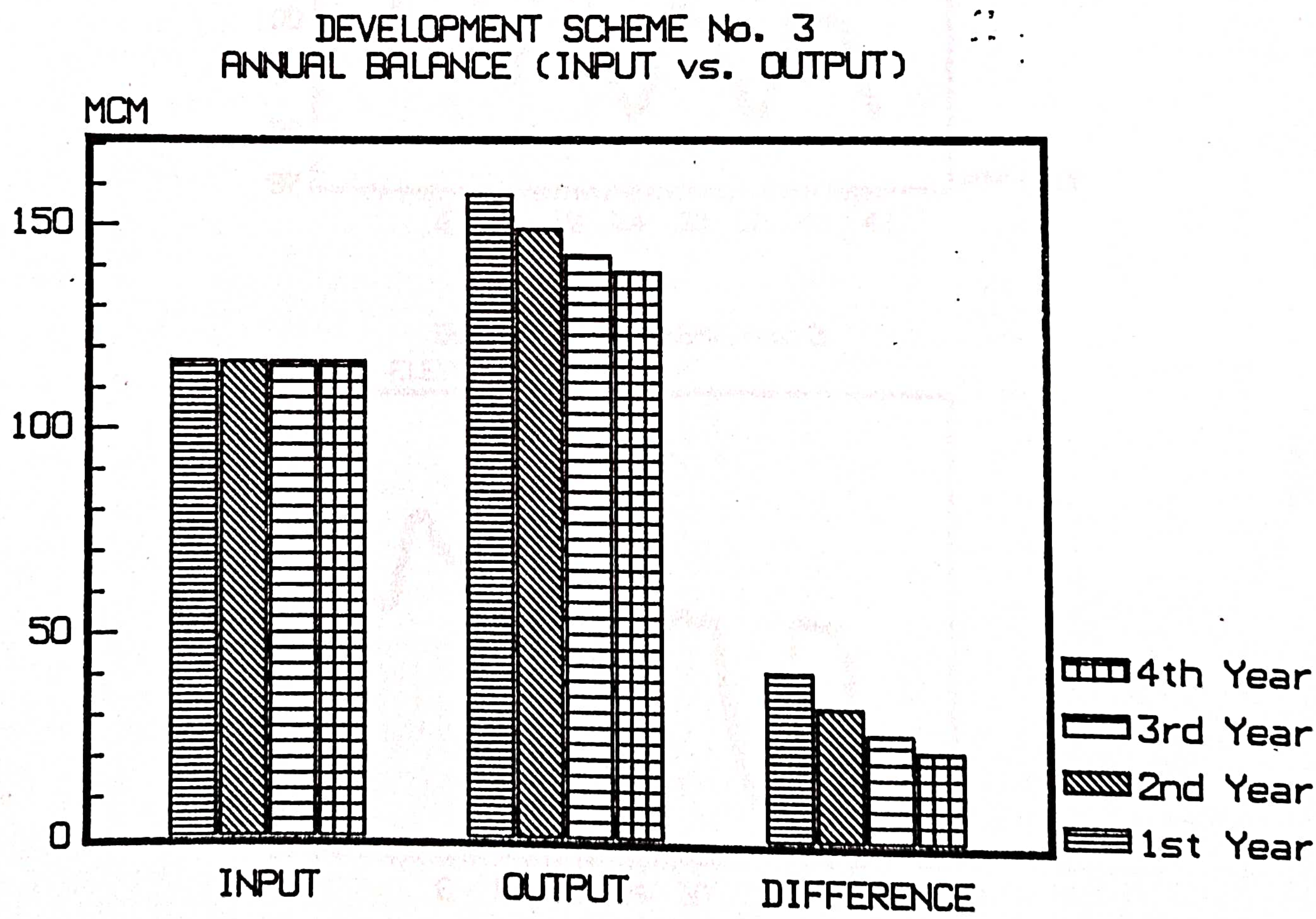
APPENDIX 48

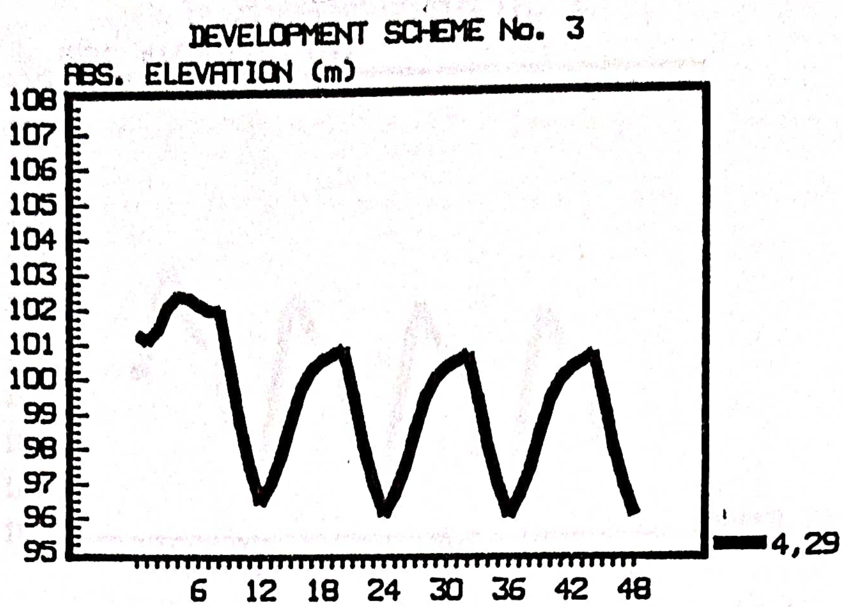
FUTURE DEVELOPMENT '3: WATER LEVELS AFTER 4 YRS

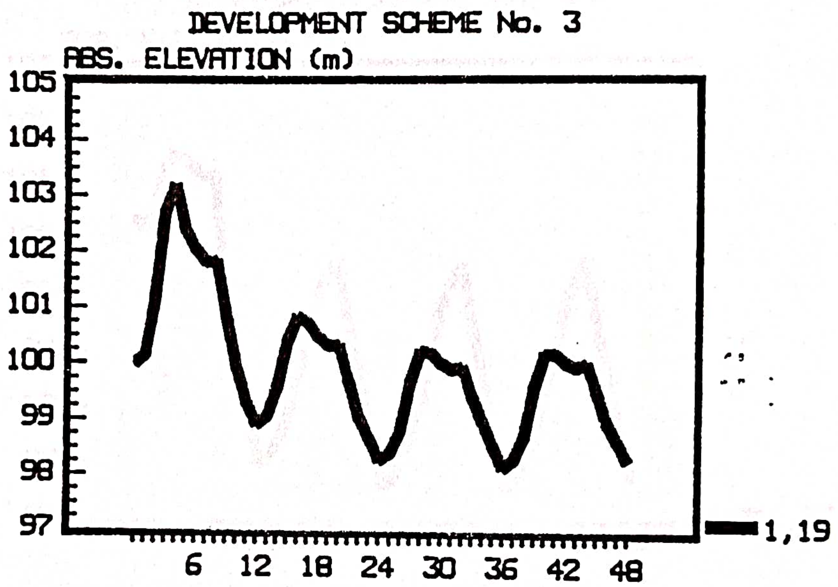


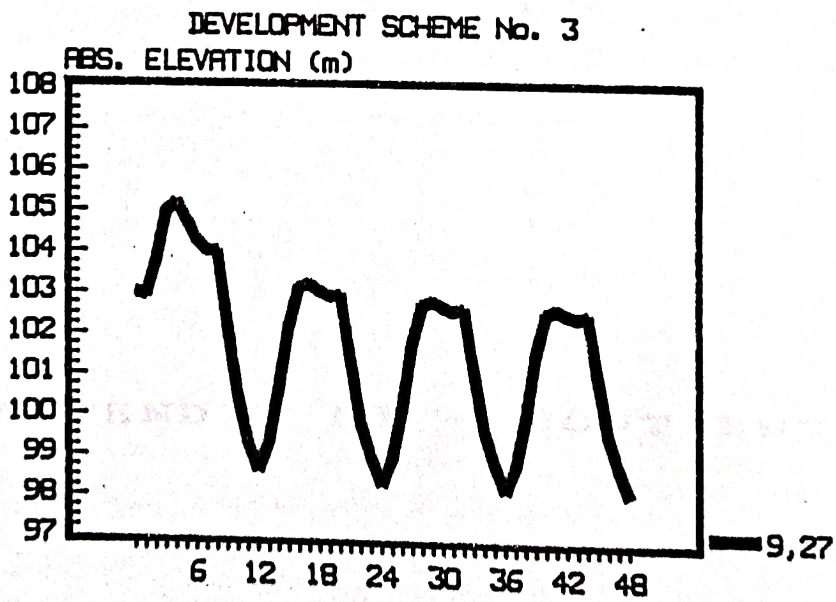
APPENDIX 49

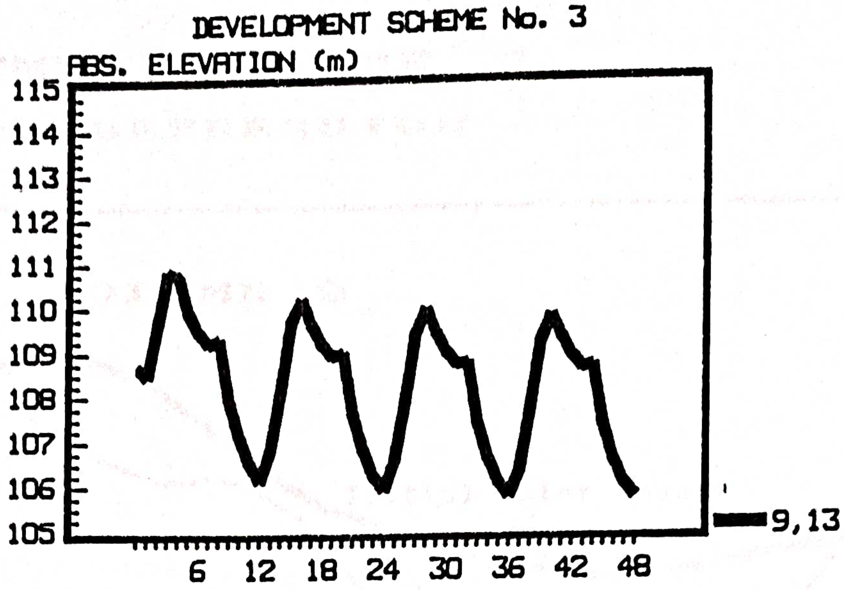

DEVELOPMENT SCHEME 3
4TH YEAR BALANCE
MCM/year
100
75
50
25
0
85.9
16.3
14.3
71.3
60.4
6.9
4th year
Rain.Inf.
Inflow
Ret.Irr.
Pumping
Evapotr.
Outflow

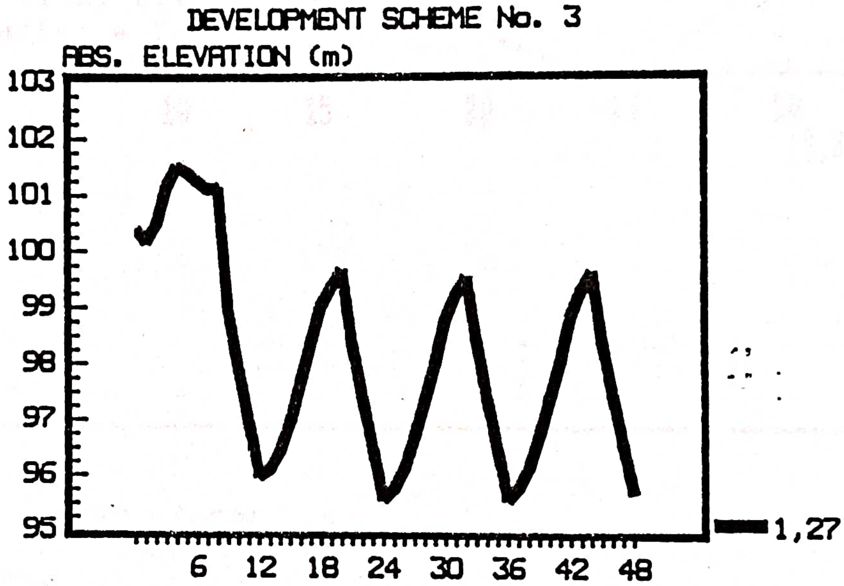

DEVELOPMENT SCHEME No. 3
ANNUAL BALANCE (INPUT vs. OUTPUT)
MCM
150
100
50
0
INPUT
OUTPUT
DIFFERENCE
4th Year
3rd Year
2nd Year
1st Year


DEVELOPMENT SCHEME No. 3
ABS. ELEVATION (m)
108
107
106
105
104
103
102
101
100
99
98
97
96
95
6 12 18 24 30 36 42 48
4,29


DEVELOPMENT SCHEME No. 3
ABS. ELEVATION (m)
105
104
103
102
101
100
99
98
97
6 12 18 24 30 36 42 48
1,19


DEVELOPMENT SCHEME No. 3
ABS. ELEVATION (m)
108
107
106
105
104
103
102
101
100
99
98
97
6 12 18 24 30 36 42 48
9,27

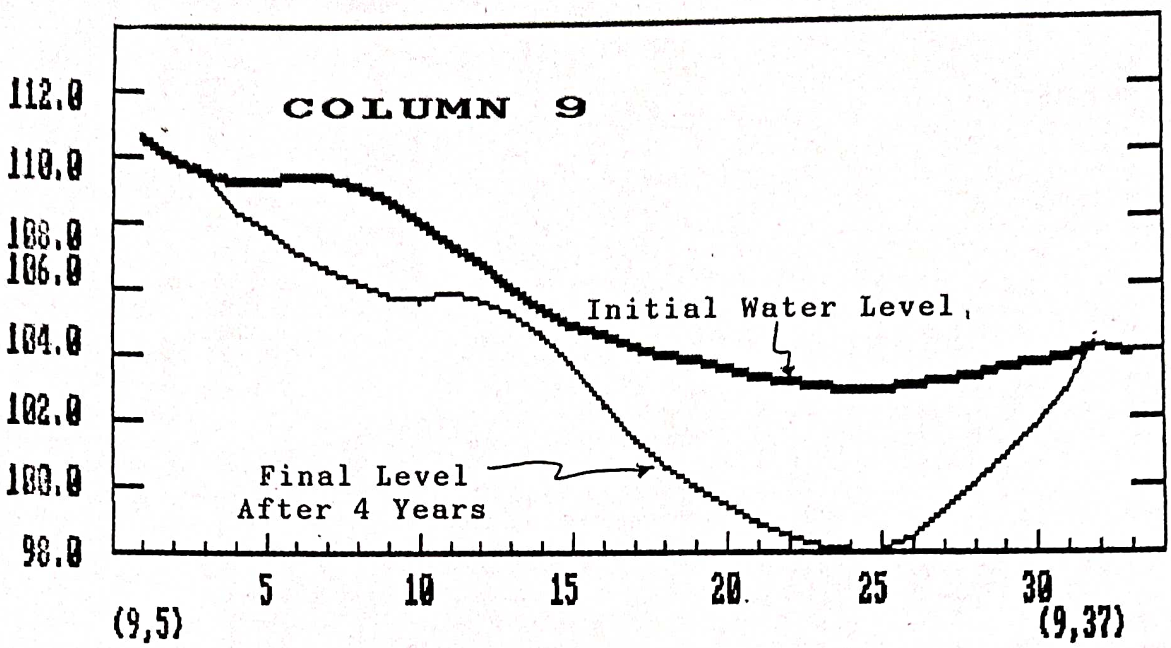


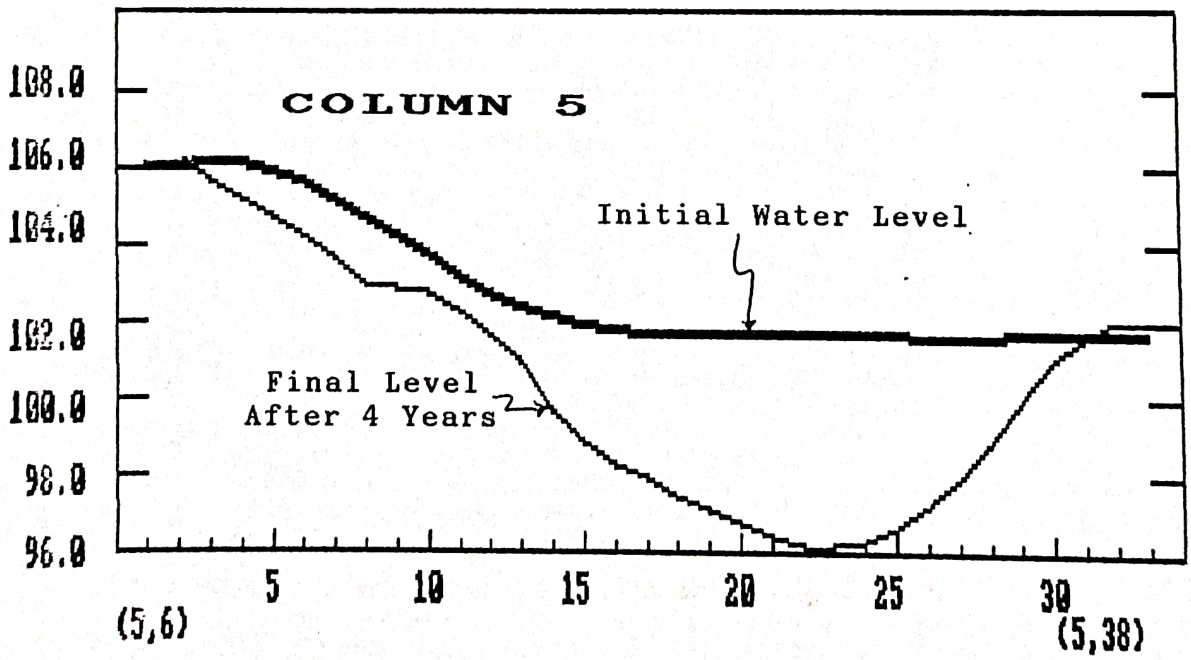


APPENDIX 51 — CONTINUED

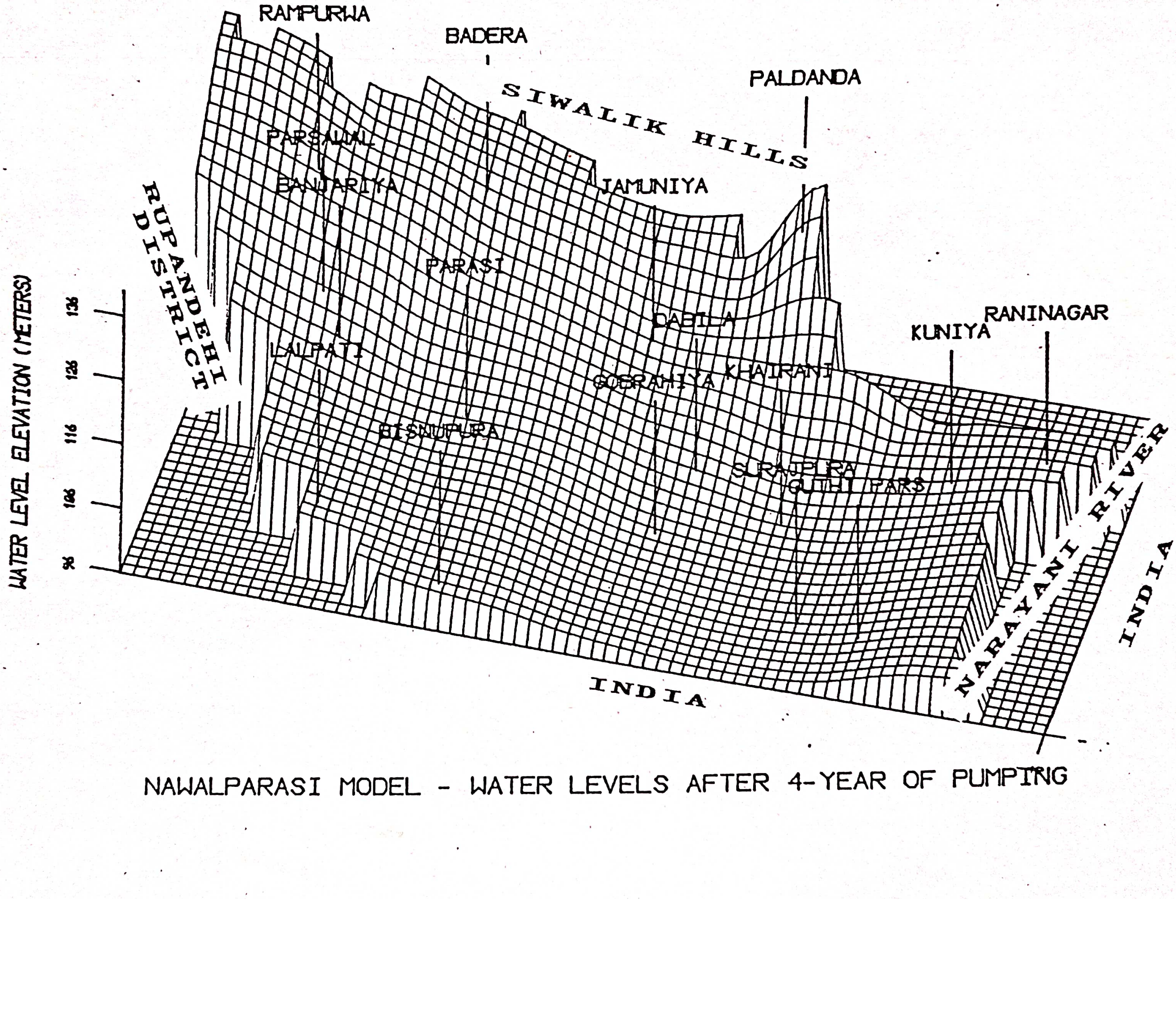
DEVELOPMENT SCHEME 3

CONES OF DEPRESSION





APPENDIX 52



NAWALPARASI MODEL - WATER LEVELS AFTER 4-YEAR OF PUMPING