United Nations Development Programme

and

His Majesty's Government of Nepal Project

NEP/86/025

SHALLOW GROUND WATER INVESTIGATIONS IN TERAI

TECHNICAL REPORT No. 17

SUNSARI DISTRICT MATHEMATICAL MODEL

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

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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)**. Shallow Wells Drilling, Testing and Monitoring in 1987/88. Basic Documentation and Preliminary Interpretation. March 1989.
6. **NAWALPARASI (WEST)**. Mathematical Model of Shallow Ground Water System. March 1989.
7. **KAPILVASTU DISTRICT**. Shallow Wells Drilling, Testing and Monitoring in 1987/89. Basic Documentation and Preliminary Interpretation. June 1989.
8. **DANG VALLEY**. Shallow Wells Drilling, Testing and Monitoring in 1987/89. Basic Documentation and Preliminary Interpretation. June 1989.
9. **DEUKHURI VALLEY**. Shallow Wells Drilling, Testing and Monitoring in 1987/89. Basic Documentation and Preliminary Interpretation. June 1989.
10. **SUNSARI**. Shallow Wells Drilling, Testing and Monitoring in 1988/89. Basic Documentation and Preliminary interpretation. June 1989.
11. **RUPANDEHI DISTRICT**. Deep Wells Drilling, Testing and Monitoring in 1969-89. Basic Documentation and Preliminary Interpretation. August 1989.
12. **MORANG**. Shallow Wells Drilling,Testing and Monitoring in 1987/89. Basic Documentation and Preliminary Interpretation. September1989.
13. SHALLOW WATER LEVEL FLUCTUATION MAPS 1987 - 1989. September 1989.
14. **RUPANDEHI**. Shallow Wells Drilling, Testing and Monitoring in 1987/89. Basic Documentation and Preliminary Interpretation. September 1989.
15. **MAHOTTARI**. Shallow Wells Drilling, Testing and Monitoring in 1987/1989. Basic Documentation and Preliminary Interpretation.
16. **JHAPA**. Shallow Wells Drilling, Testing and Monitoring in 1987-1989. Basic Documentation and Preliminary Interpretation.

ABBREVIATIONS:

UN/DTCD - United Nations Department of Technical Co-operation for Development
UNDP - United Nations Development Programme
USAID - United States Agency for International Development
GWRDB - Ground Water Resources Development Board
GDC - Groundwater Development Consultants (International) Ltd.
ADBN - Agricultural Development Bank of Nepal
STW - Shallow Tube Well
DTW - Deep Tube Well
MCM - Million Cubic Meters

EXECUTIVE SUMMARY

The model of the shallow ground water system of the Sunsari district was primarily made to arrive at a global water balance of the whole district, and to indicate a maximum development potential for future ground water exploitation. In the process, all components of the system have been verified. The model is based on 17 newly drilled "UN project" wells, shallow wells drilled by GWRDB for farmers, and deep tube wells drilled by GWRDB as exploration wells. Also, the basis for modeling are observation wells and continuous monitoring of depth to water levels over the last three years. Pumping tests provided aquifer parameters necessary for modelling.

The whole simulation was divided into four phases. The phase I was to match an initial map of water levels which was constructed on the basis of field monitoring in May 1989. The primary result of this phase 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 this phase was that the recharge in the dry portion of a year was equivalent to about 2.1 MCM/month (million cubic meters), plus about 1.6 MCM as inflow from hill sides. The recharge that comes from the hills on the north, is in a form of subsurface flow through dry river beds that cut the Siwalik hills. Out of this cumulative recharge of some 3.7 MCM, evaporation may consume about 1.8 MCM, and 1.3 MCM may outflow into India. What remains, that is about 0.6 MCM, may flow into the Sapta Koshi River. The exchange of water at the end of the dry period is minor. Water table is deep, and out of evaporation reach. There is no rainfall to contribute significantly to recharge.

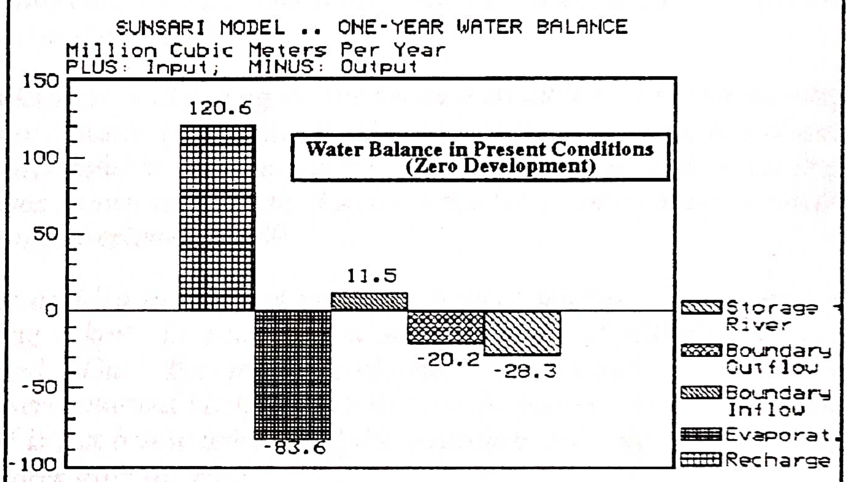


Fig.1

The second phase was that of unsteady-state calibration of the model in the period from May through September 1989. This is the period of the rise of water levels in the monsoon season. The rise is well documented in some 14 observation wells. The model produced water balance for the monsoon season. The recharge to aquifer dominates and as a result the levels are rising. This recharge is quantified by the model. 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 and depletion of the storage are balanced, one may conclude about the recharge-discharge relationship. This phase was called the "verification" of the model. The model indicated that, in one-year cycle, most of the water recharged from rainfall (120.6 MCM per year) and inflow from hill side (11.5 MCM) is lost through evaporation (83.6 MCM) and outflow into India (20.2 MCM). If the system in balance in the year of verification, there is an outflow into the Sapta Koshi River of about 28.3 MCM. This balance is graphically shown in Fig.1.

From water balance in one-year verification phase, one may conclude that a future ground water development from shallow aquifers may come mostly on expense of reduced evaporation, outflow into the Sapta Koshi River, and outflow into India. The annual evaporation loss, which amounts to about 83.6 MCM, can be reduced by lowering water levels to a depth that will prevent the losses. As indicated in appendices, the area with water table close to land surface is in the central part, north-west, and south-east. The outflow into the Sapta Koshi can be reduced or eliminated by pumping from shallow wells located along a stretch parallel to the river course. It is a favorable coincidence that along the left bank of the Sapta Koshi River the shallow aquifer in Sunsari district is most promising, having clean sand and gravel content and very high transmissivity of more than 1500 m^2/day. The outflow to India, of some 20.2 MCM per year, can be reduced or stopped altogether by pumping on a larger scale near the border.

With the total active model area of about 892 km^2, and an average annual rainfall of 1700 mm, the total volume of rain in an average year is about 1465 MCM. Out of this about 132 MCM recharges the shallow aquifer, which is only 9% on average. In areas where the near-the-surface layer is more permeable, this percentage may be higher, but there are many places in which direct infiltration of rainfall is low because of extensive impermeable surface cover. The overall percentage of 9 is important conclusion of this study, which invalidates earlier reported values in former studies of over 20 and even 30%.

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 Sunsari model was shown to correctly duplicate the behavior of shallow water table in the period from May through September 1989.

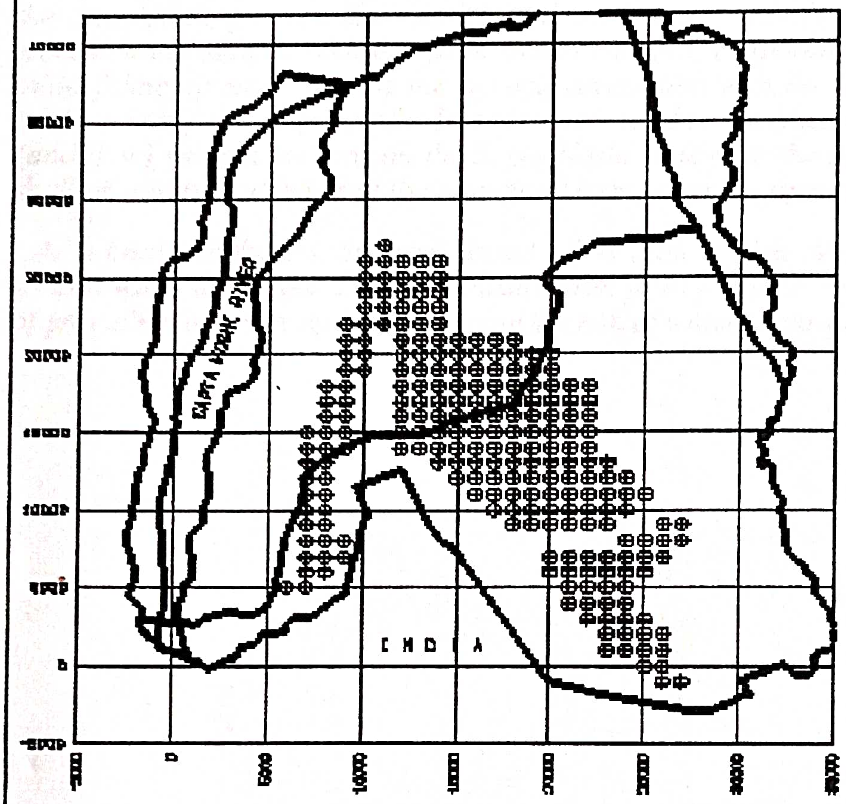
After several check runs, it was decided to fully test two development scheme. The scheme A included 147 cells, each covering 1 km^2. In each cell, a same amount of 420,000 m^3 was pumped in the 5-month period. Thus the total development amounted to about 62 MCM/season. Out of this 20% were returned back to the system in the form of return irrigation. The total pumping of 61.7 MCM is just below one half of the maximum possible "safe yield" of the district, without induced recharge from the river.

The development scheme was tested over a period of four years, on a cyclic basis: pumping in 5 dry months (more in February and March than in other months), idling in the remaining seven months.

Since the results were encouraging, more wells were located in the development labeled Scheme B. The criteria for locating the wells were the following: (a) acceptable transmissivity, (b) water table close to the surface, (c) location not very close to the river. The total number of cells is 232, the area covered by development 232 km^2, and the total abstraction about 97.4 MCM. With the spacing of 300 m among wells, the total number of wells may be about 2500. The volume of water may be sufficient to irrigate about 12,000 ha, provided that an average agricultural demand is about 8,000 m^3/ha/season. The location of Scheme B development is shown in Fig.2.

The water balance in the Scheme B shows the major main points. The recharge is the same as in Scheme A, 121 MCM per year. Pumping is increased from 62 MCM to 97.4 MCM. Evaporation loss is about the same, 69.2 MCM. Inflow across the northern model boundary, that is from hill side, is the same, 11.5 MCM, while the outflow to India is nil in the fourth year.

Fig.2



SCHEME B.
PUMPING 97.4 MCM

POSSIBLE AREA FOR IRRIGATION:
12,175 hectares

TOTAL NUMBER OF WELLS:
2550

SPACING BETWEEN WELLS: 300 m

Thus the balance equation may look as follows:

```
Recharge + Inflow + Ret.Irr. = Evaporation + Pumping + Storage Change
  121    +  11.5  +  16.7    =    69.2     + 97.4    -   17.4  MCM/yr
```

The deficit of about 17.4 MCM per year may come from two sources: (a) contribution from the Sapta Koshi river flow, (b) from storage, which is still being used. The ultimate balance, with extended time of abstraction, can come either from the river or from inflow from the hill side. The volume of 17.4 MCM/year is about 550 l/sec, which is negligent considering the average river flowrate. The balance in the fourth year of simulation is shown in Fig.3.

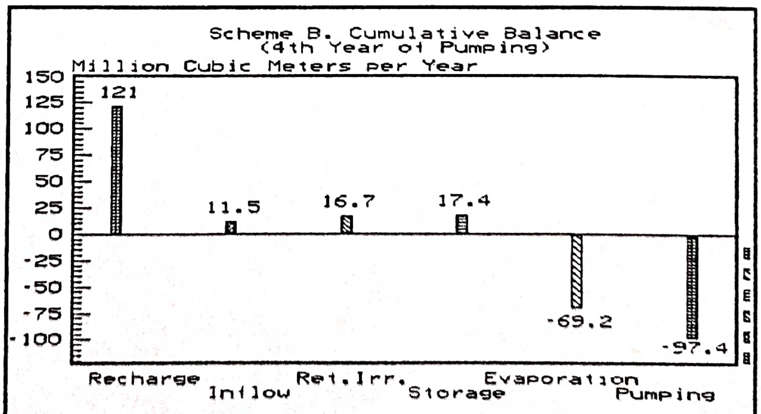


fIG.3

The model of Sunsari 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. Although previous reports have speculated about the maximum permissible number of shallow wells in various districts of the

Terai, this modelling study formulated not only the number of wells, but suggested the area which may be favorable 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 Sapta Koshi River. This last may be the weak point of the study. It is recommended to establish either one additional river stage (and flow) gauging stations on the Sapta Koshi (one near the border with India), or to drill two shallow observation wells at the river bank to monitor the river stage.

As a final conclusion, Sunsari district offers quite a high development potential for shallow-ground-water-sustained irrigation. Abstraction from phreatic aquifer has a side beneficial effect of providing for drainage, and reducing the risk of water logging and salinization of soils.

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1. BACKGROUND INFORMATION

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. The government implementing agency is Ground Water Resources Development Board of the Department of Irrigation, Ministry of Water Resources. The project is designed as a four-and-half year project primarily oriented to field-data collection, establishment of ground-water data bases, and to assessment of development potentials of shallow aquifers all over the Terai. The project started in June 1987.

The project is to produce the following tangible outputs:

(a) Computerized data base with about 2000 shallow wells from all over the Terai. Information on lithology, hydrogeological parameters, water levels, etc.

(b) Maps of pre-monsoon (maximum) and post-monsoon (minimum) water depths expressed in relative terms from land surface and in absolute elevations above mean sea level.

(c) Water level graphs from selected observation points in a minimum period of one year.

(d) Reports on mathematical modelling.

(e) Report on drilling methods and results in shallow water well drilling in the Terai.

(f) Assessment of shallow aquifer development potentials in each of districts.

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.

1.2. Basis for the Model and Report

The model of Sunsari district is based on the following:

(a) NEP/86/025 project wells (for ease of reference called "project" wells) - 17 newly drilled shallow wells between October 1988 and January 1989. Locations are shown in Appendix 3.

(b) Shallow wells drilled by GWRDB for farmers, financed by ADBN in 1982/83.

(c) Deep tube wells drilled by GWRDB between 1976 and 1982.

(d) Pumping tests conducted in "project" wells between December 1988 and February 1989. (e) Water level observations since May 1987. Location of observation wells, which were used for model calibration, are shown in Appendix 4.

Most, if not all, of previous information is compiled and reported in Technical Report No.10, titled "SUNSARI DISTRICT: SHALLOW WELLS DRILLING, TESTING AND MONITORING IN 1987-1989, BASIC DOCUMENTATION AND PRELIMINARY INTERPRETATION".

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

Sunsari district belongs to the Eastern Region. The sketch location of Sunsari within Nepal is shown in Appendix 1. More detailed, although still a sketch, the model area is shown in Appendix 2. The district area is about 1240 km^2; out of this, 100 km^2 belongs to the Bhabar zone. 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 30 to 40 meters. The contour line of 150 m is considered to be the physical end of the Terai's Quaternary sediments. Thus, the active model area is about 892 km^2, excluding higher parts near the hills, in which presumably shallow aquifer becomes marginal or missing.

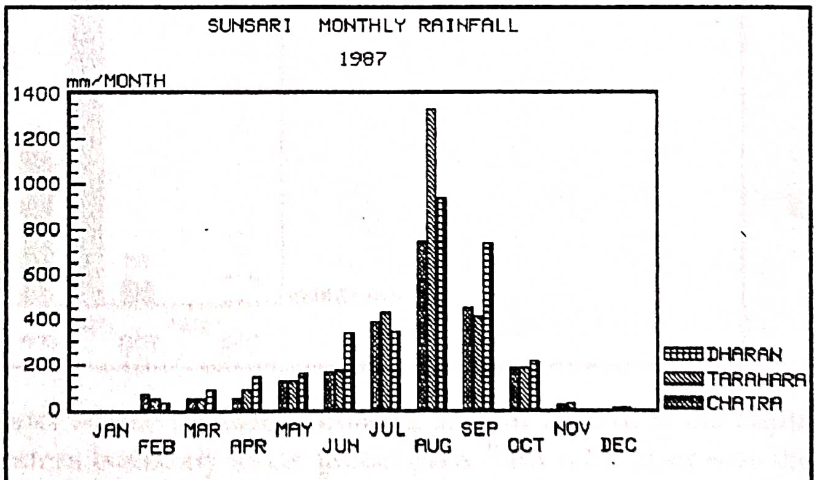


Fig. 1

The main characteristics of the climate in Sunsari 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 rainfall stations (Dharan, Tarahara, Chatara, Biratnagar) are shown in Appendix 2. Monthly rainfall for three stations in 1987 is shown in Fig. 1, in 1988 for two stations in Fig. 2, and in 1989 for Biratnagar station in Fig. 3. The long-term average for Biratnagar is about 1732 mm, while the rainfall in all three last years was far above the long-term average: 1987 2657 mm, 1988 2088 mm, 1989 2728 mm. Average monthly rainfall exceeds average evaporation in a normal year during only 4 months, June to September. For better understanding of the shallow aquifer behavior in the period of calibration (May 1989 - September 1989) the more-than-average rainfall in district should be considered.

Fig. 2

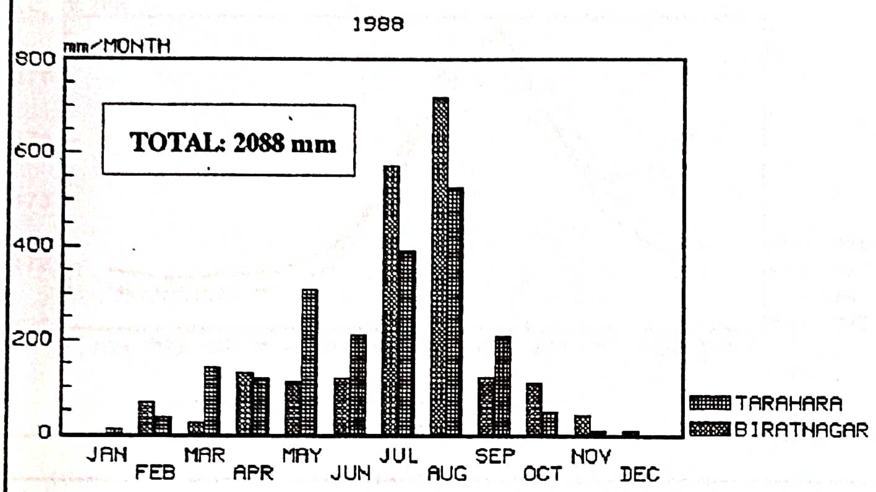
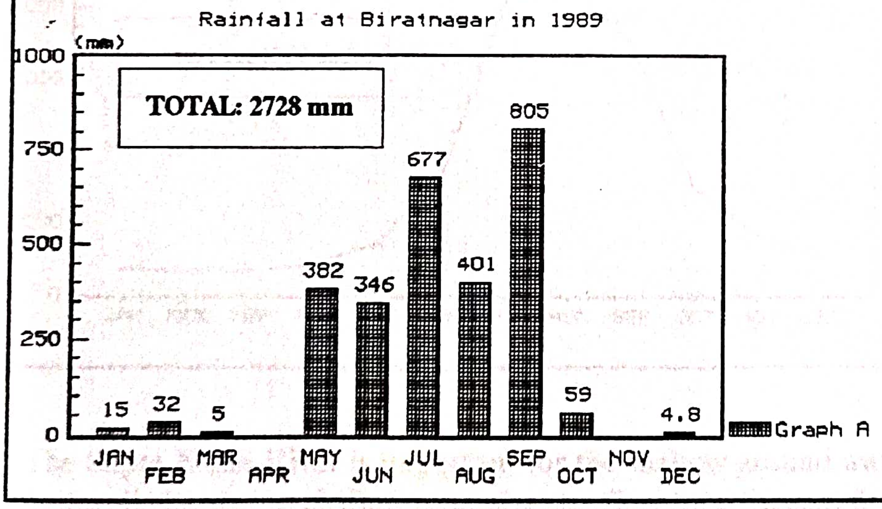


Fig. 3



The major potential surface water source for supplementing natural rainfall is the Sapta Koshi River which makes the western boundary to the model area. This is the river with the second highest discharge in Nepal (average: 1550 m^3/sec in 1977-1985). The river flow height (Fig. 4) and river discharge (Fig. 5) are recorded at Chatara (Chatra) station, just at the place where the river exits from Siwalik hills and enters the Terai. The land surface elevation at the gauging station is 170 m. In the month of August, the Koshi has its highest water level which is about 4 m higher than in February. At the border with India, the Koshi is dammed up by a one kilometer long dam, so that even in premonsoon season, the river never gets dry. Almost ninety percent of the annual flow of the Koshi occurs in the months May to October and only ten in the remaining 6 months.

Fig. 4

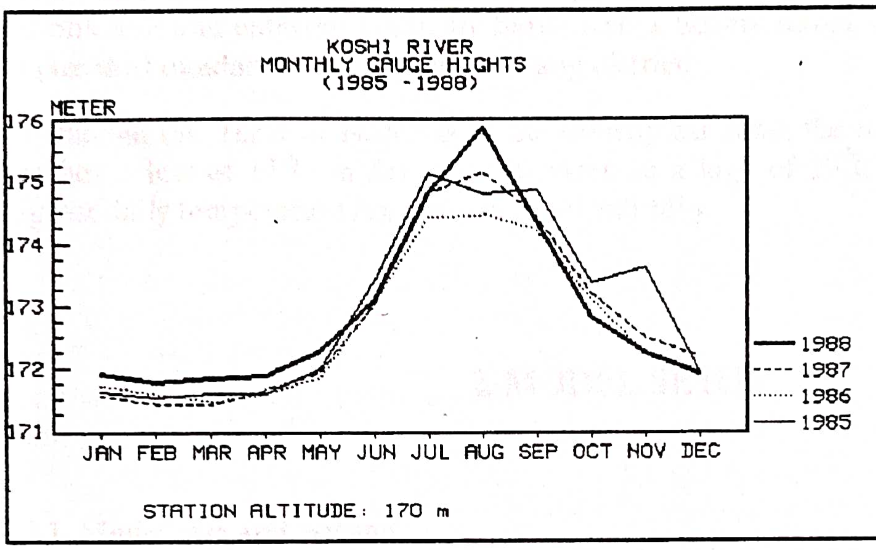
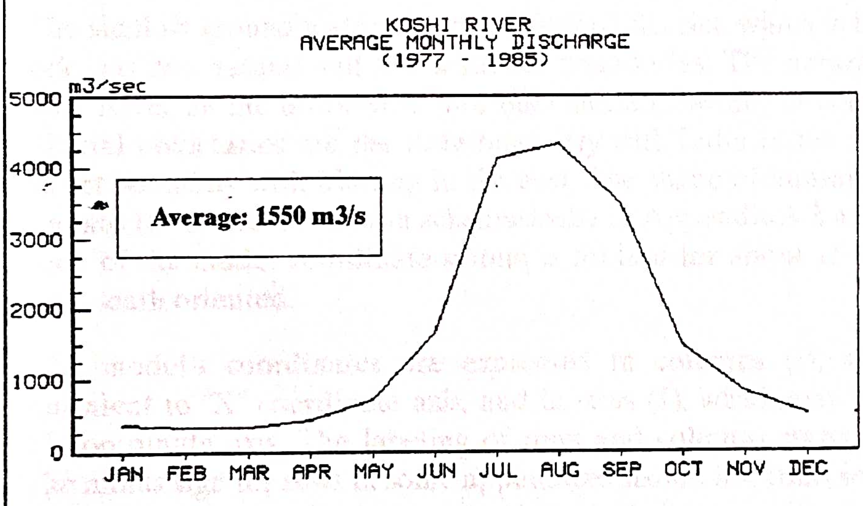


Fig. 5



The Sapta Koshi River is important for the shallow ground water system because it makes a hydraulic barrier to shallow ground water flow from Sunsari district into or from neighboring Saptari district. Due to lack of information about the river height at the damsite, the time of opening of flood gates and their discharge, the connection between ground water table and river water level in this southern part is not well known.

While the role of the Sapta Koshi River may be that of a constant-head boundary preventing any shallow ground water exchange across its banks, the role of other rivers in Sunsari district is not clear. Most of streams are intermittent, flowing only during the monsoon time. The Siwalik (Churia) hills within the Sunsari 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 Sapta Koshi. Some less significant surface flows, intermittent, leaving the Siwalik hills and entering Terai, are Sarda Khola, Sehera Khola, and Budhi Nadi. The latter makes the boundary with east-lying Morang district.

Although the Terai of Nepal is in the subtropical zone, the mean monthly temperature reaches a low of 17°C in January compared to a high of 29°C in June and/or July. The highest daily temperature is usually in April and May.

2. MODEL SETUP

2.1. Model Size and Network

The shallow ground water system of Sunsari district, which is the subject of this modelling work, has two natural and two artificial boundaries. The natural boundaries are the Sapta Koshi River on the north-west, 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 district boundary with Morang in the east. The shape of Sunsari district and its transformation into the model are shown schematically in Appendices 3 and 4, respectively. The orientation of the model coordinate system is rotated for about 15 degrees, to make the model north-south oriented.

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 labeling of rows and columns starts in the northwestern 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 1435 km^2, which is discretized into 1435 equal-size cells. The size of each cell in the model is 1000 m by 1000 m, i.e. the area occupied by one cell is 1,000,000 m^2 big. The number of columns is 35, and that of rows is 41. It is a medium-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 right bank of the Sapta Koshi River is eliminated from simulation. This is a standard procedure since the aquifer in Saptari, on the other side of the river, is not hydraulically (and physically) connected with the water in Sunsari district in the east. In other words, the Sapta Koshi River is taken as a constant-head boundary which is the physical termination of the Sunsari 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.

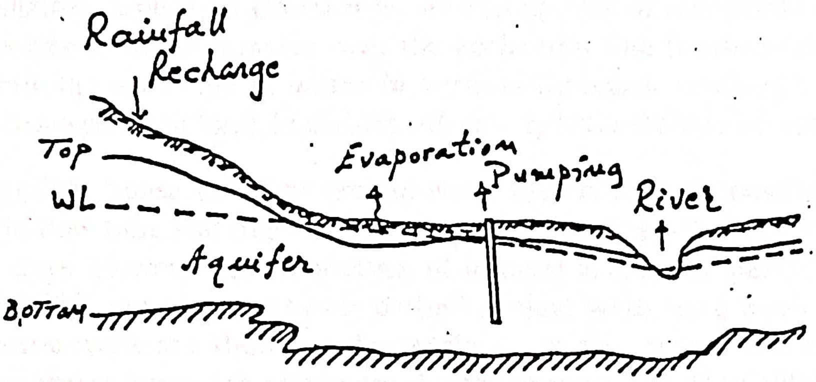
However, the area to the east, which is also eliminated and which is in Morang district, does contain a shallow ground water system, very similar to the one in Sunsari district. That area was eliminated from the modelling on the following grounds: (a) one of targets of the modelling is to produce the water balance for Sunsari 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 Morang district, if development is in Sunsari, or "export", if development is in Morang. However, the planning of shallow ground water development calls equally for increased pumping in Morang as well as in Sunsari district. It is on the safe side to assume that any development in Sunsari should count only with the water recharged in that district. To conclude, there is an error introduced when the Morang portion of the system is eliminated, but that error is on the safe side. The south-east and south 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. Modeled Processes and Aquifer Parameters

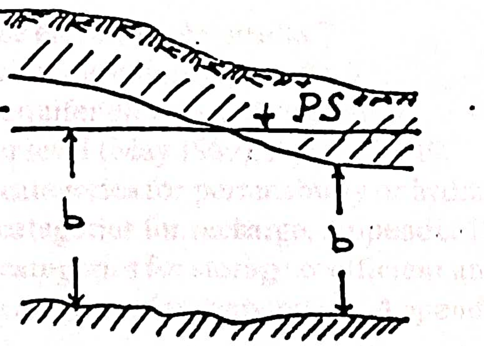
The shallow ground water system of the Terai is recharged directly from the surface in places in which a more or less permeable layer occurs near the land surface. It receives the water which infiltrates after rainfall, or which originates from rivers and other surface streams. Although the water from 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 Sunsari district the extension of the Bhabar zone is only about 100 km^2, and that is mostly in the northeastern portion 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 Sapta Koshi 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 behavior is shown here below in Fig. 6, and the real geometry of shallow aquifer, from north to south, in Figures 7.



Although the ground water system modeled 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 - Transmissivity

T= Kb 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 deep tube wells drilled by

GWRDB. The nonhomogeneity of the system is clearly evidenced in lithological cross-sections in Appendix 5. The appendix contains five typical lithological cross-sections. (Detailed interpretation of lithology is given in Technical Report No. 10, Basic Documentation for Sunsari District.)

In thirteen 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 transmissivity is high, normally over 1500 m^2/day, reaching a maximum of over 4000 m^2/day. 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 Sunsari shallow ground water system is made possible by monitoring water levels in shallow tube and dug wells in the period starting with May 1987 and continuing until recent days. However, for modeling, of interest is only the period from May 1989 through January 1990, in which the newly drilled project wells have been observed. Locations of observation wells are shown in Appendix 4. In this period two extremes are observed: minimum water levels (or maximum depths to water) in May 1989, and maximum water level in September/October 1989.

2.3. Input Data

The following input data are required to make a model of a shallow unconfined aquifer:

(a) Land surface elevation, Appendix 7.
(b) Top-of-aquifer elevation, Appendix 8
(c) Bottom-of-aquifer elevation, Appendix 9.
(d) Initial water level (May 1989), Appendix 10.
(e) Codes and categories for permeability or hydraulic conductivity, Appendix 11.
(f) Codes and categories for recharge, Appendix 12.
(g) Codes and categories for storage coefficient and/or effective porosity, Appendix 13.
(h) Codes and categories for evaporation, Appendix 14

The model produced maps derived from input data: depth to top of shallow aquifer (Appendix 15), depth to bottom of shallow aquifer (Appendix 16), depth to water level in May 1989 (Appendix 17), and saturated thickness of shallow aquifer (Appendix 18). Very illustrative are also geometrical cross-sections as shown in Appendices 15, for selected columns and rows. These may be compared with lithological cross sections derived from driller's data logs (Appendices 5).

From the map showing depth-to-shallow-aquifer (Appendix 15) it is clear that aquifer is almost everywhere overlain by several meters of less permeable formation. This is normally silty and sandy clay, which may be more or less permeable. It may accept and transmit some of rainfall because its permeability is not controlled entirely by its lithology. Agricultural practices, plants' roots, weathering, and like, contribute more or less to its permeability. The thickness of overlying semipermeable layer is also seen in geometrical cross-sections in Figures 7 (three pages further). The map in Appendix 16, depth-to-bottom of aquifer, shows actually the depth of shallow aquifer as interpreted by this model. In the central part it is about 44 m, while normally it is 30 and 40 meters.

Water levels in May 1989 are low, as shown in Appendix 17. Except in some isolated areas where levels are less than 3 meters from ground surface, in May 1989 they are normally between 4 and 6 meters deep.

Very important is the model interpretation of saturated thickness of shallow aquifer in May 1989 as shown in Appendix 18. Except in north-western corner and south-eastern part, it is everywhere more than 20 meters. It reaches a maximum in the very center, about 42 m.

2.4. Phases of Modelling

The modelling started with **steady-state calibration** of the model. The month of May 1989 was selected for the initial phase of the modelling. The water-level contour map (Appendix 10) 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 have been 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 Sapta Koshi 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, **unsteady-state calibration**, was to confirm the rise of levels over the period from May 1989 through September 1989. For this many points all over the modeled area were used, as shown in Appendix 4. These points, in which historical observations of water levels exist, are "calibration cells", or model-quality controlling cells.

Coupled to the second phase, the third phase of the modelling was to simulate the system behavior 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 September 1989 and May 1990. This is a hypothetical phase, because observed levels are missing for the period October 1989 - May 1990. The model should have proved that the May levels in 1990 would have come close to the ones in May 1989, 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 1990 levels should be slightly above the May 1989 levels because of over-average rains in 1989.)

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.

2.5. 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 Sunsari 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
Boundary data Land Surface Top of Aquifer Bottom of Aquifer Permeability Storage Coefficient Recharge Evaporation Sapta Koshi River Initial Levels				Water Balance Map of Levels Hydrographs Depth to Water Evaporation Distribution Permeability Distribution Storage Coeff. Distribution

The role of input data cannot be overemphasized. A model is as good only as the data used to make it. As far as the Sunsari 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.)

2.6. 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:

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

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 5,7,8,9,15,16,18 (land surface, top-of-aquifer, bottom-of-aquifer, depths to top and bottom, saturated thickness, etc.)

The cross-sections through two columns and two rows of the model are shown in Figures 7. The blue-colored 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 change of land surface slope is evident some 15 or so kilometers from the hills (Figure 7/1, column 24). Although the sketch shows the "bottom" of the shallow aquifer, it is in no

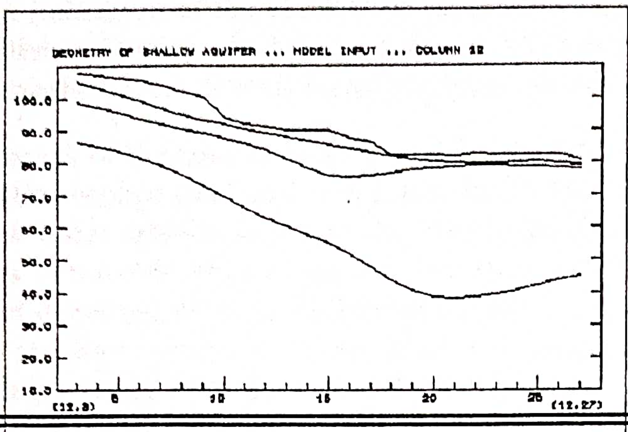


Fig. 7/1

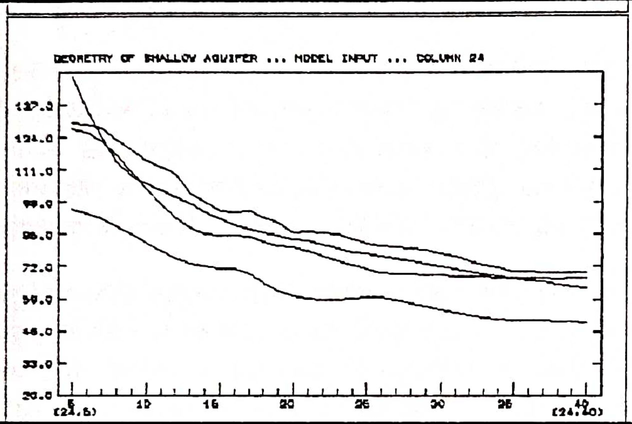


Fig. 7/2

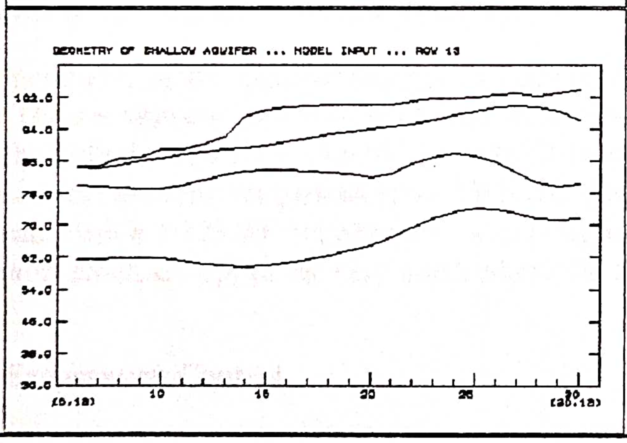


Fig. 7/3

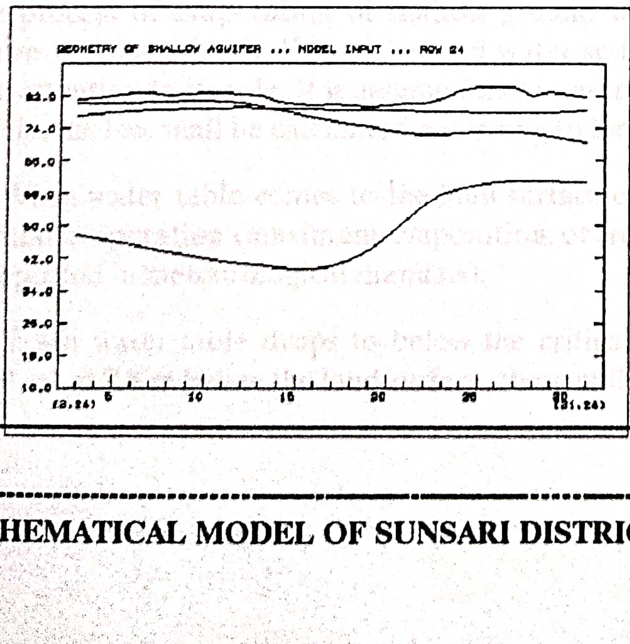


Fig. 7/4

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 Sunsari 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. Especially in a very thick Bhabar formation near hills, the upper portion of otherwise permeable medium may be unsaturated. Both lines, notable seepage and saturation lines, are dynamic concepts. They are constantly shifting, depending on the season and the vertical position of the water table.

In figures and 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 15, the depth to the bottom of shallow aquifer is shown in Appendix 16, and the saturated thickness of aquifer at the beginning of simulation (May 1989) is shown in Appendix 18.

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 a local subcontract provided by GWRDB. For other points, the land surface elevation was read from a 1:125,000 topographic map (English version), with an accuracy of some 1-2 m in most cases, except in the very north where the accuracy could be several meters.

2.7. Evaporation Control

The process of evaporation of shallow ground water is one of the most dominant and decisive processes in the Sunsari 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 2.8 m below the land surface, there will be zero evaporation loss.

(c) Between 2.8 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.

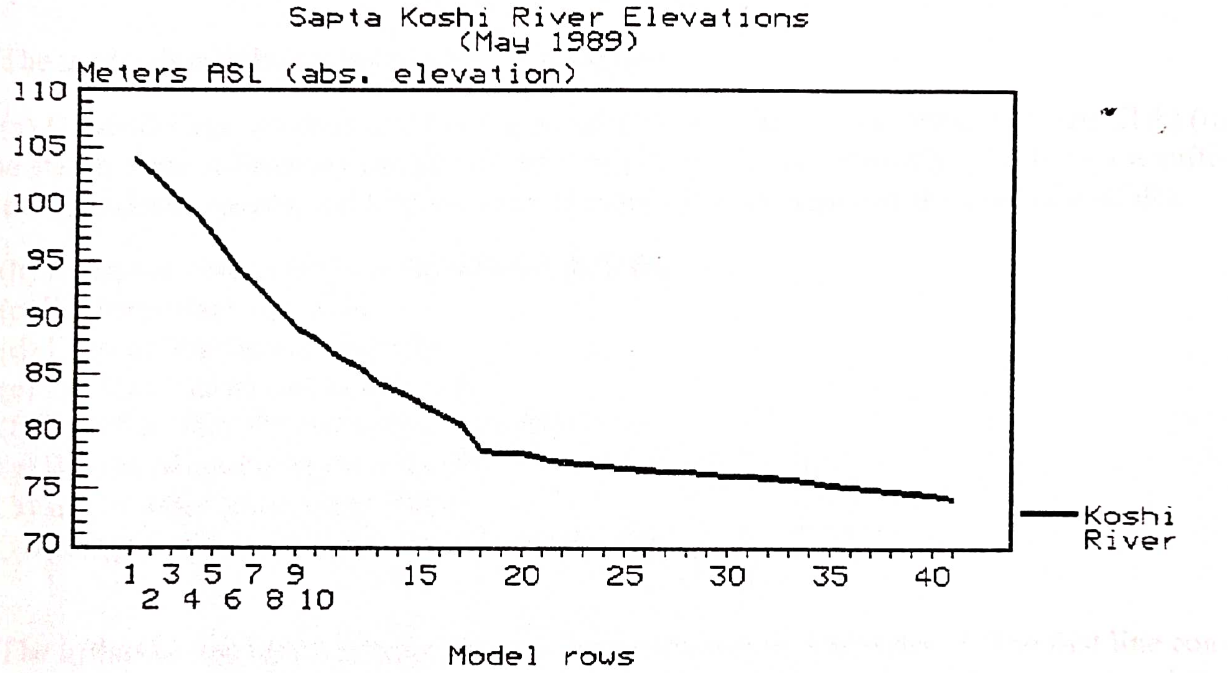


Fig.8

2.8. Sapta Koshi River

The Sapta Koshi River makes the western 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. As shown in Fig. 4 at gauging station Chatra the river stage is from minimum over 171 m to maximum about 176 meters. Chatra is located in higher parts of Terai. The slope of the river, as it is entered into the model in the month of May 1989 is shown in Fig. 8.

3. STEADY-STATE CALIBRATION (MAY 1989)

3.1. Water Level Contour Map in May 1989

The basis for the steady-state calibration is the contour map of water levels in May 1989 (Appendix 10). The map is produced by subtracting the depth to water table in selected wells from absolute land surface elevation. More than 20 well points covering all parts of the model were used to construct this map. The model is expected, in the steady-state calibration to duplicate this map.

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 1x1010 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 1989).
(i) Storage coefficients and/or effective porosities.

The hydraulic conductivity input data file is reproduced in Appendix 11. 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,35I1, 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 70 m/day, etc. 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 11 is the final outcome of the modelling (calibration) process.

The recharge data input file is shown in Appendix 12. 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 0.011 is 11 mm/day, or 330 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 14. 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 43rd in this case) contains the daily maximum (free-surface) evaporation rates for each time interval. In the file shown in Appendix 14, the value such as 0.006 (for May-June 1989) is interpreted as daily potential evaporation of 6 mm. (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 Appendices 8 and 9, respectively.

The initial water levels input data file, with its graphical equivalent shown in Appendix 10, 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 areal distribution of locations with known lithology is shown in Appendix 5/1. At least 17 wells 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 western part of the district, toward the Sapta Koshi River. Likewise, there is missing information in the central-north, between lithological cross-sections II and III. 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 several hundred m^2/day.

The number of 11 pumping tests on which the transmissivity distribution is based is insufficient. Therefore, during calibration phase, a completely new distribution of transmissivities had resulted, from an attempt to match, by model, the nature.

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 table of individual "matching" values as shown here below.

COMPARISON BETWEEN FIELD MEASUREMENTS AND MODEL
(END OF STEADY-STATE CALIBRATION)

Obs. Well Name	I	J	Hinput	Hend	Difference
Khanar	28	15	93.83	93.87	-0.04
Chandbela	25	18	87.72	87.14	0.58
Kushaha	30	27	73.04	73.97	-0.93
Shimariya	27	20	85.75	84.80	0.95
Amahibela	28	35	67.00	66.73	0.27
Ramnagar	19	30	72.54	73.19	-0.65
Bhokraha	10	21	79.09	80.33	-1.24
Devanganj	24	37	66.13	65.51	0.62
Lauki	11	26	80.15	78.84	1.31
Prakashpur	10	16	84.26	83.88	0.38
Jhumka	18	14	91.36	91.81	-0.45
Tarahara	25	7	133.00	133.23	-0.23
Kalabanjar	14	6	104.10	102.89	1.21
Singiyahi	13	11	93.10	92.22	0.88
Harinagar Old	21	35	66.40	66.39	0.01
Babiya Old	18	29	73.43	74.50	-1.07
Bhokraha Old	13	25	79.19	79.21	-0.02
Tanmuna Old	28	26	75.72	76.13	-0.41
Dhanpuri Old	15	6	104.20	104.26	-0.06
Baklauri Old	17	10	98.91	98.90	0.01

Average difference in this run: 0.57 [m]

The average "deviation from observed" values is 57 cm, for 20 cells. In four cells it is slightly over 1.0 meter. With information in hands, which is preliminary, and considering the conclusions to be derived from such a model, it is believed sufficiently accurate for this purpose.

The map of water level contours in May 1989 is shown in Appendix 10. The success of the steady-state calibration becomes evident when this map is compared with a similar map reported in Technical Report No. 10, produced by field measurements only. 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 northeastern part, and much milder in the southern part toward India and the Sapta Koshi River. The map needs additional information in the area near the Sapta Koshi River.

Yet it is believed that the map as shown in Appendix 10 is a good starting point for the unsteady-state calibration of the rise of levels in the monsoon season of 1989.

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.

STEP	RECHARGE m3/day	PUMPING m3/day	EVAPORAT. m3/day	RET. IRR. m3/day	INFLOW m3/day	OUTFLOW m3/day
1	-71501.	0.	60319.	0.	-54900.	43200.

As shown in table above, the total recharge from infiltrated rain, as shown by the model, in the dry season was about 71,501 m^3/day, which makes an equivalent of 2.1 MCM/month (million cubic meters). The evaporation loss is equal to 60,319 m^3/day, or 1.8 MCM per month. The outflow into India across 40 km section is about 43,200 m^3/day, or 1.3 MCM/month. The inflow from the hilly side (either as underflow below dry river beds, or springs discharge, or surface runoff) amounts to about 54,900 m^3/day, or 1.6 MCM/month.

Thus, what remains as a surplus of recharge flows into the Sapta Koshi River. This is a very small volume of only about 22,882 m^3/day, or 686,000 m^3/month.

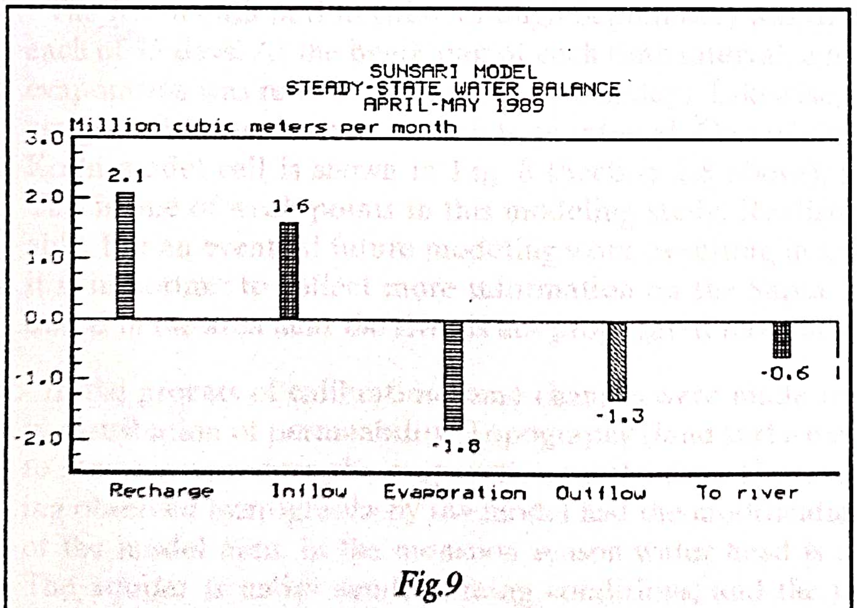


Fig.9

One must admit that the model did not take into account any pumping from shallow tube wells. If about 100 STWs were pumping in March-April on average 10 l/sec, 4 hours each day, the total daily abstraction could be as high as 14,400 m^3/day, or 432,000 m^3/month, which is evidently a very minor amount. In this simulation, the abstraction through shallow wells is lumped into the evaporation loss. The hypothetical balance in the dry season of 1989, could be as schematically shown in Fig. 9 (page before).

It appears that the recharge from direct infiltration of rainfall balances with evaporation loss plus eventual 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 19898 - SEPTEMBER 1989 and MODEL VERIFICATION THROUGH MAY 1990

4.1. Basis for Calibration

Twenty plus observation wells were under once-a-month monitoring in the period from May 1988 through September 1989 and on (Appendix 4). On the basis of observations, a contour map of water levels in September 1989 (in absolute elevations) was drawn. This map and hydrographs of selected wells are appended to Technical Report No. 10, and are not repeated here. The rainfall record is available for the year 1989 in Biratnagar, and so is the information on daily potential ("pan") evaporation. On the basis of this, the daily rainfall and daily potential evaporation were input into the model.

4.2. Calibration and Verification Process

The five-month period (May through September) was divided into 8 equal time intervals, each of 15 days. 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 Sapta Koshi River cells were assigned different values in each time interval. One of simulated hydrographs of the Sapta Koshi model cell is shown in Fig. 8 (Section 2.8 above), for the period of river stage rise. This is one of weak points in this modeling study. Realistic data on the river are not available. For an eventual future modeling work, resulting in more than preliminary assessment, it is important to collect more information on the Sapta Koshi River. Yet, the error introduced in the area near the river is not propagated too much into the interior.

In the process of calibration some changes were made in the distribution of recharge and in distribution of permeability. Topography (land surface elevation) was "manipulated with" to increase or reduce the evaporation mechanism. However, almost decisive role in matching observed hydrographs by the model had the modification of storage coefficients. In most of the model area, in the monsoon season water head is above the top of shallow aquifer. The aquifer is under semiconfining conditions, and the rise of heads is controlled by the storage coefficient. The final outcome of the values of the storage coefficient is presented in Appendix 19. Some changes have been made also in the distribution of evaporation.

4.3. Results of Unsteady-State Calibration

The model produced several outputs in this phase of simulation:

(a) Distribution of Storage Coefficients, under confined conditions, as shown in Appendix 19.

(b) Map of Water Levels in September 1989 (Appendix 20), which

matches a similar map constructed from field observations. (c) The rise of levels from May to September 1989, shown in Appendix 21, which should be compared with a similar map in Technical Report No. 10.

(d) Depth to water in September 1989, shown in Appendix 22, which should be compared with a similar map constructed from field observations.

(e) Hydrographs at selected points, shown in Appendices 23, and compared to the hydrographs constructed from field observations.

(f) Evaporation losses in September 1989 (when water table is nearest the land surface), as shown in Appendix 24.

(g) Water Balance, which is reproduced here below, and in Fig. 10.

STEP	RECHARGE m3/day	PUMPING m3/day	EVAPORAT. m3/day	RET. IRR. m3/day	INFLOW m3/day	OUTFLOW m3/day
1	-297920.	0.	77508.	0.	-31900.	56100.
1	-453920.	0.	89438.	0.	-31900.	56100.
2	-1148760.	0.	108010.	0.	-31900.	56100.
2	-1148760.	0.	118425.	0.	-31900.	56100.
3	-1148760.	0.	456399.	0.	-31900.	56100.
3	-1148760.	0.	495890.	0.	-31900.	56100.
4	-765840.	0.	382720.	0.	-31900.	56100.
4	-765840.	0.	362241.	0.	-31900.	56100.

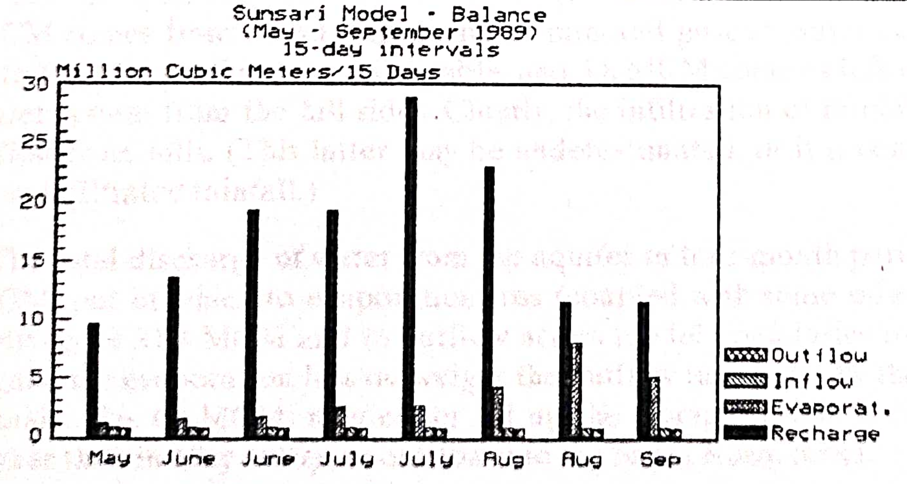


Fig.10

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 sub-surface 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 12, 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 19 cells along the northern edge of the model in the form of artificial recharge (through wells). Individual rates amounted to 1000 to 6000 m^3/day per one cell of 1000 m length. This is equivalent to about 12 l/sec to 69 l/sec per one cell.

Outflow, which is shown in the table above, is simulated as artificial discharge through wells in 33 cells in boundary cells along the district boundary with India. This is a compensation for cutting off the aquifer which normally extends into India. Contrary to expectations, this component of the water balance is not a minor one, especially not in dry period. Individual rates amounted to 300 to 3000 m^3/day per one cell, or an equivalent of 3.5 to 35 l/sec per cell. Actually, both inflow and outflow had not been changed from steady-state phase. (This is obviously an inconsistency, since more water must enter the shallow ground water system and leave from it in the months of high water table and plenty of rainfall.)

The balance shown above may be interpreted in the following way. The total input of water into the shallow ground water system in four monsoon months between June and September of 1989 is equal to about 107 MCM (million cubic meters). Out of this volume, about 103.2 MCM comes from direct infiltration of rain and ground water accretion on account of infiltrated rain reaching the water table, and 3.8 MCM come as inflow into the shallow ground water system from the hill sides. Clearly, the infiltration of rainfall is much superior to the inflow from hills. (This latter may be underestimated, or it is coupled with direct recharge from infiltrated rainfall.)

The total discharge of water from the aquifer in four-month period amounts to about 38.1 MCM, out of which to evaporation loss (coupled with some minor pumping from shallow wells) goes 31.4 MCM and to outflow across model boundaries to India another 6.7 MCM. Again, the evaporation loss outweighs the outflow into India by the factor of almost 5. What remains, i.e. 69 MCM, may either fill up the storage (levels in September 1989 are much higher than in May 1989), or outflow into the Sapta Koshi River.

The 15-day water balance is shown in Fig. 10 (two pages earlier). As shown in Appendix 24, the evaporation loss is mostly in central part of the model, plus there is an area in north-west in which water table comes in September also very close to the ground surface. (The "evaporation loss map" should be compared with Appendix 22, Depth to water in September.) However, although the water table is very close to the surface, the loss is still small because the water table is within a semiconfined layer.

4.4. Comparison between Observed and Simulated Hydrographs

This comparison is actually the measure of "fit" and quality of the model. Fourteen hydrographs are presented in Appendices 23. 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 (e.g. low levels in June in Amahibela; decline of levels from July in Bhokraha; etc.) Also, it was impossible to find the process which could meaningfully reproduce the sharp rise of level of 3 meters in Tanmuna well from July to August. 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: Prakashpur, Khanar, Shimariya, Ramnagar, Devanganj, Jhumka, Kalabanjar, Singiyahi, Harinagar. Acceptable fit is in wells: Chandbela, Amahibela. Less acceptable fit is in wells: Kushaha, Bhokraha, Tanmuna. 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.

4.5. Verification of Shallow Aquifer Behavior over One-Year Period

Since at the time of modeling work (November-December 1989) one-year period had not been closed by monitoring levels in newly drilled wells, the unsteady-state calibration could have covered only the monsoon rise of levels in 1989. The "dry" portion of hydrographs was missing and conclusions on recharge and discharge after monsoon terminates could not be tested. Thus, one hypothetic phase was incorporated between unsteady-state calibration and

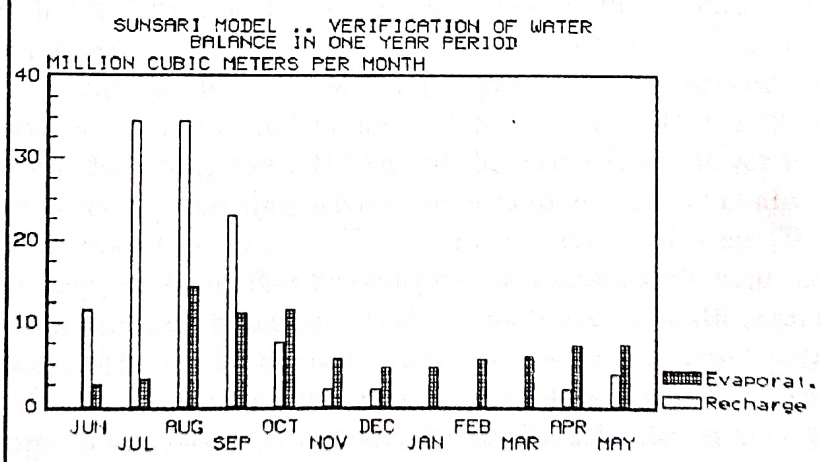
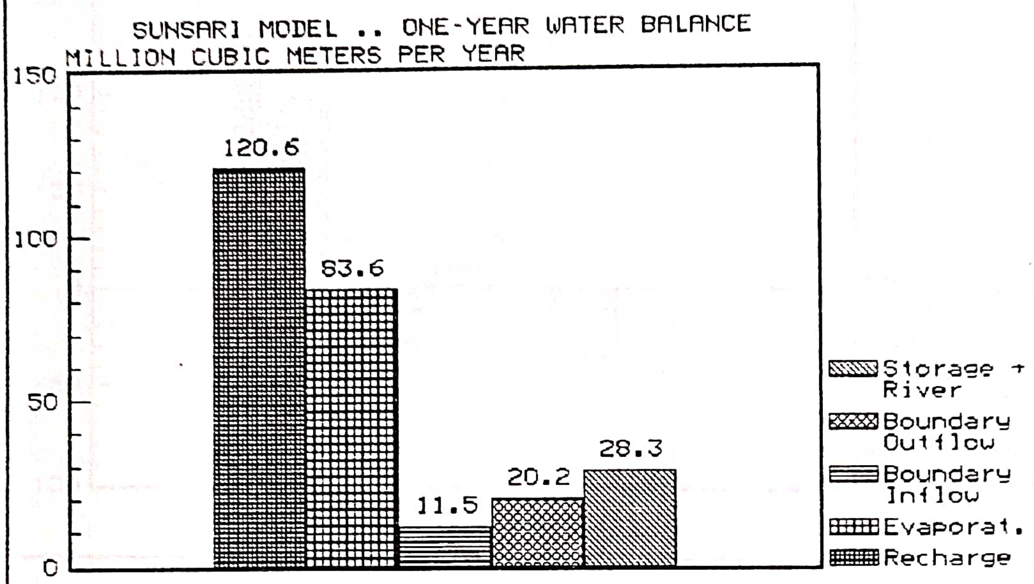


Fig.11

future forecast phase. This is called the verification of system components and previous conclusions in an hypothetically extended period of one year. The objective is to prove that water levels in May of 1990 should come close to levels in May 1989, under a defined and confirmed set of recharge rates and percentages, evaporation parameters, and aquifer properties.

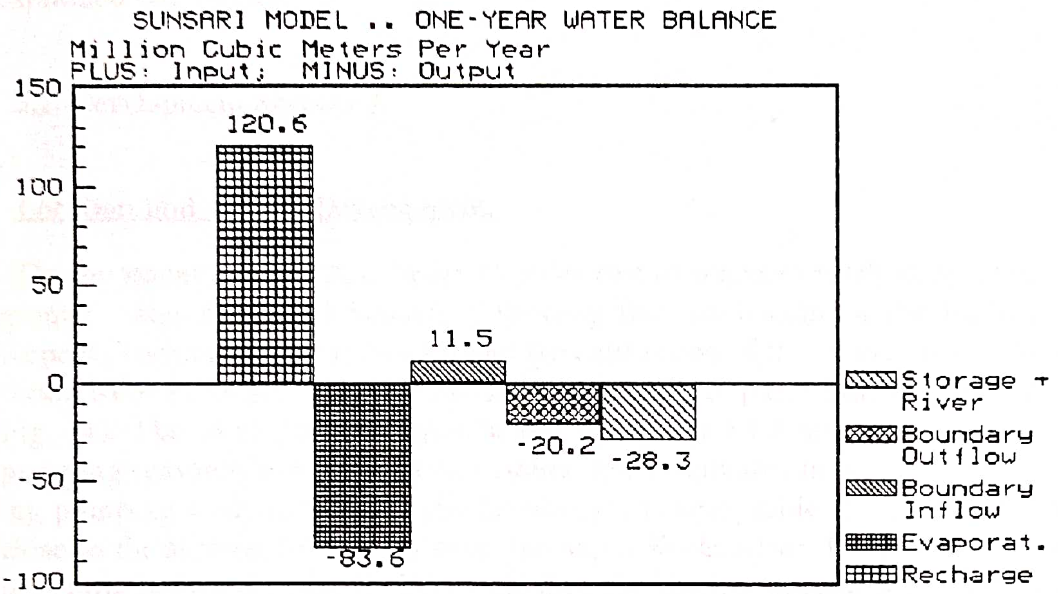
Fig.12



The result of this phase is shown in one-year water balance in Figures 11, 12, 13, and in hydrographs (Appendices 25). From this water balance one may conclude that a future ground water development from shallow aquifers may come mostly on expense of reduced evaporation, outflow into the Sapta Koshi River, and outflow into India. The evaporation loss, which amounts to about 83.6 MCM (million cubic meters) per year, can be reduced by lowering water levels to a depth that will prevent the losses. As indicated in Appendix 24, the area with water table close to land surface is in the central part and north-west. The outflow into the Sapta Koshi, which could be about 28 MCM per year, can be reduced or eliminated by pumping from shallow wells located along a stretch parallel to the river course. It is a favorable coincidence that along the left bank of the Sapta Koshi River the shallow aquifer in Sunsari district is most promising, having clean sand and gravel content and very high transmissivity of more than 1500 m^2/day. The outflow to India, of some 20.2 MCM per year, can be reduced or stopped altogether by pumping on a larger scale near the border. This applies to both parts of the state boundary, west of Lauki and in south corner between Ramnagar and Amahibela. The water balance shown in Fig. 13, coupled with aquifer parameters (Appendices 11, 13, 19), and recharge and evaporation categories (Appendices 12, 14), produced hydrographs as shown in Appendices 25. Clearly, the balance is such that water table comes back after one year to where it was a year before (May 1990, versus May 1989).

It is believed that the model can be used to predict the impact on shallow ground water system of a medium-scale ground water development over an extended period of time.

Fig.13



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 Sunsari model was shown to correctly duplicate the behavior of shallow water table in the period from May through September 1989. Likewise, it was also successful in quantifying 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.10 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, behavior 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.

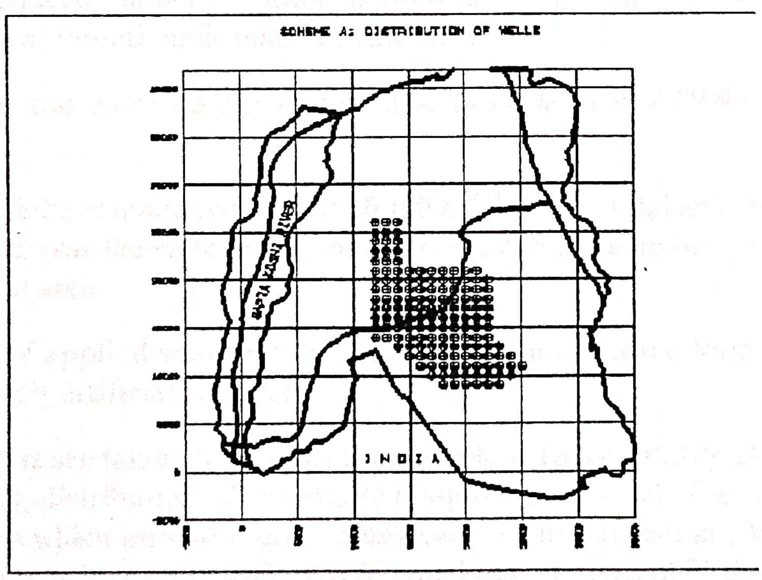
After several check runs, it was decided to fully test two development schemes, which are explained one by one.

5.2. Development Scheme A

<u>Location and Area of Development.</u>

Development scheme A is believed to be one of schemes easily supported by the shallow ground water system of Sunsari. Following the conclusions of the Basic Documentation Report (Technical Report No. 10) and the calibration of this model, it was decided to locate future wells in an area of some 147 km^2 in the central part of the district (Appendix 26 and Fig. 14). The total pumping rate in this scheme is 61.7 million cubic meters (MCM) in pumping season which starts in November and terminates in April. The criterion for locating pumping wells (cells) was the following: (a) acceptable transmissivity, (b) water table close to the surface, (c) site far from the Sapta Koshi 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 (83.6 MCM/year), outflow of about 20.2 MCM/year to India, and outflow into the Sapta Koshi River of about 28 MCM. Some induced recharge from the Sapta Koshi River may augment the total "safe yield" of the Sunsari shallow ground water system. The total pumping of 61.7 MCM is just below one half of the maximum possible "safe yield" of the district, without induced recharge from the river.

Fig.14



Number of Pumping Cells and Wells

The number of pumping cells is 147. 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 11, if the wells are located at 300 m distance one from the other. Thus the total number of wells could be about 1600. For the purpose of the forecast, it was assumed that each cell is producing 420,000 m^3/season each year. Actually, the daily pumping rate of all cells is 1500 m^3 in November, 2000 in December, 2250 in January, 3000 in February and March, and 2250 in April. This is equivalent to an average of about 32.4 l/sec from each square kilometer throughout the pumping season. With an average agricultural demand of 8,000 m^3/ha/season, with 420,000 m^3 one may irrigate about 52 ha, or one half of the total area in each square kilometer. If wells are spaced at 300 m (11 wells in one sq.km), each well should be pumping about 38,000 m^3 in a season of five months, which means that one well may irrigate between 3 and 4 hectares. Individual wells' discharge rates, according to the previous calculation, are about 3 l/sec on average constantyly throughout the pumping season. This is translated into an average 18 l/sec if one well pumps 4 hours daily, or 12 l/sec if it pumps 6 hours daily. These are acceptable rates.

Underlying Assumptions

(a) It was assumed that recharge in the future shall be distributed in the same way as it was in the past, as shown in Appendix 12.

(b) Inflow from hilly sides is kept constant throughout the period of simulation (31,900 m3/day or 11.5 MCM in a year), which is less than in the period of calibration and verification. The reason for reduced amount of inflow is twofold: (i) the year 1989 was extremely rainy, (ii) this first test was intentionally made on safe side.

(c) Sapta Koshi River was modeled exactly the same as in the year 1989-90 (as shown in Appendix 29/5).

(d) The outflow into India is made constant at 56,100 m^3/day, or a total annual 20.2 MCM. In reality, the outflow across the state border must be constantly decreasing, following the lowering of levels in that area.

(e) Twenty percents of applied water returns to shallow aquifer in the form of return irrigation. This is effectively artificial recharge.

(f) 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 1989 levels which were also used in unsteady- state calibration (Appendix 10). The period of simulation is four years, split into 48 equal time periods of 30 days each. Thus one "modeling year" has 360 days.

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.

Results

The results are shown in Appendices 27 (water levels after 4 pumping seasons (May); 28 (decline of levels after fourth year); 29 (hydrographs at selected cells, including the Sapta Koshi cell); 30 (depth to water table after four years of pumping); 31 (saturated thickness of shallow aquifer after four years of pumping). Each of these appendices explains the behavior of shallow aquifer under hypothetic stress, and consequences of pumping.

Water balance, with all components for each simulated month, is presented herebelow in cubic meters per day, and in Figures 15,16,17,18,19.

STEP	RECHARGE m3/day	PUMPING m3/day	EVAPORAT. m3/day	RET. IRR. m3/day	INFLOW m3/day	OUTFLOW m3/day
1	-382920.	0.	83508.	0.	-31900.	56100.
2	-1148760.	0.	113138.	0.	-31900.	56100.
3	-1148760.	0.	476830.	0.	-31900.	56100.
4	-765840.	0.	373010.	0.	-31900.	56100.
5	-255280.	0.	390797.	0.	-31900.	56100.
6	-63820.	220500.	186777.	-44100.	-31900.	56100.
7	-63820.	294000.	119497.	-58800.	-31900.	56100.
8	0.	330750.	125787.	-66150.	-31900.	56100.
9	0.	441000.	135229.	-88200.	-31900.	56100.
10	0.	441000.	149909.	-88200.	-31900.	56100.
11	-63820.	330750.	166833.	-66150.	-31900.	56100.
12	-127640.	0.	166353.	0.	-31900.	56100.
13	-382920.	0.	162943.	0.	-31900.	56100.
14	-1148760.	0.	163255.	0.	-31900.	56100.
15	-1148760.	0.	246014.	0.	-31900.	56100.
16	-765840.	0.	323739.	0.	-31900.	56100.
17	-255280.	0.	274261.	0.	-31900.	56100.
18	-63820.	220500.	193472.	-44100.	-31900.	56100.
19	-63820.	294000.	131979.	-58800.	-31900.	56100.
20	0.	330750.	129348.	-66150.	-31900.	56100.
21	0.	441000.	144507.	-88200.	-31900.	56100.
22	0.	441000.	148057.	-88200.	-31900.	56100.
23	-63820.	330750.	163151.	-66150.	-31900.	56100.
24	-127640.	0.	171892.	0.	-31900.	56100.
25	-382920.	0.	167206.	0.	-31900.	56100.
26	-1148760.	0.	166296.	0.	-31900.	56100.
27	-1148760.	0.	251599.	0.	-31900.	56100.
28	-765840.	0.	321357.	0.	-31900.	56100.
29	-255280.	0.	267100.	0.	-31900.	56100.

30	-63820.	220500.	192617.	-44100.	-31900.	56100.
31	-63820.	294000.	135186.	-58800.	-31900.	56100.
32	0.	330750.	137096.	-66150.	-31900.	56100.
33	0.	441000.	138980.	-88200.	-31900.	56100.
34	0.	441000.	155055.	-88200.	-31900.	56100.
35	-63820.	330750.	170218.	-66150.	-31900.	56100.
36	-127640.	0.	171460.	0.	-31900.	56100.
37	-382920.	0.	167557.	0.	-31900.	56100.
38	-1148760.	0.	168387.	0.	-31900.	56100.
39	-1148760.	0.	246610.	0.	-31900.	56100.
40	-765840.	0.	329984.	0.	-31900.	56100.
41	-255280.	0.	262944.	0.	-31900.	56100.
42	-63820.	220500.	197261.	-44100.	-31900.	56100.
43	-63820.	294000.	135992.	-58800.	-31900.	56100.
44	0.	330750.	135905.	-66150.	-31900.	56100.
45	0.	441000.	146430.	-88200.	-31900.	56100.
46	0.	441000.	157899.	-88200.	-31900.	56100.
47	-63820.	330750.	171874.	-66150.	-31900.	56100.
48	-127640.	0.	173862.	0.	-31900.	56100.

Thus the water balance in each of four years of simulation may look as follows.

All values in MCM/year

Year	Recharge	Inflow	Return	Pumping	Evaporation	Outflow
1	121	12	11	62	74	20
2	121	12	11	62	65	20
3	121	12	11	62	64	20
4	121	12	11	62	63	20

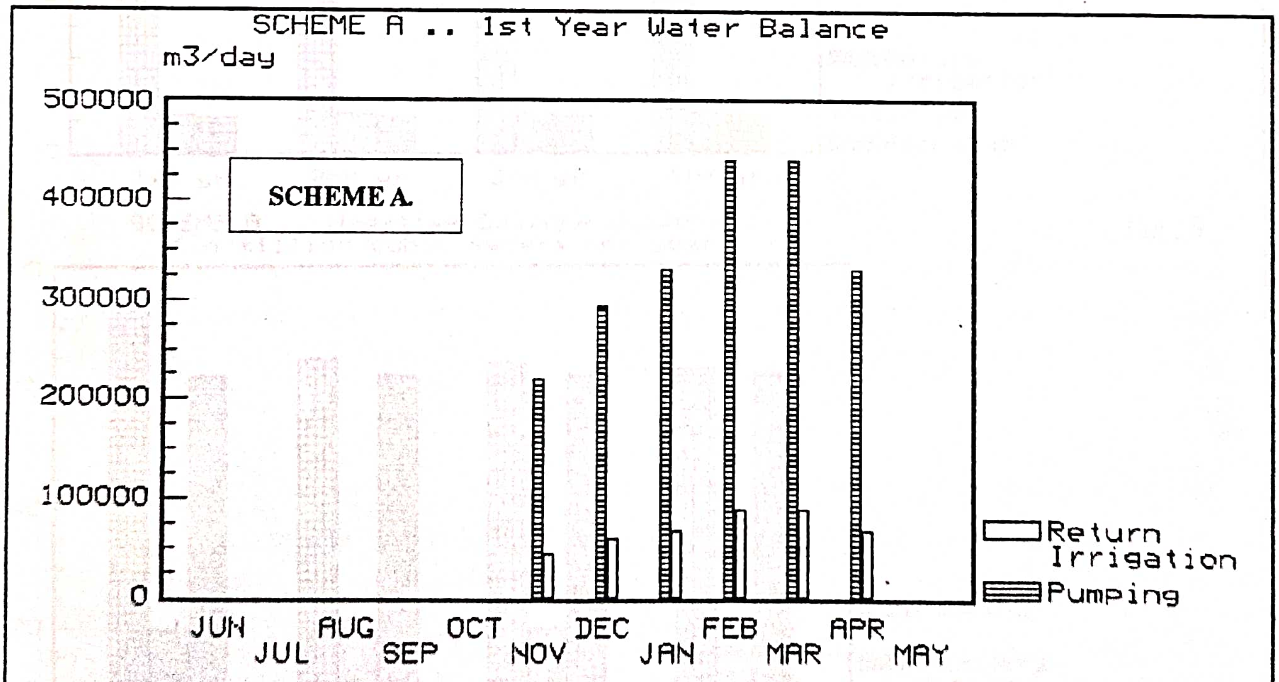


Fig.15

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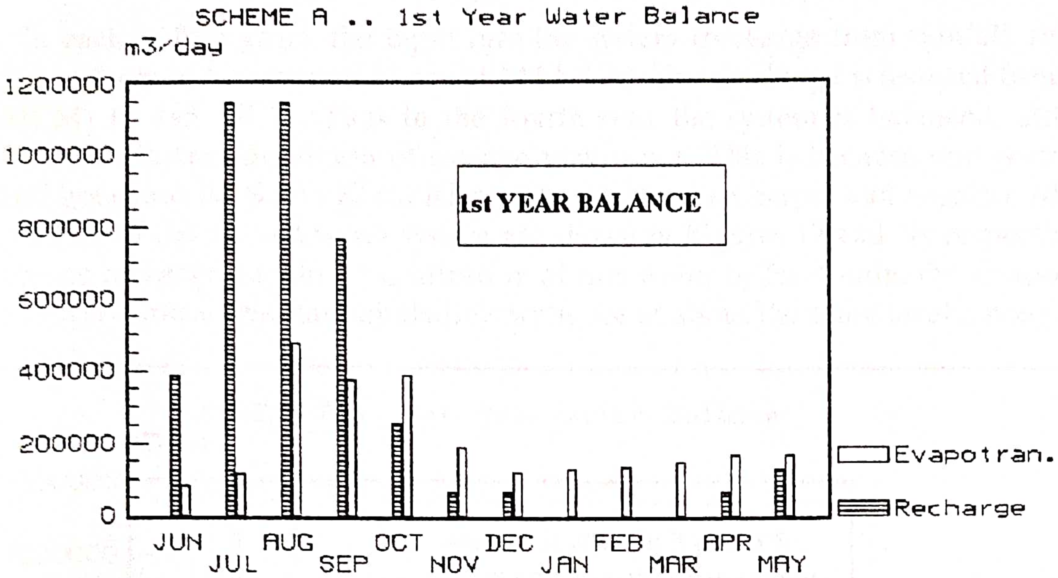


Fig.17

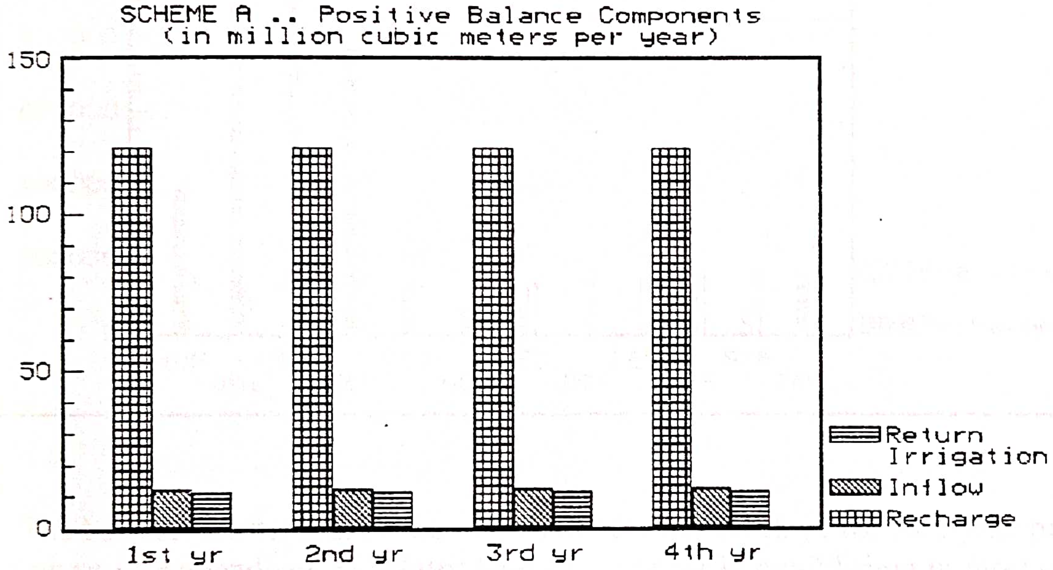
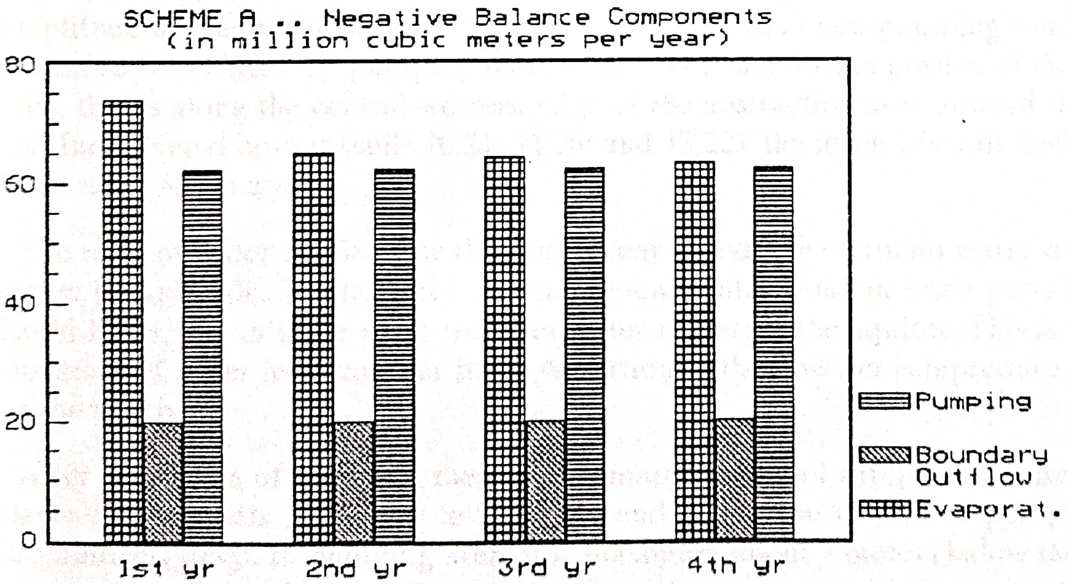
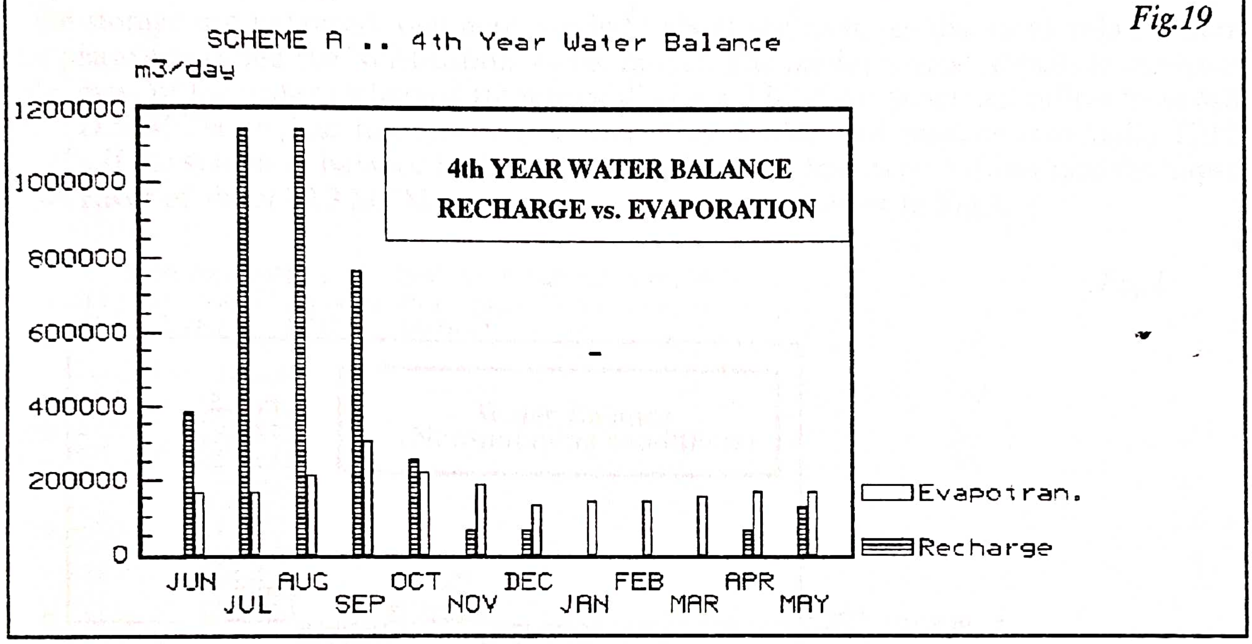


Fig.18



In each of four years, the input into the system (recharge from rainfall, return irrigation, inflow from hills) amounts to about 144 MCM. The discharge is reduced from first year (156 MCM) to 145 MCM. Thus in the fourth year the system is balanced, although in some localities further depletion of storage may occur. This is because one portion of recharge still goes into the Sapta Koshi River. The positive (recharge) and negative (discharge) components of the ground water system are shown in Figures 17 and 18, respectively. Evidently, among recharge, the direct infiltration of rain water by far dominates. Evaporation loss and artificial abstraction through shallow wells are at about the same level among discharge.

Fig.19



The best demonstration of the evolution of water levels in the four-year pumping scheme is given in Appendices 35. Water levels are almost in equilibrium in most of the area. The amplitude of fluctuation is much higher than under normal non-pumping conditions, but the system recovers after the pumping season ends. Yet, in a certain portion of the development area, that is along the central-western edge of the abstraction area, toward the Sapta Koshi and India-Nepal border (cells 10,21; 11,26; and 13,22), the levels are still declining at a rate of 20 cm to 50 cm a year.

The map of water levels after the fourth year of extensive ground water development as shown in Appendix 30, indicates that the ground water flows in some parts into the Sapta Koshi River, but in some parts the river water recharges the aquifer. This is clear from the curvature of water level contour lines. A portion of the flow net is reproduced in the sketch on the next page.

After four years of pumping there still remains plenty of saturated aquifer thickness, as shown in Appendix 37. Water level at the end of the fourth year of pumping is also not prohibitively deep. In pumping area, it is maximum about 7 meters below the land surface.

is deep, and out of evaporation reach. There is no rainfall to contribute significantly to recharge.

The second phase was that of unsteady-state calibration of the model in the period from May through September 1989. This is the period of the rise of water levels in the monsoon season. The rise is well documented in some 14 observation wells. The model produced water balance for the monsoon season. The recharge to aquifer dominates and as a result the levels are rising. This recharge is quantified by the model. 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 and depletion of the storage are balanced, one may conclude about the recharge-discharge relationship. This phase was called the "verification" of the model. The model indicated that, in one-year cycle, most of the water recharged from rainfall (120.6 MCM per year) and inflow from hill side (11.5 MCM) is lost through evaporation (83.6 MCM) and outflow into India (20.2 MCM). If the system in balance in the year of verification, there is an outflow into the Sapta Koshi River of about 28.3 MCM. This balance is graphically shown in Fig.1.

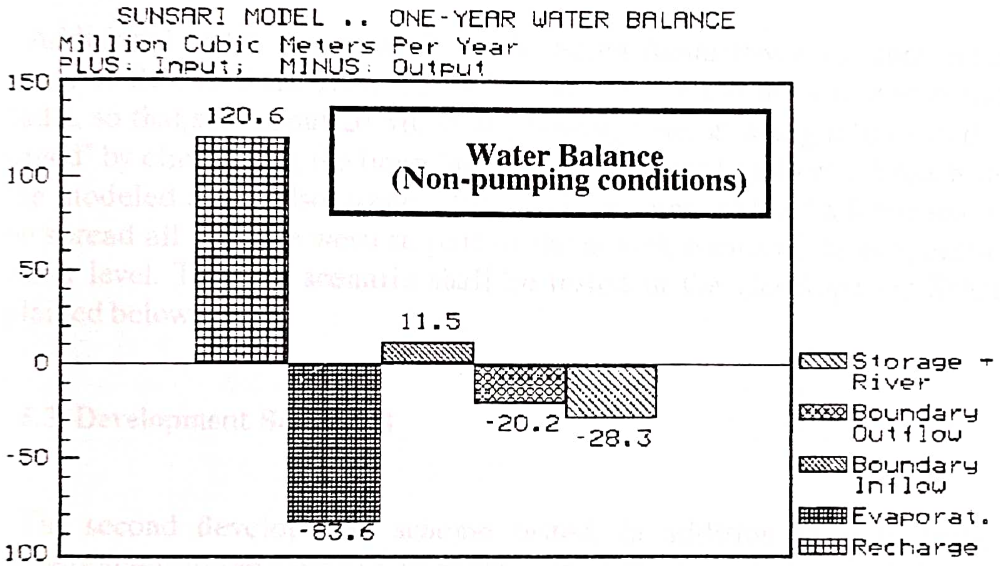


Fig.1

From water balance in one-year verification phase, one may conclude that a future ground water development from shallow aquifers may come mostly on expense of reduced evaporation, outflow into the Sapta Koshi River, and outflow into India. The annual evaporation loss, which amounts to about 83.6 MCM, can be reduced by lowering water levels to a depth that will prevent the losses. As indicated in appendices, the area with water table close to land surface is in the central part, north-west, and south-east. The outflow into the Sapta Koshi can be reduced or eliminated by pumping from shallow wells located along a stretch parallel to the river course. It is a favorable coincidence that along the left bank of the Sapta Koshi River the shallow aquifer in Sunsari district is most promising, having clean sand and gravel content and very high transmissivity of more than 1500 m^2/day. The outflow to India, of some 20.2 MCM per year, can be reduced or stopped altogether by pumping on a larger scale near the border.

(This is within the reach of suction of centrifugal pumps that are currently in use in Terai.) Only in isolated places the depth to water is close to 10 meters.

The scheme of development as tested herein was not quite successful in utilizing the evaporation loss. The loss was diminished from 83.6 MCM/year in a non-pumping year, to some 63 in the fourth year of pumping, 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 Sapta Koshi River.

It may be concluded that the scheme of development as tested in this phase of the modelling is quite acceptable, although most of parameters were on conservative, that is safe, side. It appears that such distribution of wells and their pumping rates are not the absolute development potential of the shallow ground water of Sunsari district.

Additional water can come from the Sapta Koshi River, or from preventing the ground water to flow into the river. Likewise, the scheme did not count with reduced outflow into India, so that still about 20 MCM are flowing without being intercepted. This could be "salvaged" by eliminating the boundary condition according to which this water still flows out of the modeled 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 B, which is explained below.

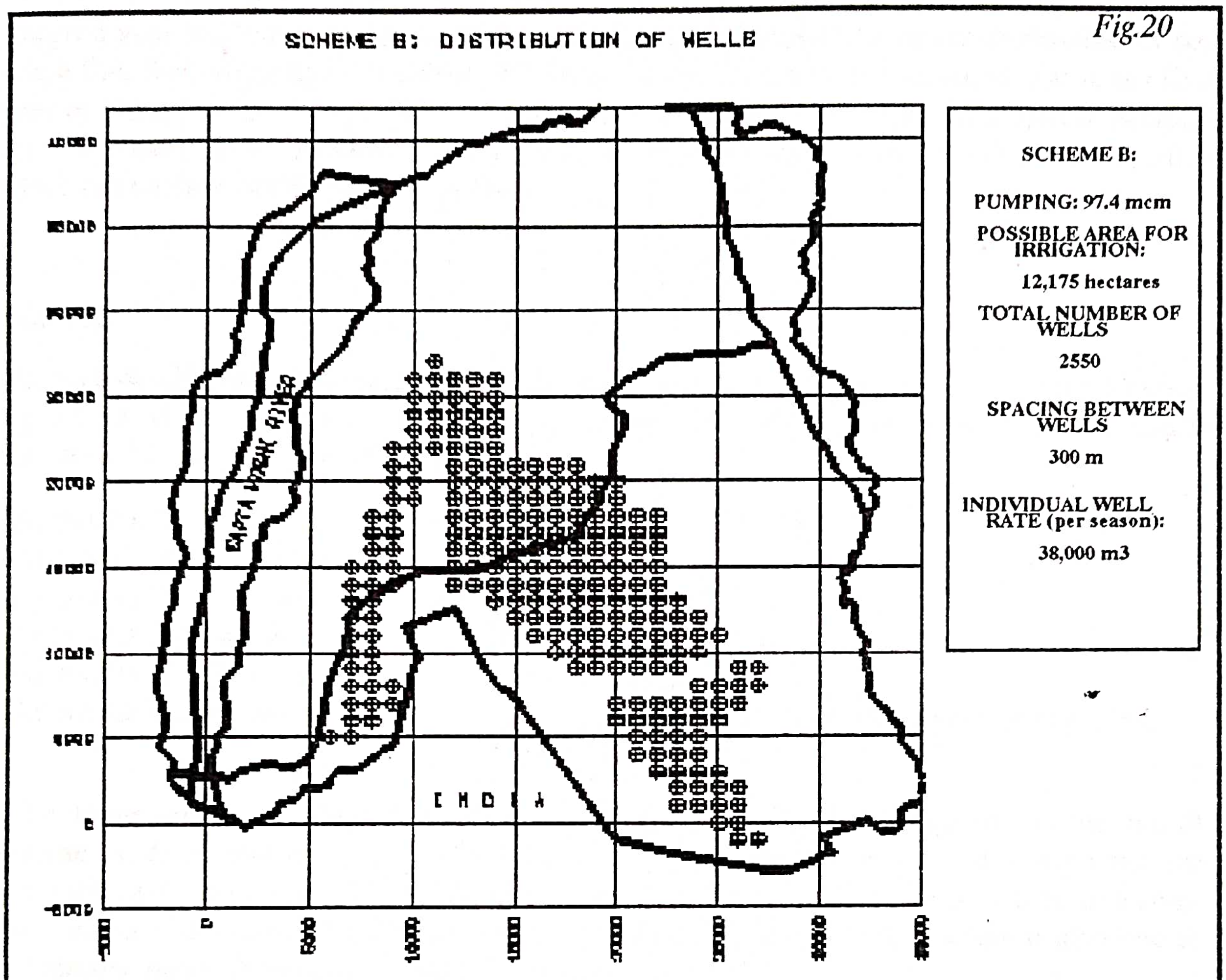
5.3. Development Scheme B

The second development scheme tested, in addition to wells from scheme A, some development to the west and to south-east of the district. Transmissivities in those areas are also high, more than 2000 m^2/day.

<u>Location and Area of Development.</u>

Pumping was added to cells west of Scheme A development, that is toward Sapta Koshi River, and south-west and south-east of Scheme A. Some wells were eliminated from former Scheme A. Thus the area involved in simulating abstraction from shallow aquifer is 232 km^2, as shown in Appendix 32, and in Fig. 20 at a reduced scale. Intentionally, wells have not been located closer to the river than 5 km, considering that (a) too optimistic conclusions would have been drawn from "induced" recharge, and (b) surface water irrigation is probably cheaper near the river banks. Yet, hydrogeologically, the area close to the river is considered as the best with respect to lithology and permeability of shallow aquifer and depth to water table.

Fig.20



Number of Pumping Cells and Wells

The number of pumping cells is 232. Using earlier calculation of spacing between wells and their individual discharges, this area could be covered with about 2550 wells, with wells spacing about 300 m. Same as in Scheme A, each cell is producing 420,000 m^3 per pumping season of five months. With an average agricultural demand of 8,000 m^3/ha/season, with 420,000 m^3 one may irrigate about 52 ha, or one half of the total area in each square kilometer. If wells are spaced at 300 m (11 wells in one sq.km), each well should be pumping about 38,000 m^3 in a season of five months, which means that one well may irrigate between 4 and 5 hectares.

Underlying Assumptions

Almost the same assumptions apply to this scheme of development as to the Scheme A. The difference is the treatment of outflow into India. It is expected that levels shall be lowered near the Indian border, and that the flow gradient shall be either diminished or become flat, thus stopping any outflow into India. In the model, it was assumed that in the first year of pumping the outflow shall be reduced to one half of what was simulated in Scheme A; in second year to another one half; and in the third year it will be halved again; after which the outflow shall cease altogether.

Results

In each of 232 cells the pumping rate amounts to 420,000 m^3/season. Thus, the total pumping is 97.4 MCM per season, nonuniformly spread from one month to another. The results are shown in several Appendices:

Appendix 33 .. Final water levels after four years of pumping.
Appendix 34 .. Drawdown after 4 years.
Appendix 35 .. Hydrographs in selected cells.
Appendix 36 .. Depth to water table after four years of pumping.
Appendix 37 .. Saturated thickness at the end of fourth year.
Appendix 38 .. Evaporation loss in individual cells at the end of fourth year of pumping.

The water level map (Appendix 33) is not materially different that the one at the end of Scheme A development (Appendix 27). The levels within the area of development are generally one to two meters lower in Scheme B. The same conclusion comes after one compares maps of drawdowns after four years in Schemes A and B. The decline is also one to two meters higher in Scheme B than in Scheme A.

However, hydrographs in the group of appendixes 35 indicate that almost within the whole development area the levels are in equilibrium, or experience almost negligible drop. There is a small area in southwest toward the river (cells 7,21 and 7,29) and east of Lauki (cell 16,28) in which levels are not stabilized after four years of pumping. Even in these cells the drop is not greater than 25 cm per each additional year of pumping. Only at the very border with India (cell 11,26), the decline is still half a meter a year. Probably, the large-scale shallow ground water development could be reduced somewhat near the state border (Lauki).

The depth to water as shown in Appendix 36 is at maximum between 8 and 10 m, in the development area. This may preclude the use of centrifugal pumps and require the use of electrical submersible or vertical turbine pumps. However, a solution may be found in digging 2 meters shaft and placing the suction portion of the pump in the shaft. Thus the water lift might be kept within the suction limit of centrifugal pumps, that is about 7 meters.

The saturated thickness of shallow aquifer, as shown in Appendix 37, is still high. Actually, most of decline of water head occurs within the semiconfined layer overlying shallow aquifer. Thus the loss of saturated thickness is marginal.

As will be shown in the balance that follows, there is still quite a high evaporation loss. Only with further lowering of water table, this loss can be eliminated.

The water balance is reproduced only for the last, fourth, year of pumping.

STEP	RECHARGE m3/day	PUMPING m3/day	EVAPORAT. m3/day	RET. IRR. m3/day	INFLOW m3/day	OUTFLOW m3/day
37	-382920.	0.	161010.	0.	-31900.	0.
38	-1148760.	0.	161067.	0.	-31900.	0.
39	-1148760.	0.	239946.	0.	-31900.	0.
40	-765840.	0.	315591.	0.	-31900.	0.
41	-255280.	0.	285923.	0.	-31900.	0.
42	-63820.	348000.	200043.	-69600.	-31900.	0.
43	-63820.	464000.	150870.	-92800.	-31900.	0.
44	0.	522000.	153269.	-104400.	-31900.	0.
45	0.	696000.	155969.	-139200.	-31900.	0.
46	0.	696000.	173831.	-139200.	-31900.	0.
47	-63820.	522000.	180140.	-104400.	-31900.	0.
48	-127640.	0.	187941.	0.	-31900.	0.

The balance components are summarized in figures 21 (positive) and 22 (negative). The recharge is the same as in Scheme A, 121 MCM per year. Pumping is increased from 62 MCM to 97.4 MCM. Evaporation loss is about the same, 69.2 MCM. Inflow across the northern model boundary, that is from hill side, is the same, 11.5 MCM, while the outflow to India is nil in the fourth year.

Fig.21

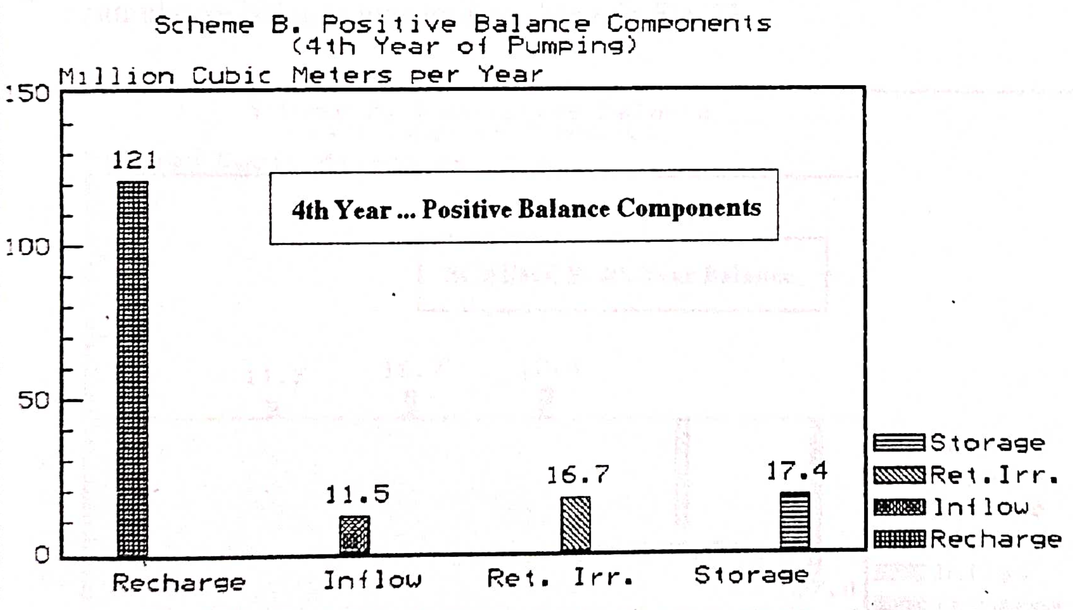
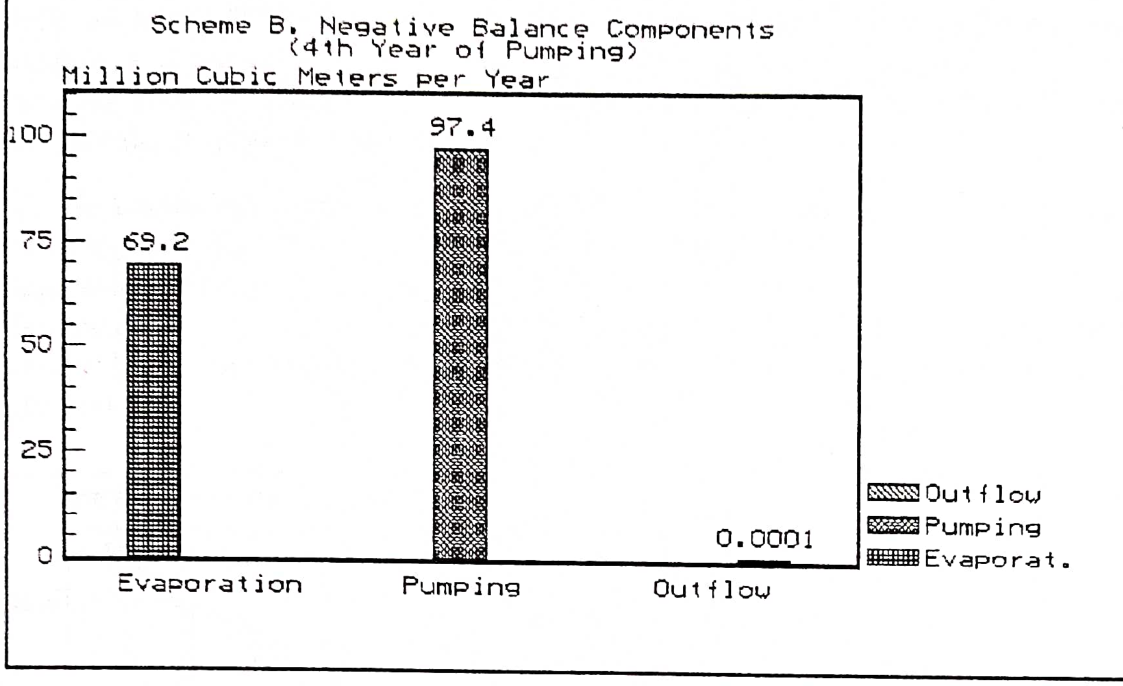


Fig.22

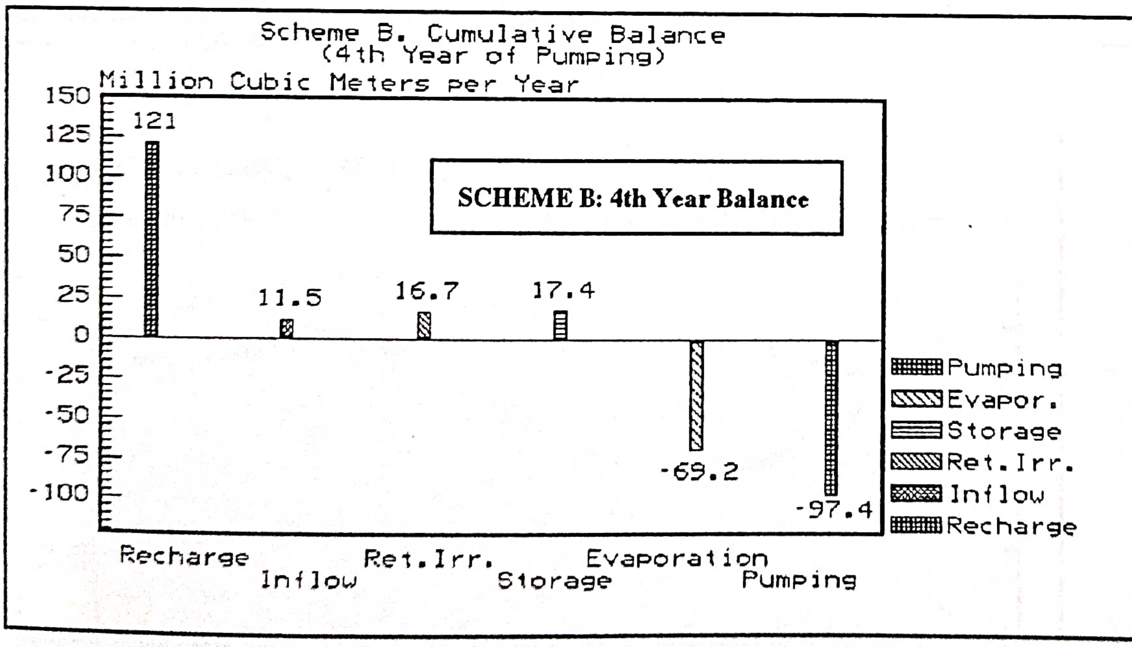


Thus the balance equation may look as follows:

```
Recharge + Inflow + Ret.Irr. = Evaporation + Pumping +/- Storage Change
  121    +  11.5  +   16.7   =     69.2    +   97.4  -      17.4   MCM/yr
```

The cumulative balance may look as shown in Fig. 23.

Fig.23



The deficit of about 17.4 MCM per year may come from two sources: (a) contribution from the Sapta Koshi river flow, (b) from storage, which is still being used. The ultimate balance, with extended time of abstraction, can come either from the river or from inflow from the hill side. The volume of 17.4 MCM/year is about 550 l/sec, which is negligent considering the average river flowrate.

Several more figures illustrate the evolution of cone of depression after the fourth year of pumping, and position of water table within shallow aquifer geometry. Figures 24 and 25 demonstrate the depression, and figures 26 and 27 geometry. In the latter two, one may see that water level (head) is still in some parts above the top of shallow aquifer, while in some parts it has barely entered the aquifer. Thus the original saturated thickness is still mostly preserved.

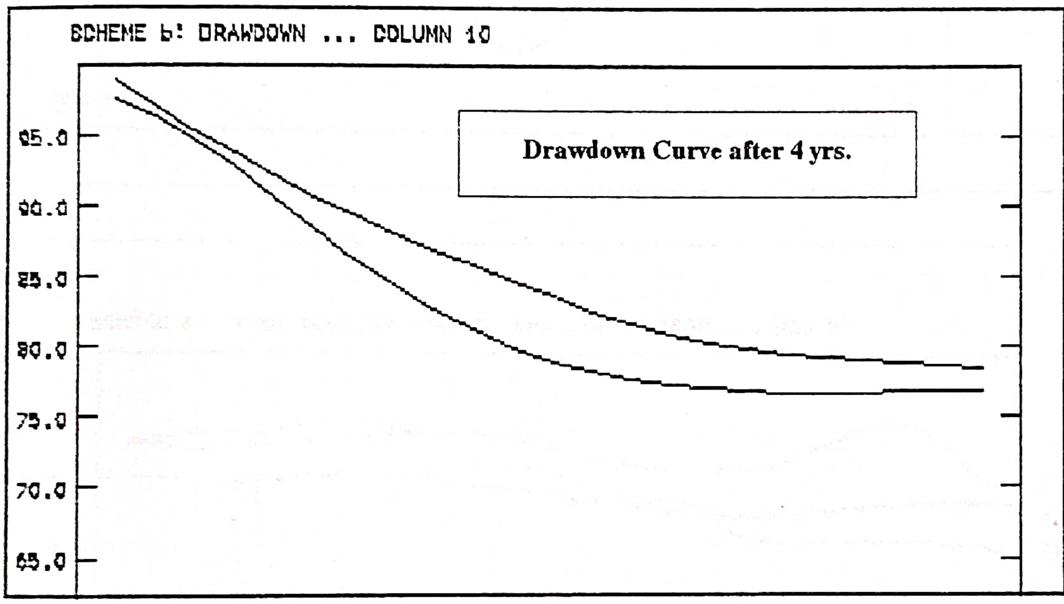


Fig.24

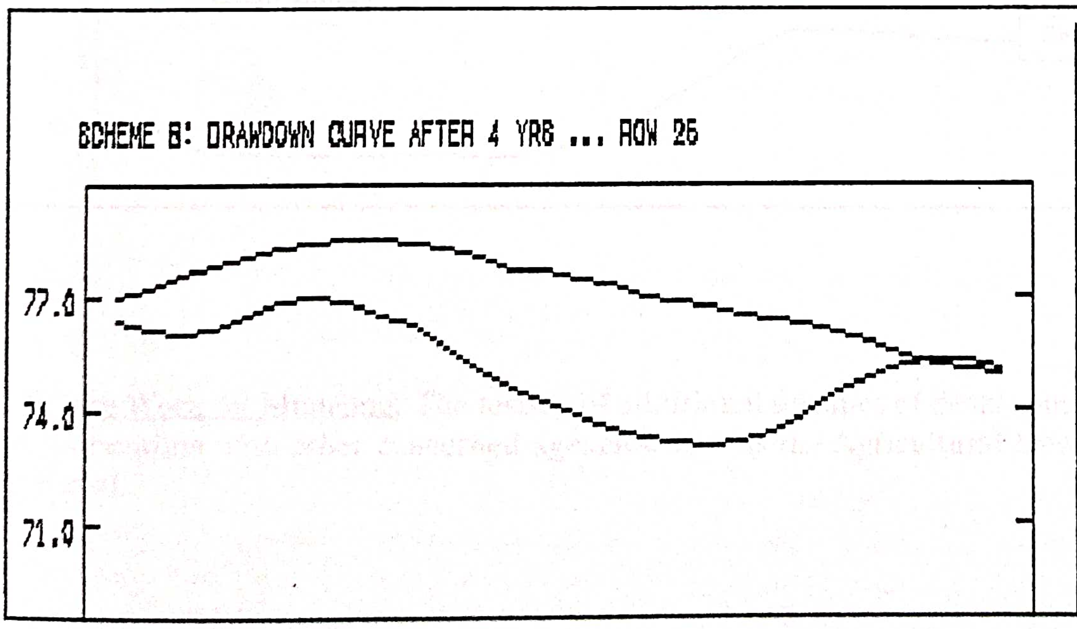


Fig.25

Fig.26

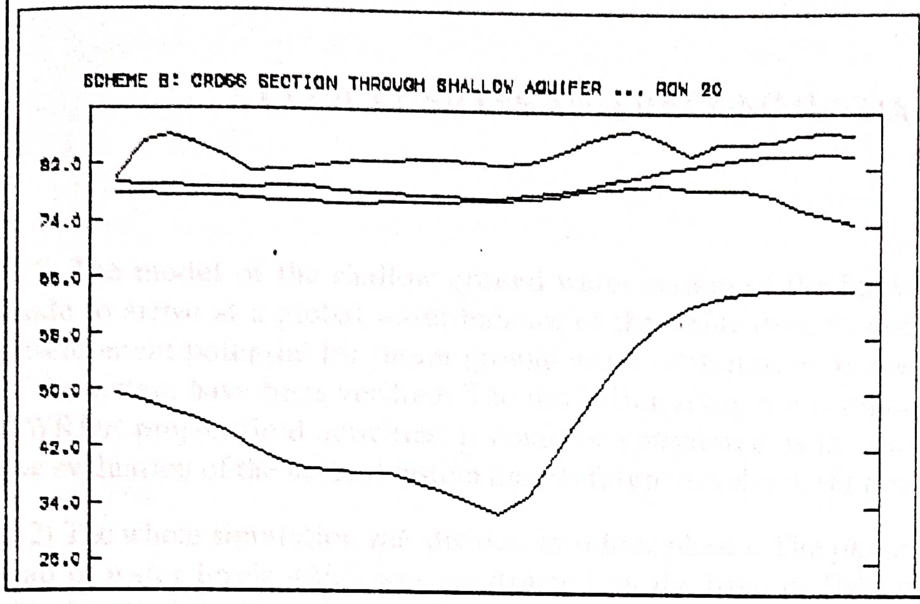
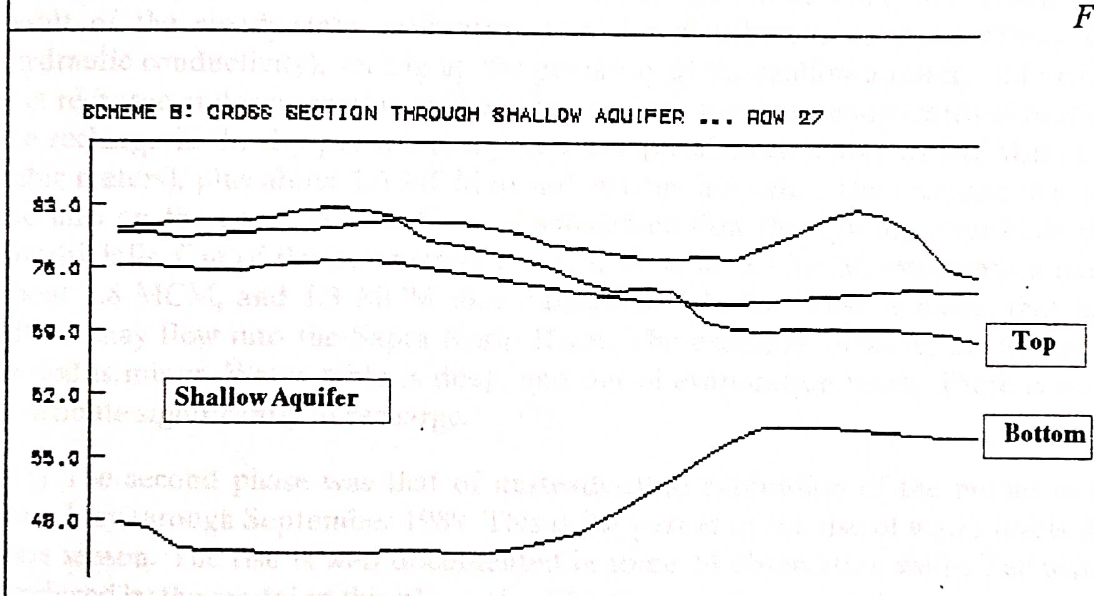


Fig.27



Future Work on Modeling. The testing of additional schemes of development can be done in cooperation with other concerned agencies, such as the Agricultural Development Bank of Nepal.

7. CONCLUSIONS AND RECOMMENDATIONS

(1) The model of the shallow ground water system of the Sunsari district was primarily made to arrive at a global water balance of the whole district, 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.

(2) The whole simulation was divided into four phases. The phase I was to match an initial map of water levels which was constructed on the basis of field monitoring in May 1989. 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 in the dry portion of a year was equivalent to about 2.1 MCM/month (million cubic meters), plus about 1.6 MCM as inflow from hill sides. The recharge that comes from the hills on the north, is in a form of subsurface flow through dry river beds that cut the Siwalik hills. Out of this cumulative recharge of some 3.7 MCM, evaporation may consume about 1.8 MCM, and 1.3 MCM may outflow into India. What remains, that is about 0.6 MCM, may flow into the Sapta Koshi River. The exchange of water at the end of the dry period is minor. Water table is deep, and out of evaporation reach. There is no rainfall to contribute significantly to recharge.

(3) The second phase was that of unsteady-state calibration of the model in the period from May through September 1989. This is the period of the rise of water levels in the monsoon season. The rise is well documented in some 14 observation wells. The water balance produced by the model in this phase of calibration may look as follows.

The total input of water into the shallow ground water system in four monsoon months between June and September of 1989 is equal to about 107 MCM (million cubic meters). Out of this volume, about 103.2 MCM come from direct infiltration of rain, and 3.8 MCM come as inflow into the shallow ground water system from the hill sides. Clearly, the infiltration of rainfall is much superior to the inflow from hills. (This latter may be underestimated, or it is coupled with direct recharge from infiltrated rainfall.)

The total discharge of water from the aquifer in four-month period amounts to about 38.1 MCM, out of which to evaporation loss (coupled with some minor pumping from shallow wells) goes 31.4 MCM and to outflow across model boundaries to India another 6.7 MCM. Again, the evaporation loss outweighs the outflow into India by the factor of almost 5. What remains, i.e. 69 MCM, may either fill up the storage (levels in September 1989 are much higher than in May 1989), or outflow into the Sapta Koshi River.

(4) 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. The model indicated that, in one-year cycle, most of the water recharged from rainfall (120.6 MCM per year) and inflow from hill side (11.5 MCM) is lost through evaporation (83.6 MCM) and outflow into India (20.2 MCM). If the system was in balance in the year of verification, there is an outflow into the Sapta Koshi River of about 28.3 MCM.

(5) The modeling study results have corrected the preliminary balance suggested in Technical Report No. 10. There, the cumulative recharge from rainfall and inflow into the model from hill sides was estimated at about 200 MCM, while the model confirmed only 132 MCM. Outflow into India was suggested at about 29 MCM, while the model "worked" with 20 MCM. From water balance in one-year verification phase, one may conclude that a future ground water development from shallow aquifers may come mostly on expense of reduced evaporation, outflow into the Sapta Koshi River, and outflow into India. The annual evaporation loss, which amounts to about 83.6 MCM, can be reduced by lowering water levels to a depth that will prevent the losses. As indicated in appendices, the area with water table close to land surface is in the central part, north-west, and south-east. The outflow into the Sapta Koshi can be reduced or eliminated by pumping from shallow wells located along a stretch parallel to the river course. It is a favorable coincidence that along the left bank of the Sapta Koshi River the shallow aquifer in Sunsari district is most promising, having clean sand and gravel content and very high transmissivity of more than 1500 m^2/day. The outflow to India, of some 20.2 MCM per year, can be reduced or stopped altogether by pumping on a larger scale near the border.

(6) With the total active model area of about 892 km^2, and an average annual rainfall of 1700 mm, the total volume of rain in an average year is about 1465 MCM. Out of this about 132 MCM recharges the shallow aquifer, which is only 9% on average. In areas where the near-the-surface layer is more permeable, this percentage may be higher, but there are many places in which direct infiltration of rainfall is low because of extensive impermeable surface cover. The overall percentage of 9 is important conclusion of this study, which invalidates earlier reported values in former studies of over 20 and even 30%.

(7) 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 Sunsari model was shown to correctly duplicate the behavior of shallow water table in the period from May through September 1989.

(8) After several check runs, it was decided to fully test two development scheme. The scheme A included 147 cells, each covering 1 km^2. In each cell, a same amount of 420,000 m^3 was pumped in the 5-month period. Thus the total development amounted to about 62

MCM/season. Out of this 20% were returned back to the system in the form of return irrigation. The total pumping of 61.7 MCM is just below one half of the maximum possible "safe yield" of the district, without induced recharge from the river.

The total volume of pumped water is sufficient to irrigate about 7,750 ha provided that an average agricultural demand is about 8,000 m^3/ha. With 420,000 m^3 per one square kilometer, one may irrigate about 52 ha, or one half of the total area in each square kilometer. If wells are spaced at 300 m (11 wells in one sq.km), each well should be pumping about 38,000 m^3 in a season of five months, which means that one well may irrigate between 3 and 4 hectares.

The criteria for locating the wells were the following: (a) acceptable transmissivity, (b) water table close to the surface, (c) location not very close to the river. With the total area involved in testing equal to 147 km^2, assuming the spacing between wells of 300 m, the total number of wells could be as high as 1600.

The development scheme was tested over a period of four years, on a cyclic basis: pumping in 5 dry months (more in February and March than in other months), idling in the remaining seven months.

(9) Since the results were encouraging, more wells were located in the development labeled Scheme B. The total cells are 232, the area covered by development 232 km^2, and the total abstraction about 97.4 MCM. With the spacing of 300 m among wells, the total number of wells may be about 2500. The volume of water may be sufficient to irrigate about 12,000 ha, provided that an average agricultural demand is about 8,000 m^3/ha/season.

The water balance in the Scheme B shows the major main points. The recharge is the same as in Scheme A, 121 MCM per year. Pumping is increased from 62 MCM to 97.4 MCM. Evaporation loss is about the same, 69.2 MCM. Inflow across the northern model boundary, that is from hill side, is the same, 11.5 MCM, while the outflow to India is nil in the fourth year.

Thus the balance equation may look as follows:

```
Recharge + Inflow + Ret.Irr. = Evaporation + Pumping + Storage Change
121      + 11.5   + 16.7     = 69.2        + 97.4    - 17.4 MCM/yr
```

The deficit of about 17.4 MCM per year may come from two sources: (a) contribution from the Sapta Koshi river flow, (b) from storage, which is still being used. The ultimate balance, with extended time of abstraction, can come either from the river or from inflow from the hill side. The volume of 17.4 MCM/year is about 550 l/sec, which is negligent considering the average river flowrate.

(10) The model of Sunsari 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. Although previous reports have speculated about the maximum permissible number of shallow wells in various districts of the Terai. this modelling study formulated not only the number of wells, but suggested the area which may be favorable 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 Sapta Koshi River. This last may be the weak point of the study. It is recommended to establish either one additional river stage (and flow) gauging stations on the Sapta Koshi (one near the border with India), or to drill two shallow observation wells at the river bank to monitor the river stage.

(11) As a final conclusion, Sunsari district offers quite a high development potential for shallow-ground-water-sustained irrigation. Abstraction from phreatic aquifer has a side beneficial effect of providing for drainage, and reducing the risk of water logging and salinization of soils.

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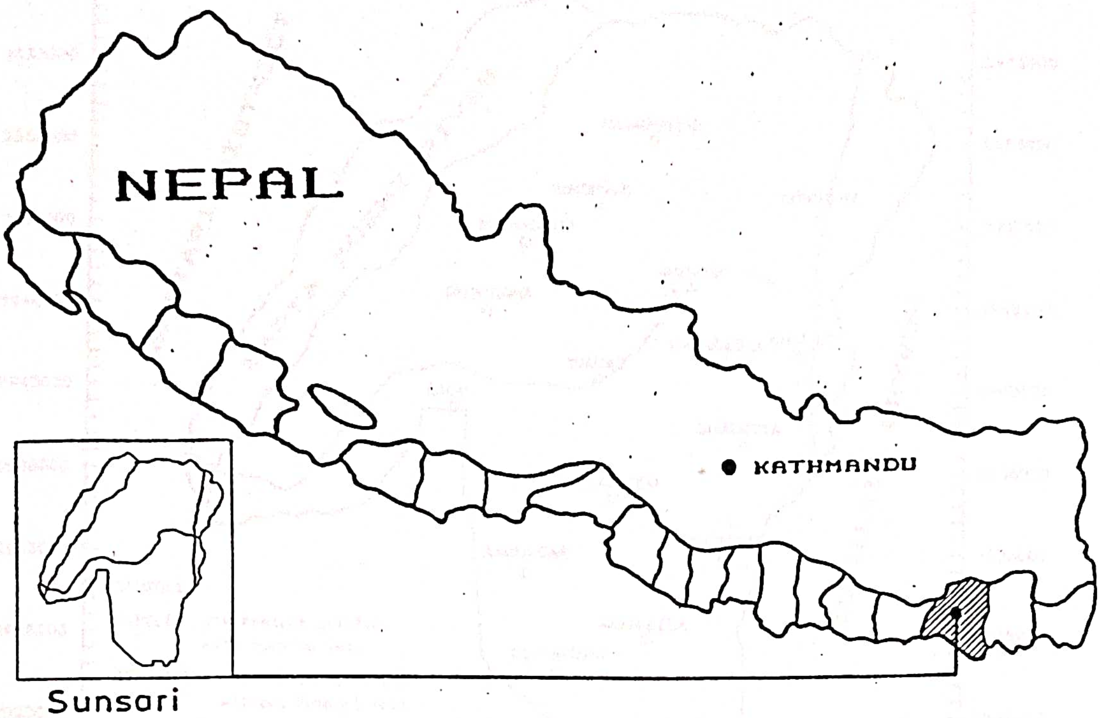
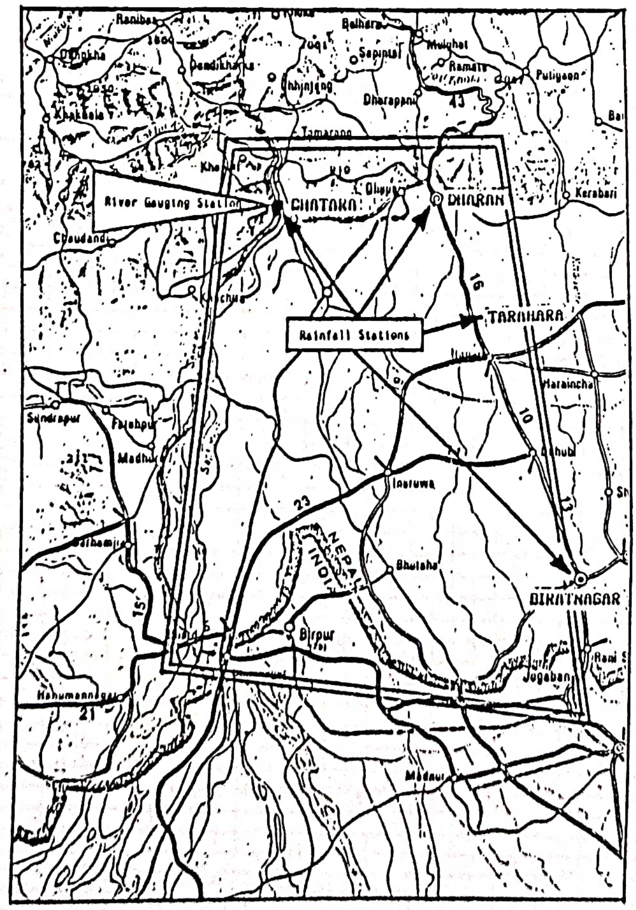
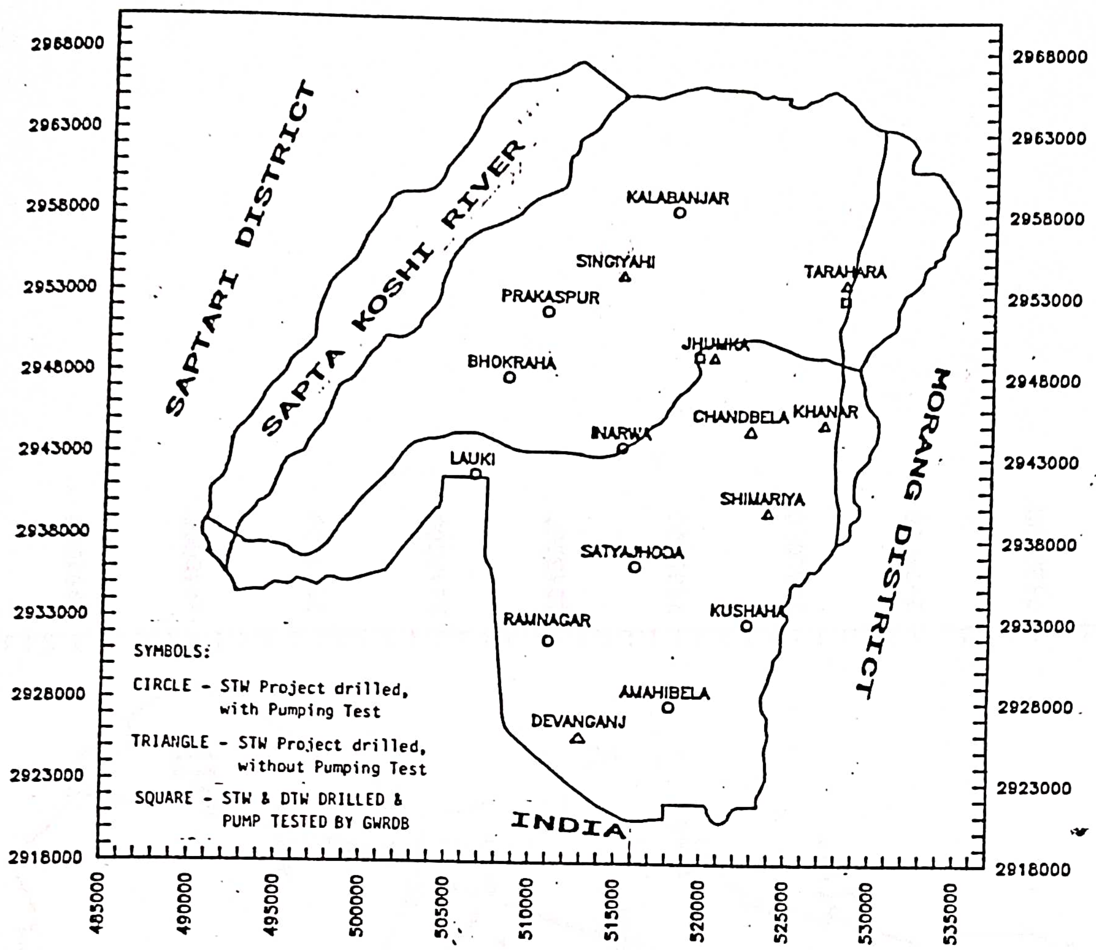


APPENDIX 1



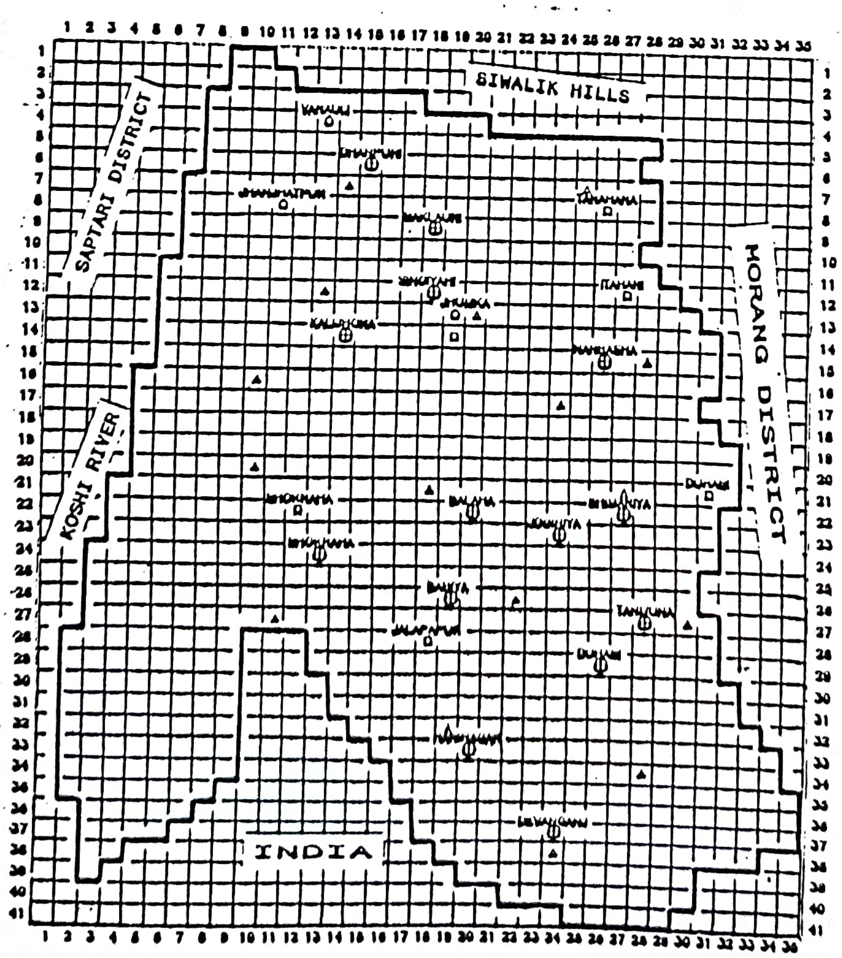
APPENDIX 2

SUNSARI PROJECT WELLS AND PUMPING TESTS



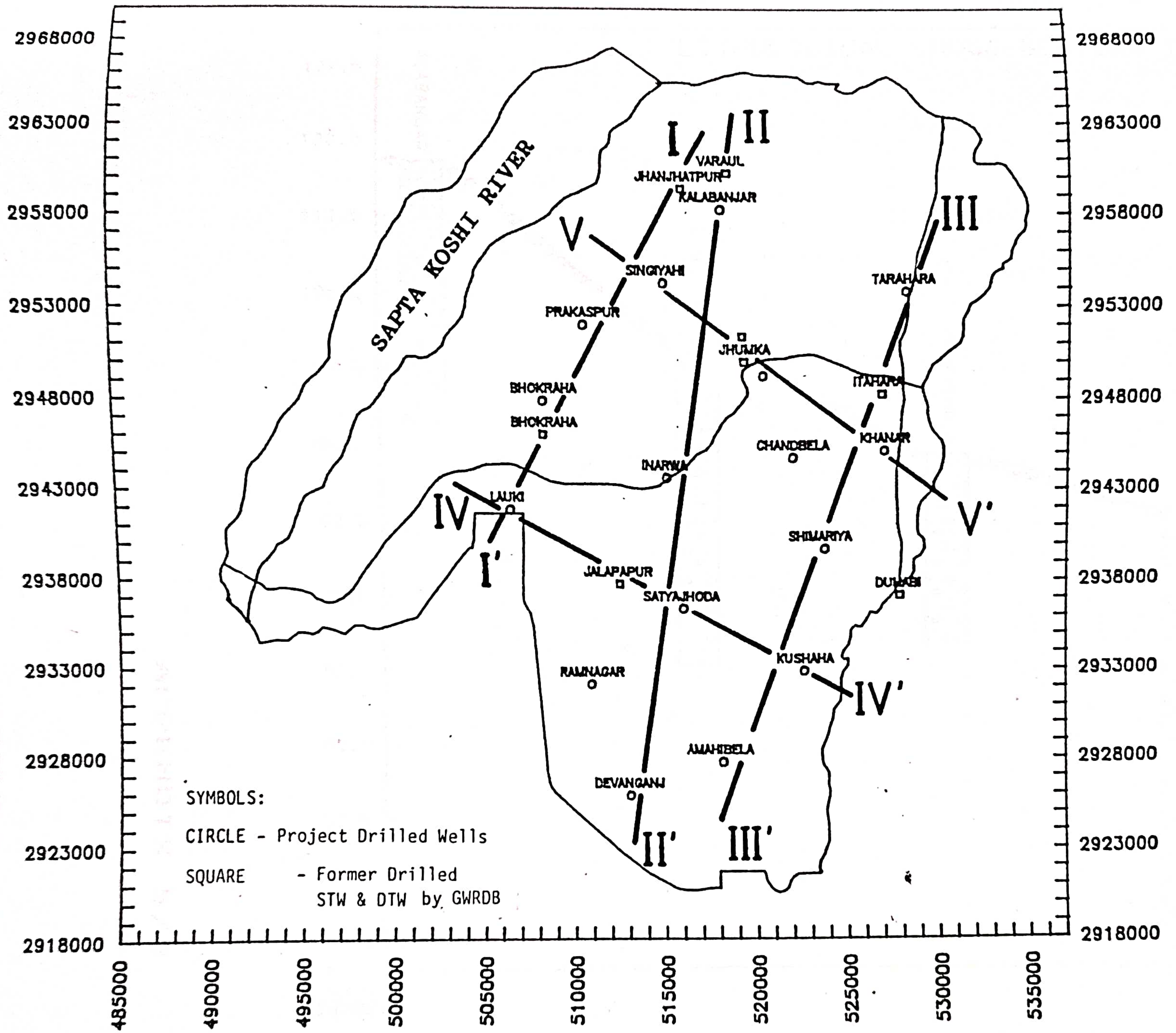
APPENDIX 3

SUNSARI: MATHEMATICAL MODEL NETWORK



APPENDIX 4

APPENDIX 5/1


SAPTA KOSHI RIVER
I
II
III
IV
V
I'
II'
III'
IV'
V'
VARAUL
JHANJHATPUR
KALABANJAR
SINGIYAHI
PRAKASPUR
BHOKRAHA
BHOKRAHA
JHUMKA
TARAHARA
ITAHARA
KHANAR
CHANDBELA
INARWA
LAUKI
SHIMARIYA
JALAPAPUR
SATYAJHODA
DULARI
KUSHAHA
RAMNAGAR
AMAHIBELA
DEVANGANJ
SYMBOLS:
CIRCLE - Project Drilled Wells
SQUARE - Former Drilled STW & DTW by GWRDB
2968000
2963000
2958000
2953000
2948000
2943000
2938000
2933000
2928000
2923000
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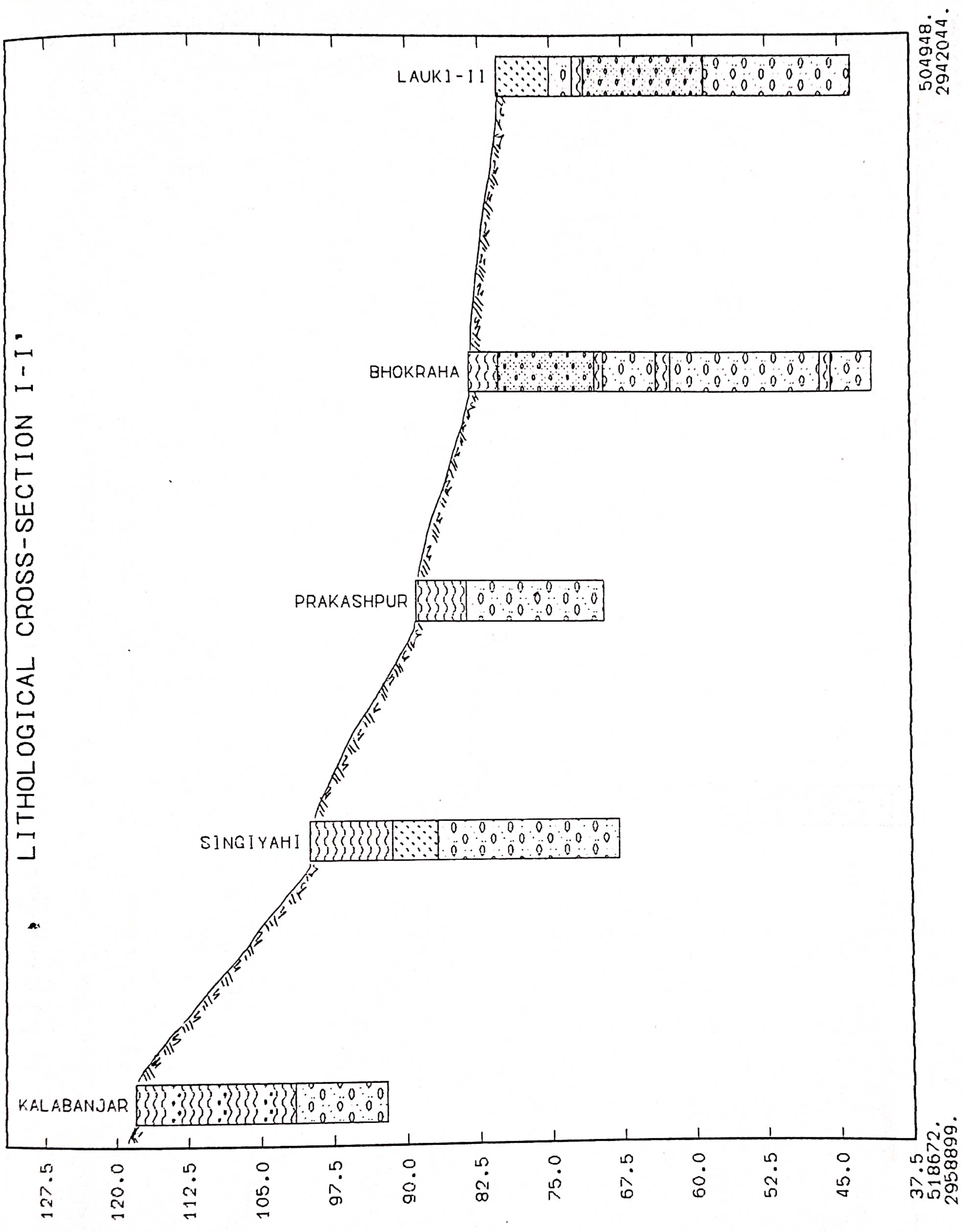
520000
525000
530000
535000


LITHOLOGICAL CROSS-SECTION I-I'
LAUKI-II
BHOKRAHA
PRAKASHPUR
SINGIYAHI
KALABANJAR
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2942044.
518672.
2958899.
127.5
120.0
112.5
105.0
97.5
90.0
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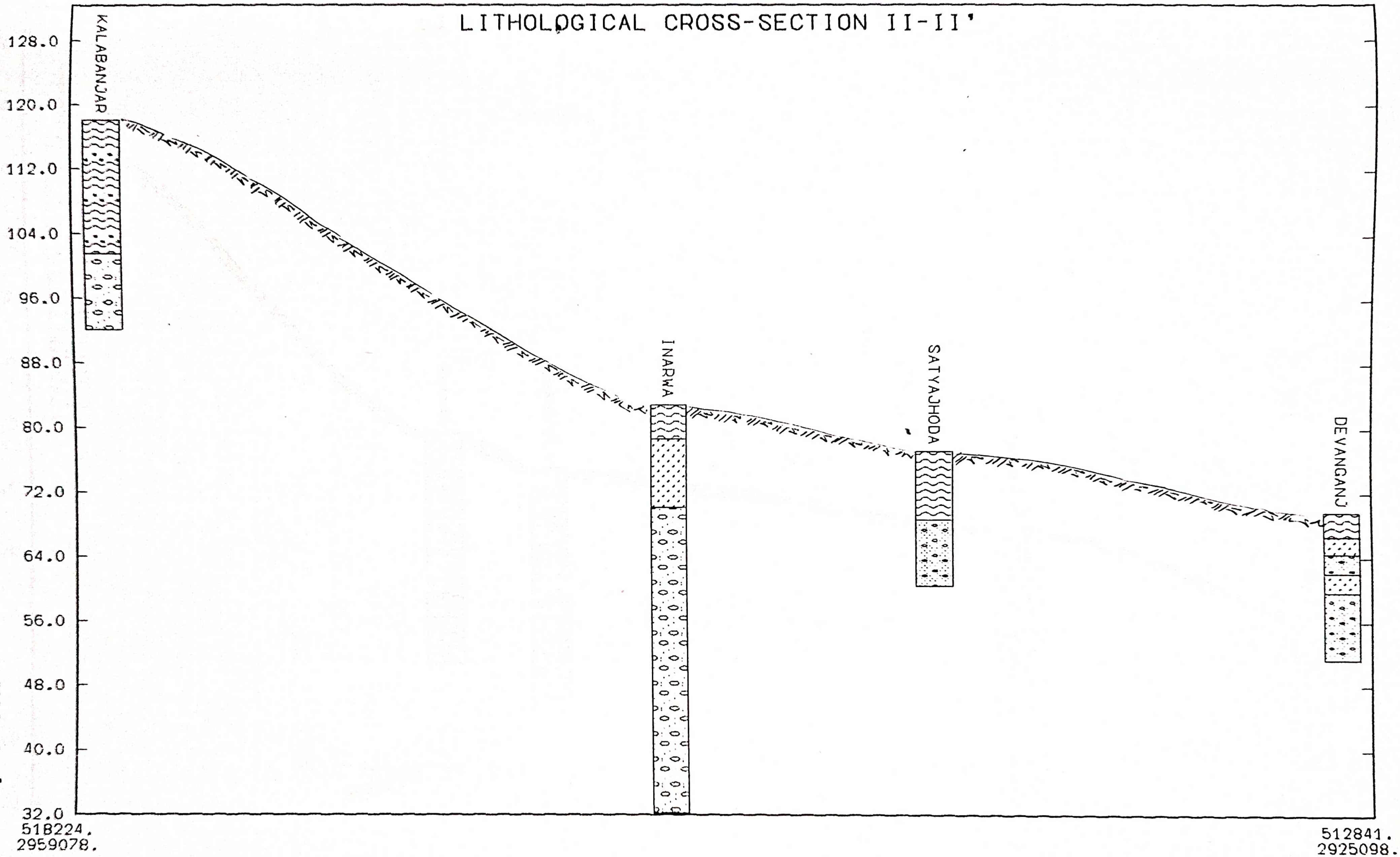
75.0
67.5
60.0
52.5
45.0
37.5

APPENDIX 5/2



LITHOLOGICAL CROSS-SECTION II-II'
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INARWA
SATYAJHODA
DEVANGANJ
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120.0
112.0
104.0
96.0
88.0
80.0
72.0
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56.0
48.0
40.0
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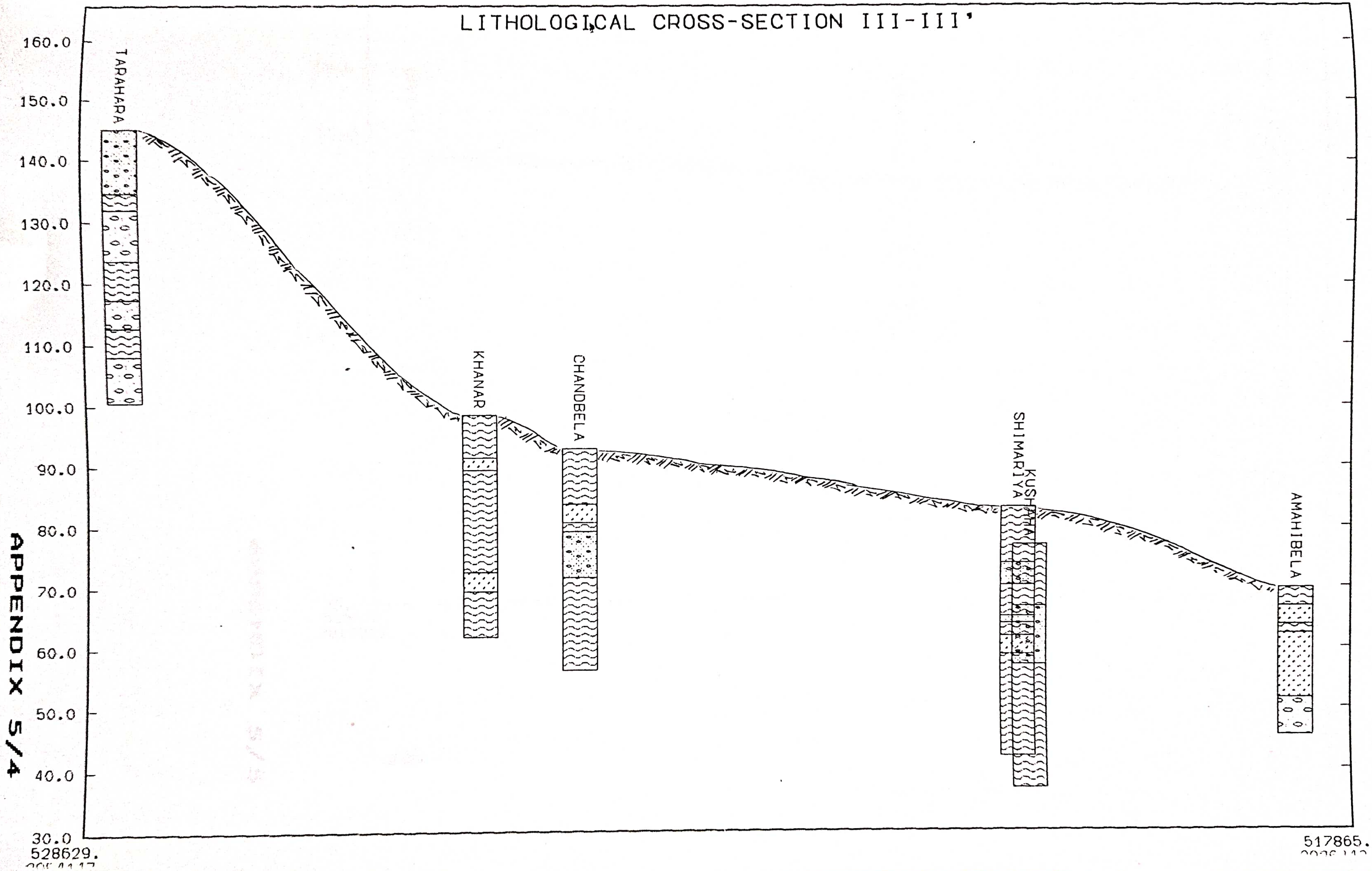
2925098.

APPENDIX 5/3


LITHOLOGICAL CROSS-SECTION III-III'
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120.0
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100.0
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70.0
60.0
50.0
40.0
30.0
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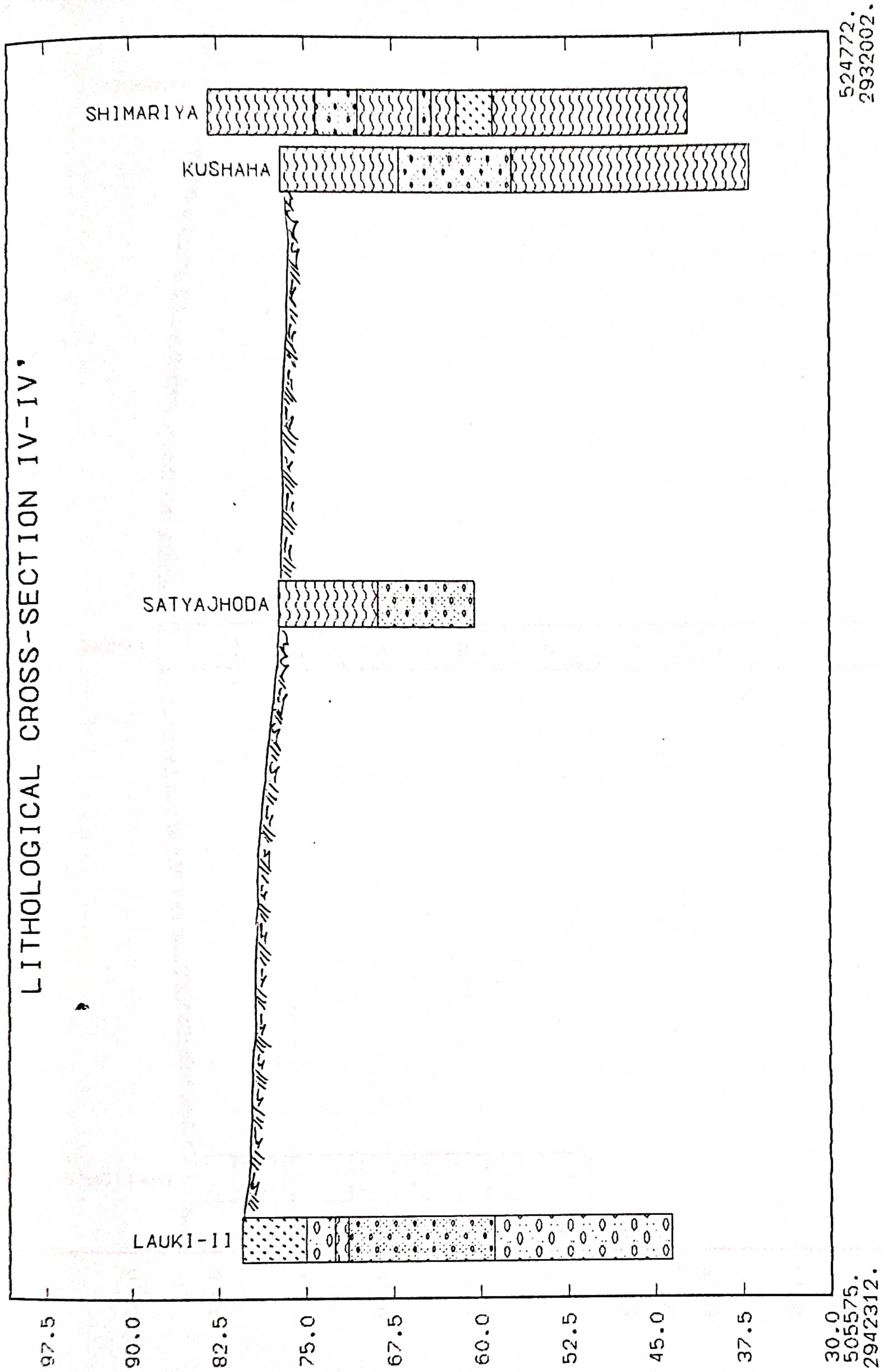
TARAHARA
KHANAR
CHANDBELA
SHIMARIYA
KUSHAHA
AMAHIBELA

APPENDIX 5/4



LITHOLOGICAL CROSS-SECTION IV-IV'
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KUSHAHA
SATYAJHODA
LAUKI-II
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2942312.
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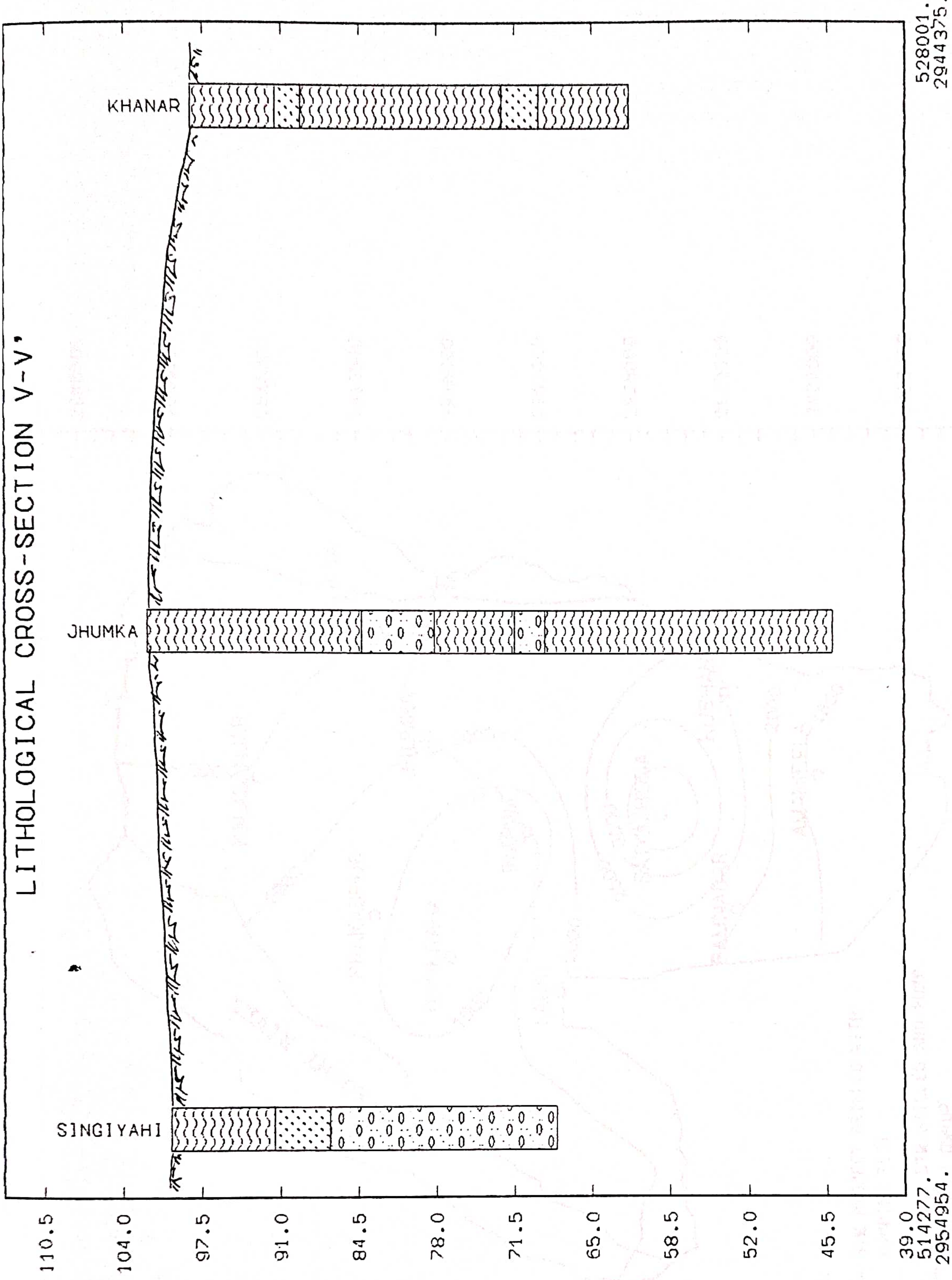
60.0
52.5
45.0
37.5
30.0

APPENDIX 5/5


LITHOLOGICAL CROSS-SECTION V-V'
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JHUMKA
SINGIYAHI
110.5
104.0
97.5
91.0
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71.5
65.0
58.5
52.0
45.5
39.0
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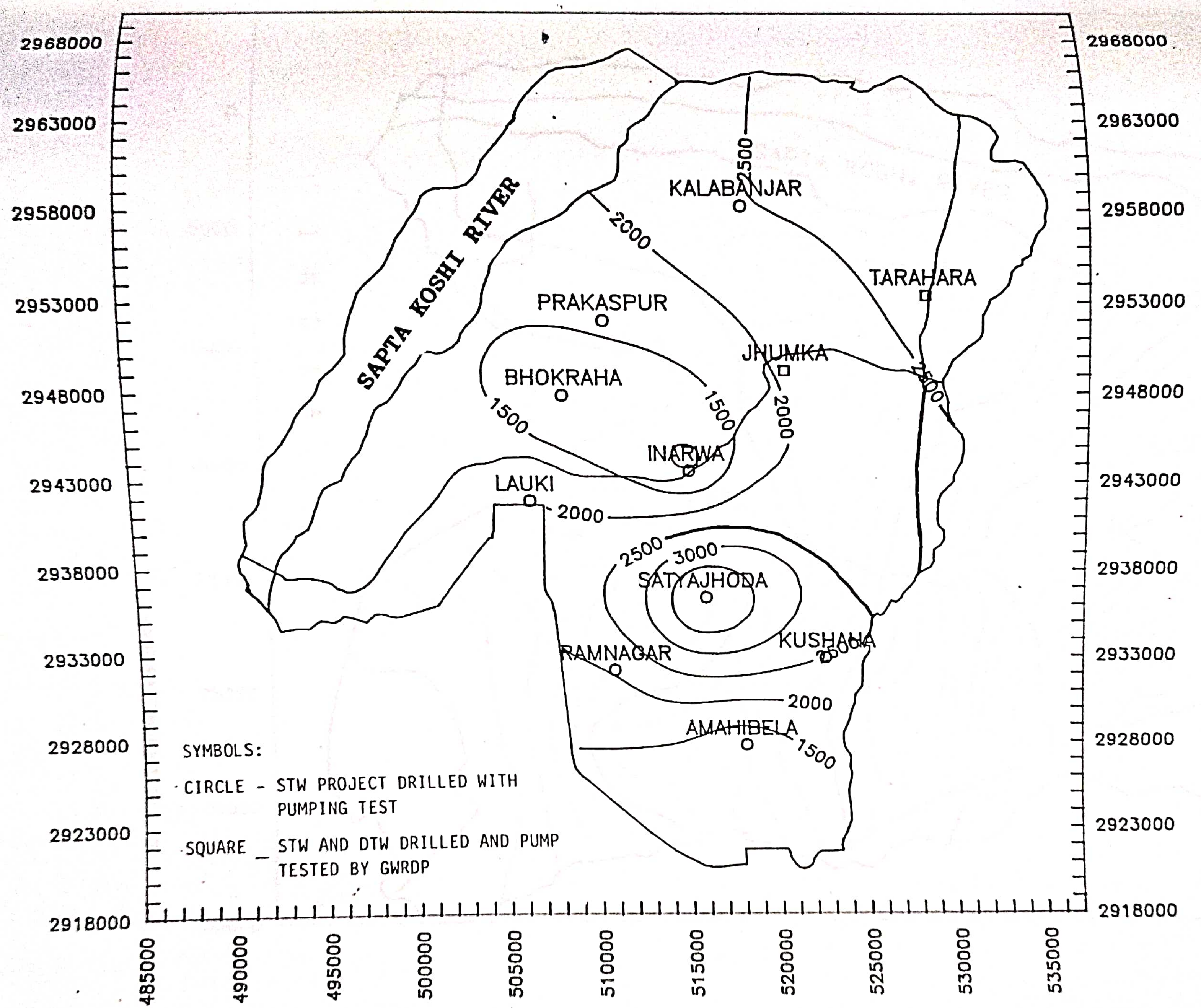
2944375.

APPENDIX 5/6

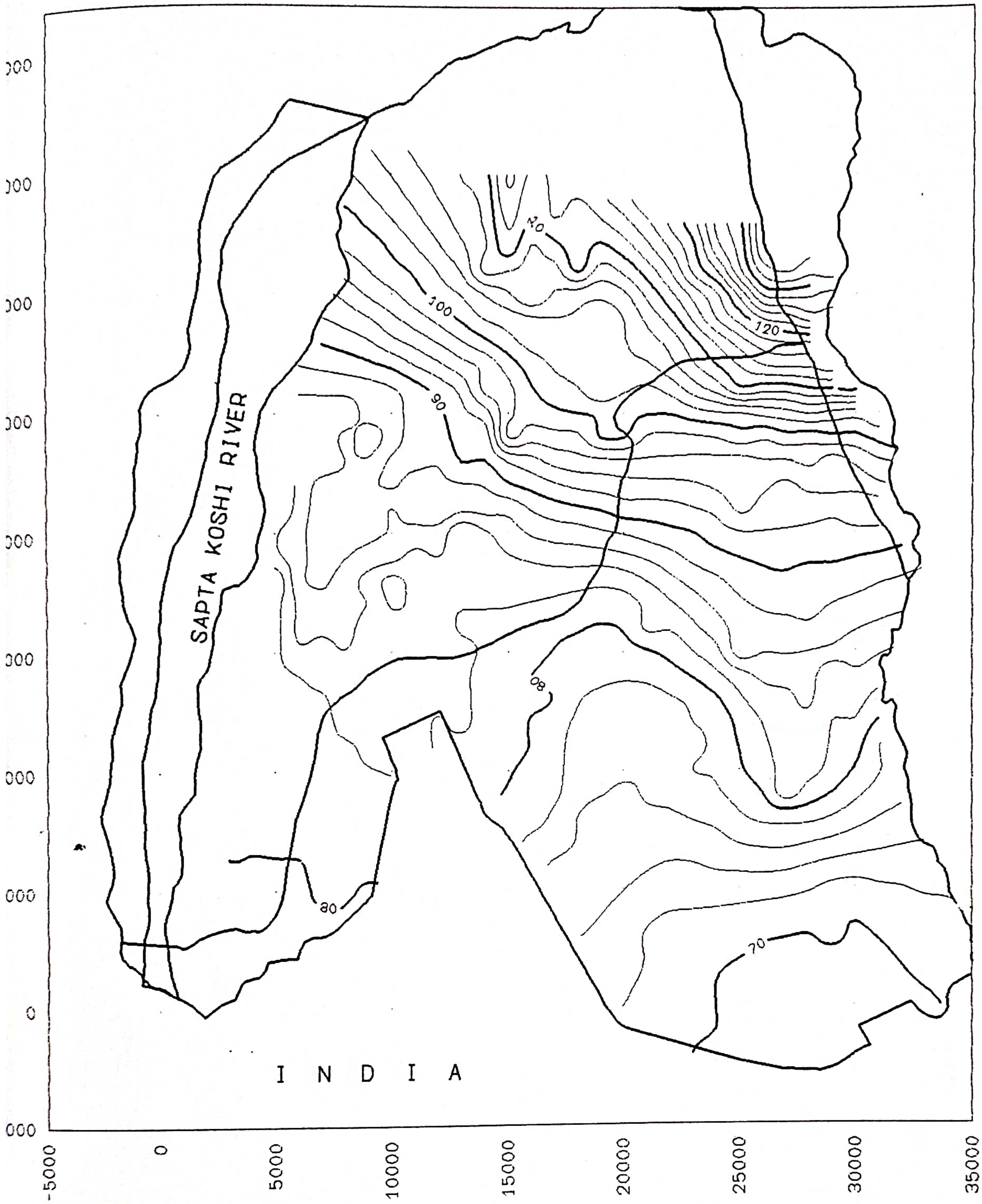
APPENDIX 6

SUNSARI TRANSMISSIVITIES (M2/DAY)



MODEL OF SUNSARI DISTRICT

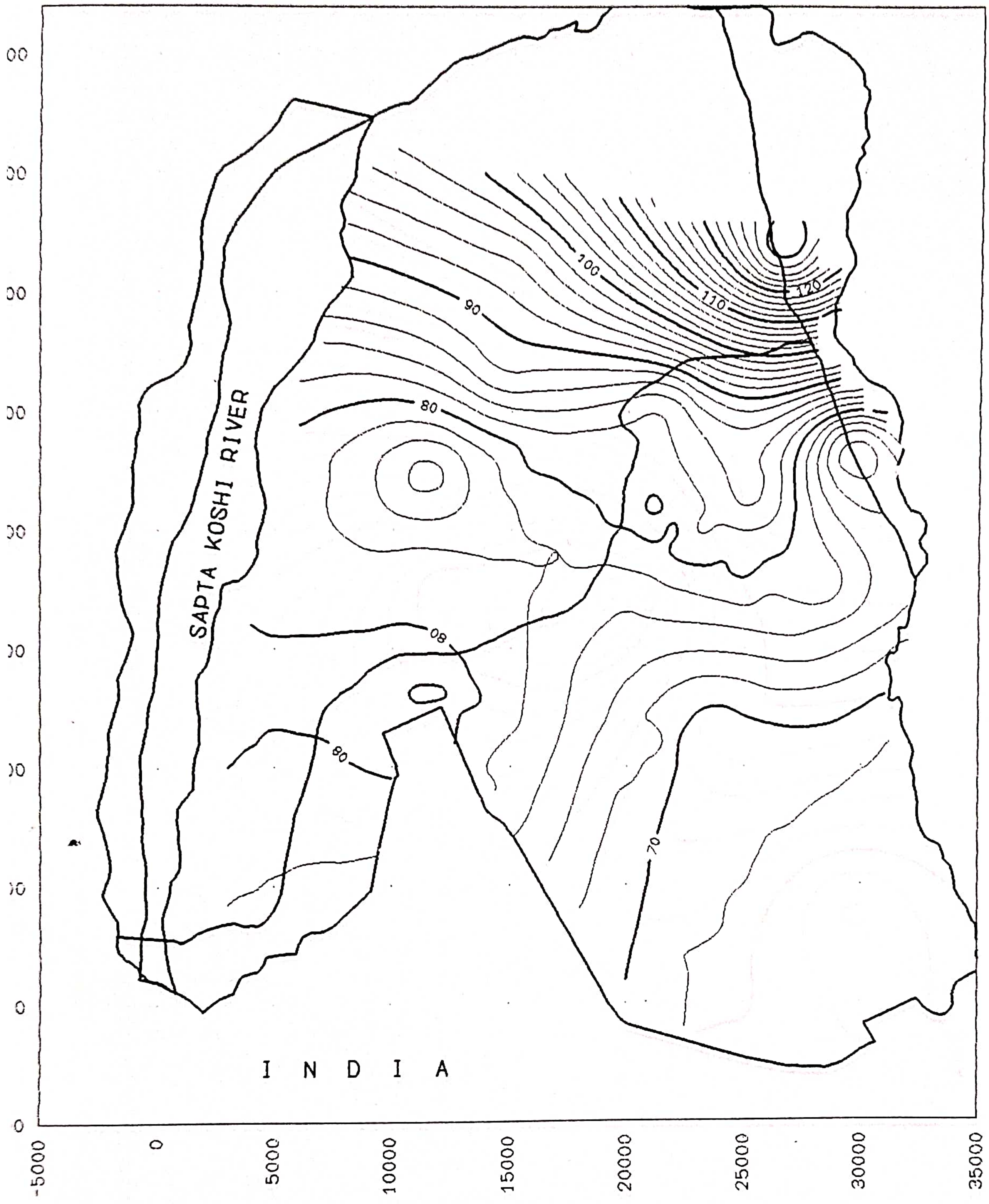
LAND SURFACE ELEVATIONS (in meters)



APPENDIX 7

MODEL OF SUNSARI DISTRICT

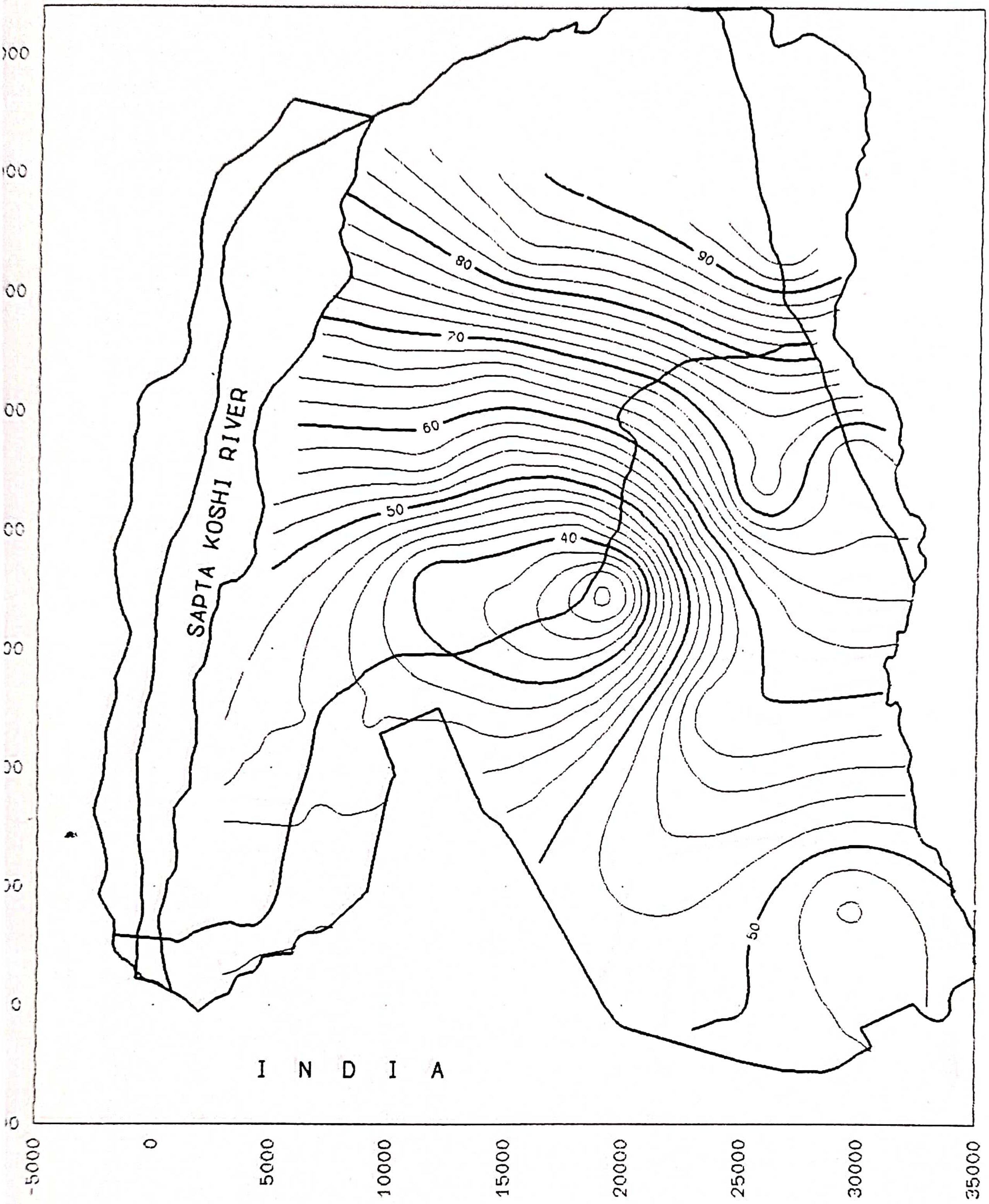
ELEVATIONS OF TOP OF SHALLOW AQUIFER



APPENDIX 8

MODEL OF SUNSARI DISTRICT

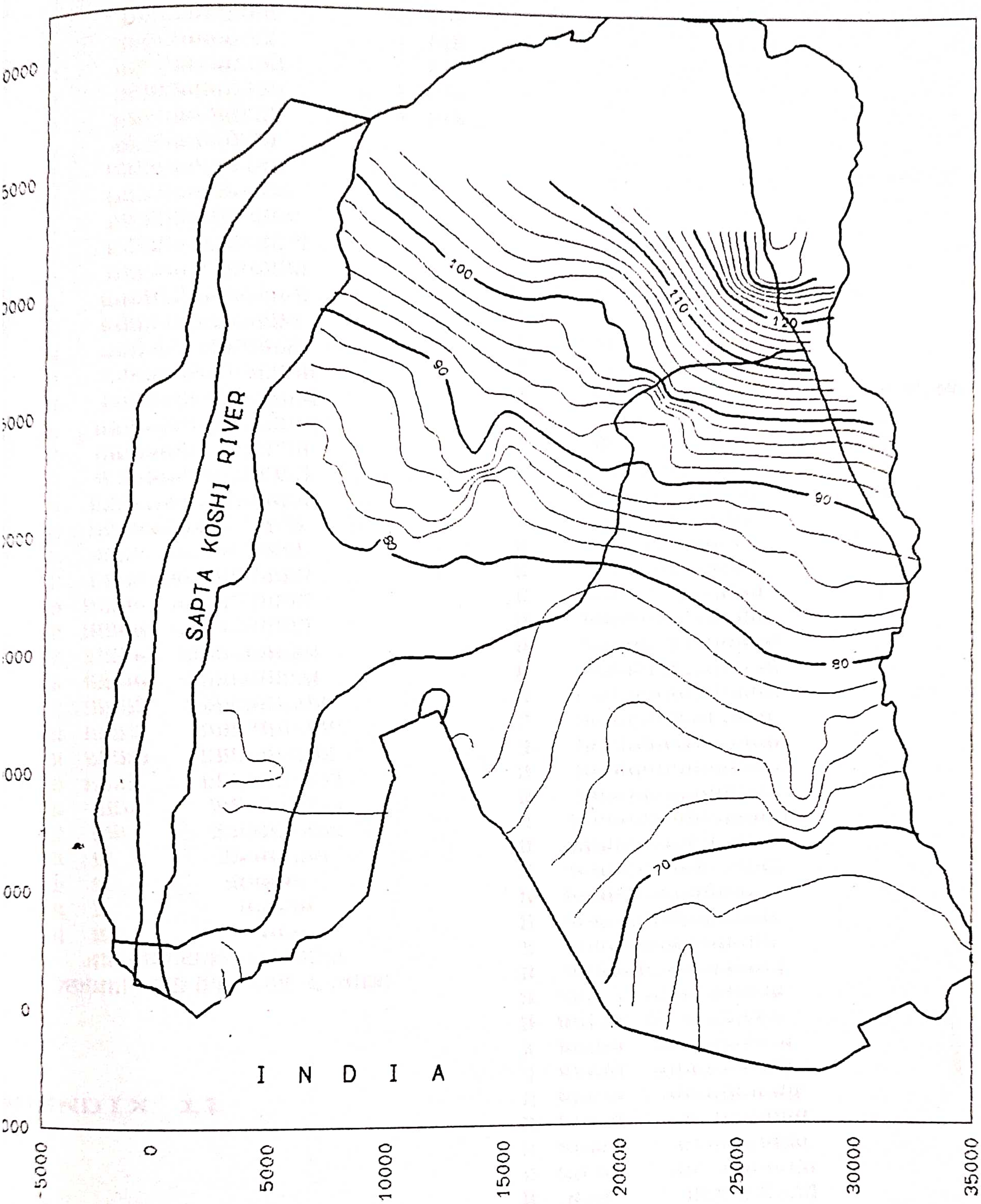
ELEVATIONS OF BOTTOM OF SHALLOW AQUIFER



APPENDIX 9

MODEL OF SUNSARI DISTRICT

WATER LEVELS IN MAY 1989 (ABSOLUTE ELEVATIONS)



APPENDIX 10

```
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 2         6555
 3        65554433344
 4        65554433344444
 5        655544333444442111111
 6        655554334444444211111
 7       65555533344444442111111
 8       65555533344554442111111
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13      65555555554433355533333322
14      655555555444333555333222222
15      655555544443333355443333333
16     6666655555554444454444444433
17     666555444444455555455555544
18     6665554444444555545555555444
19     66655544444455555555555555444
20     66655555444455555555555555544
21    666655564444455555444433334444
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23    55555566666455555554333332355
24   555555566666556666676444443366
25   55555556666555667777777755555
26   55555555555444555577777555555
27   555555555544444455777775555577
28  555554444   4444455677777777777
29  555554444   4445555677777777777
30  555554444    5555556666665555666
31  555554444    5555556666665555666
32  555555555     5555556666655555555
33  555555555      5555555555555555555
34  555555555       555555555555555555
35  55555555        5555566655555555555
36   555555          555556665555555555
37   55555           555556665555555555
38   555              555444444444444
39   55                55444444444
40   55                  4444444444
41   55                     444444
    12345678901234567890123456789012345
  PERMEABILITY CODES (STEADY-STATE CALIBRATION)
```

```
BLANK   K=  0 [M/DAY]
    1   K= 10
    2   K= 30
    3   K= 50
    4   K= 70
    5   K= 90
    6   K=120
    7   K=150
    8   K=250
    9   K=400
```

PENDIX 11

```
0.1 0.05 0.08 0.1 0.16 0.15 0.175 0.20 0.25 1E21
 1         944
 2         9444
 3        9444444444
 4        9444444444444
 5        94444444444444444444
 6        94444444444444444444
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16     944444444444444444444444444
17     94444444444444444444444444
18     944444444444444444444444444
19     9444444444444444444444444444
20     9444444444444444444444444444
21    94444444444444444444444444444
22    9444444444444444444444444444
23    9444444444444444444444444444
24   94444444444444444444444444444
25   9444444444444444444444444444
26   9444444444444444444444444444
27   94444444444444444444444444444
28  94444444    444444444444444444
29  94444444    444444444444444444
30  94444444     444444444444444444
31  94444444     444444444444444444
32  94444444      444444444444444444
33  94444444       444444444444444444
34  94444444        44444444444444444
35  9444444         4444444444444444444
36   944444          333222223333333333
37   94444           222222122333333333
38   944              222222223333333
39   94                33322233333
40   94                  333333333
41   94                     33333
    12345678901234567890123456789012345
      EFFECTIVE POROSITY DATA FILE
```

```
0 or Blank: Eff. por.  0.1
        1:             0.05
        2:             0.08
        3:             0.1
        4:             0.16
```

APPENDIX 12

```
8 0.12 0.16 0.20 0.24 0.28 0.32 0.36 0.40
      55
      555
     5555544333
     5555555443333
     554442222333333333333
     55554111223333332223
    5555541011223333320122
    55555211122223333322222
    55552211122233333322222
    33333333333300032222
   3333333333333000112222
   3333333333332200011122222
   3333333333332110011111222
   3333333333332100011111111
   3333333333332211111110111
  3333333333332211111111111
  33333333333322111110112222
  33333333333322221111222222
  333333333333222222223333333
  333333333333222222223344333
 33333333333332222222234443333
 3333333333333222222223444333
 3333333333333222222223444333
33333333333333222222244443333
3333555555533222222222222222
44445555555322222222222222211
4444555555532222222222223322211
4444555  3322222222222333221l
4444555  222222222222333333211
4444444   222222222222222222111
4444444   222222222222222222111
4444444    22222222222222211111
4444444     222222222222211111111
33333333     2222222222211111111
3333333      2222222222111111111
 33333        2222222221111111111
 3333         2222222221111111111
 33            22222222211111111
 3              2222222221111
                  222221111
                     22211
5  0.011   0.020  0.015 0.015 0.001
   JUNE   JULY    AUG   SEP   OCT
INFALL FROM  AIRPORT BIRATNAGAR)
lues are in m/day)
```

CODES:

0 - RECHARGE 0.00
1 - 0.08
2 - 0.12
3 - 0.16
4 - 0.20
5 - 0.24
6 - 0.28
7 - 0.32
8 - 0.36
9 - 0.40

APPENDIX 13

```
2.8 0.6 0.10
 1        11
 2        111
 3       1111111111
 4       1110000000000
 5       11111000000000000000
 6       1111100011000000000
 7      1111110001111000000000
 8      1111111001111100000000
 9      1111111111111110000000
10      111111111111110000000
11     1111111111111111000000000
12     1111111111110000000000000
13     11111111111100000111111111
14     111111111111000011111111111
15     111111111111111111111100011
16    1111111111111111111000000111
17    111111111111111111000011111
18    11111111111111111110001111111
19    1111111111111111111111111111
20    1111111111111111111111111111
21   11111111111111111111111111111
22   1111111111111111111111111111
23   1111111111111111111111111111
24  11111111111111111111111111111
25  1111111110111111111111111111
26  1111111000111111111111111111
27  11111111111111111111111111111
28 1111111   1111111111111111111
29 1111111   1111111111111111111
30 1111111    1111111111111111111
31 1111111    1111111111111111111
32 1111111     1111111111111111111
33 1111111      1111111111111111111
34 1111111       1111111111111111111
35 111111        1111111111111111111
36  11111         1111111111111111111
37  1111          1111111111111111111
38  11             111111111111111
39  1               11111111111
40                    111111111
41                       11111
0.006 0.0046 0.0036 0.0043 0.0034 0.0029 0.0025 0.001
MAY   JUN    JUL    AUG    SEP    OCT    NOV    DEC
 (Values are in m/day)
```

Critical depth, shape factor, % in semipermeable

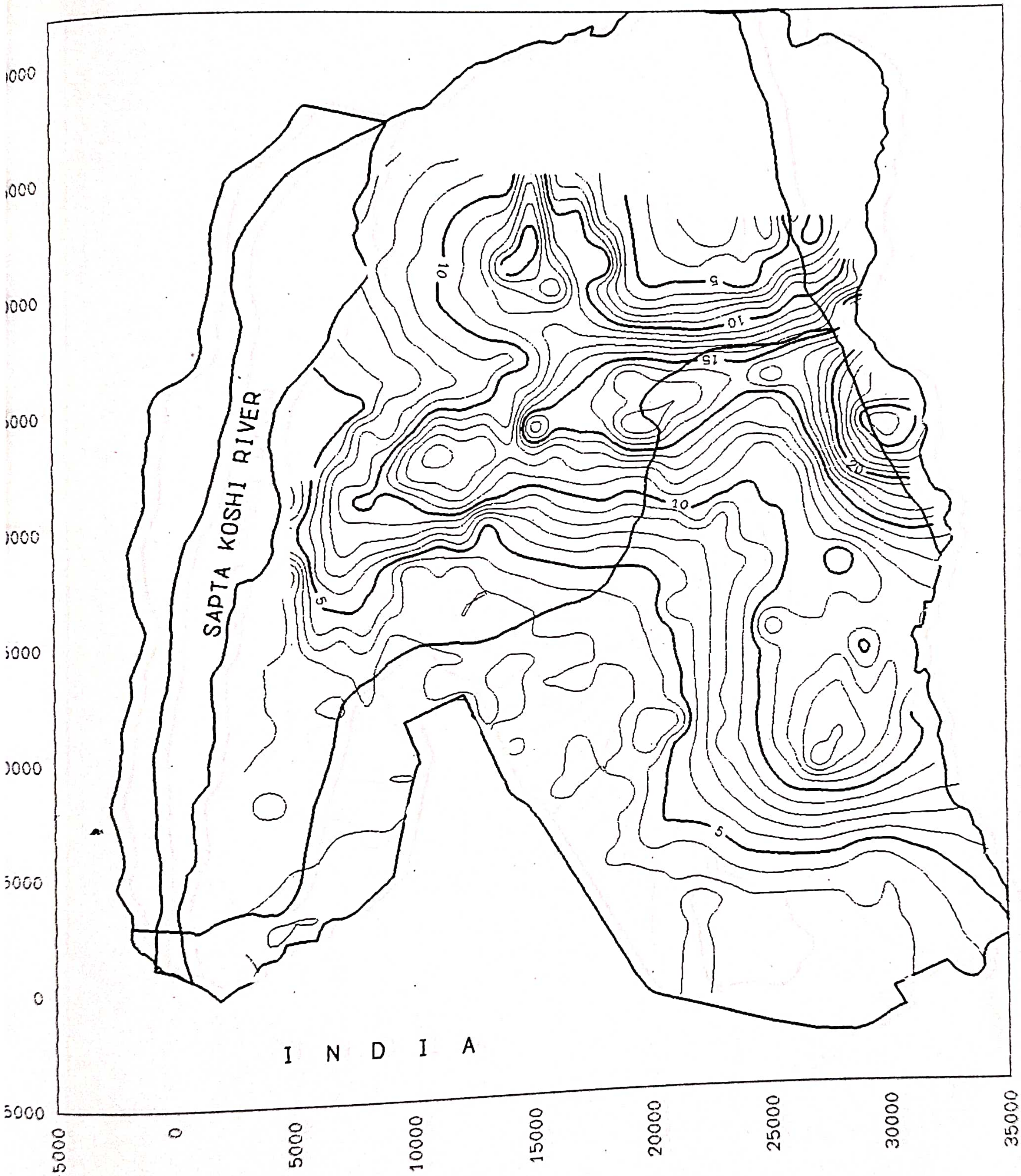
EVAPORATION DATA FILE

0 = ZERO EVAPORATION
1 = PERMEABLE SURFACE
(Evaporation loss possible when water table comes closer than 3.0 m from the surface)

APPENDIX 14

MODEL OF SUNSARI DISTRICT

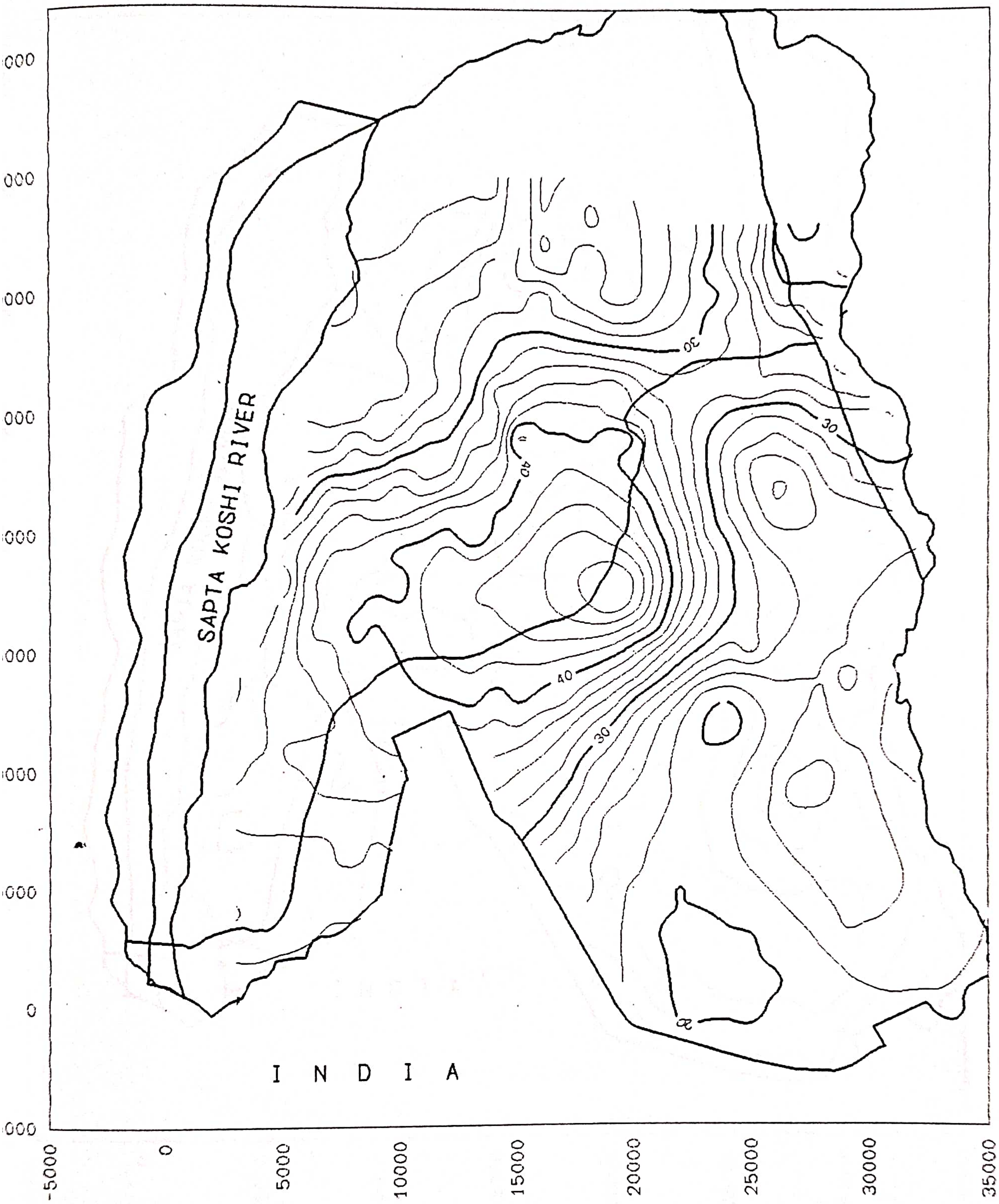
DEPTH TO TOP OF SHALLOW AQUIFER (M)



APPENDIX 15

MODEL OF SUNSARI DISTRICT

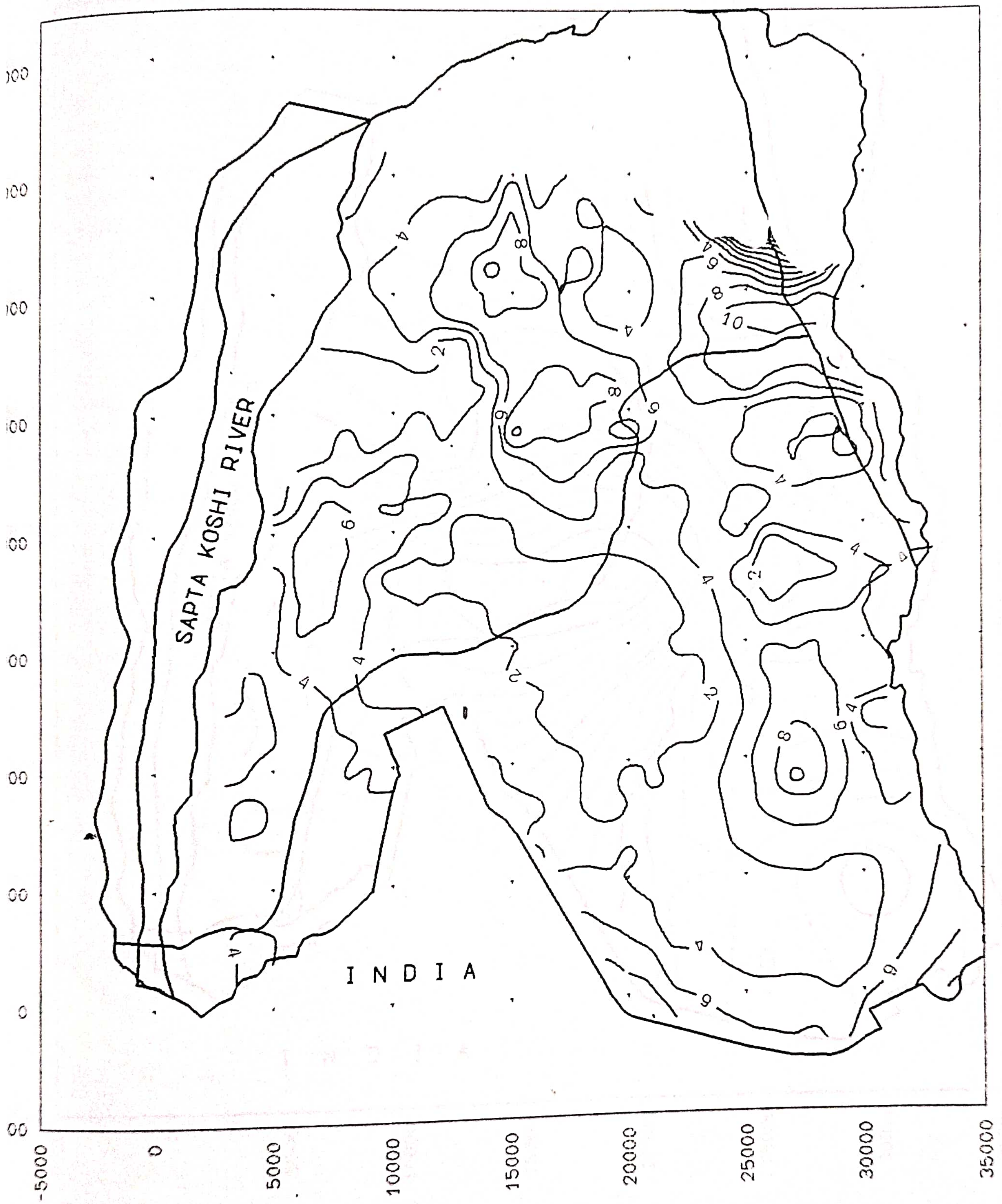
DEPTH TO BOTTOM OF SHALLOW AQUIFER (M)



APPENDIX 16

MODEL OF SUNSARI DISTRICT

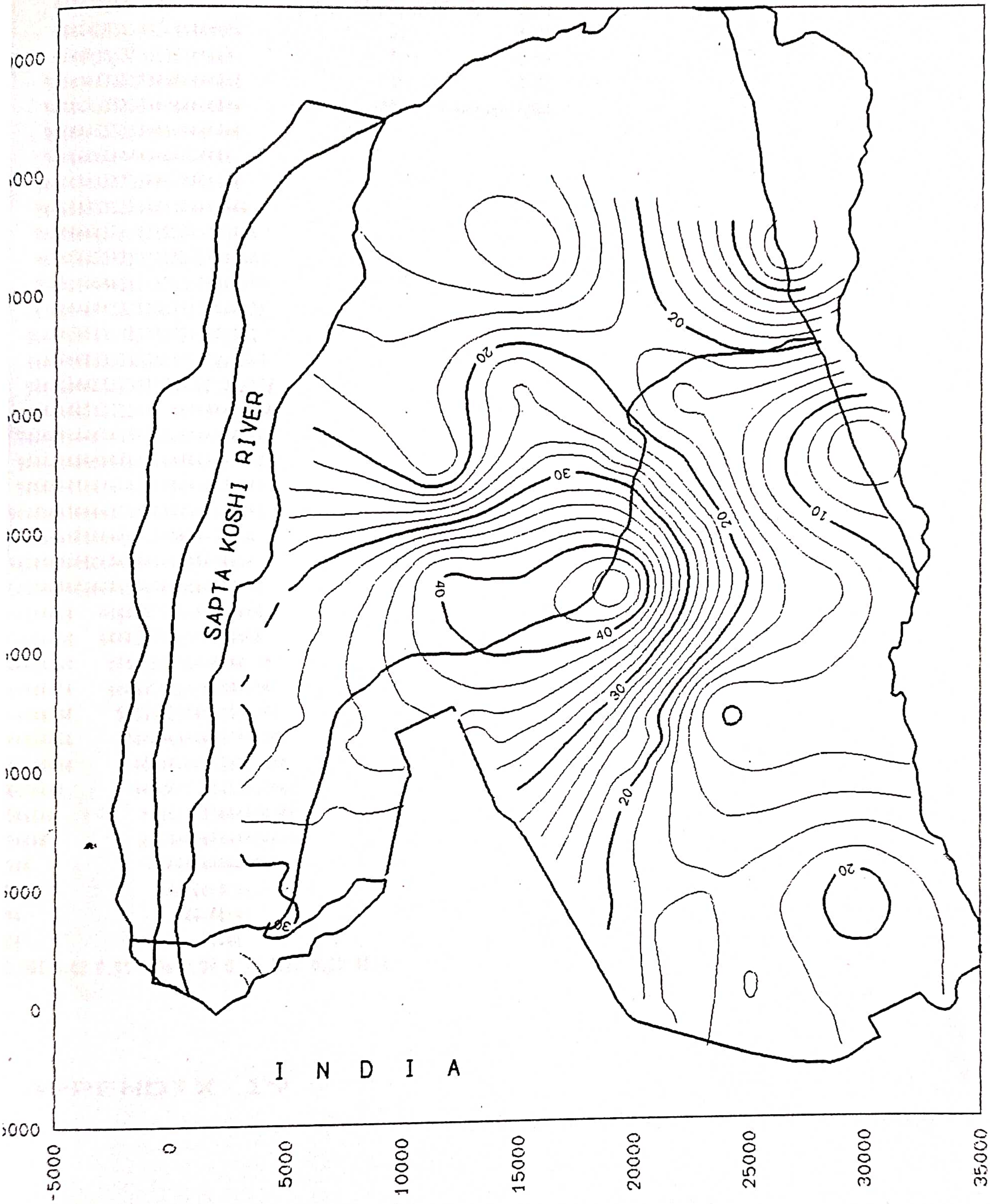
DEPTH TO WATER IN MAY 1989



APPENDIX 17

MODEL OF SUNSARI DISTRICT

SATURATED THICKNESS OF SHALLOW AQUIFER IN MAY 1989



APPENDIX 18

```
0.001 0.01 0.02 0.03 0.04 0.05 0.10 0.12 1E21
     944
     9444
    94444333333
    94444333333333
    9444433333333444444444
    944443333333444444444
   9444444333333444444444
   9444443333333444444444
   9444443333334444444444
   94444444444444444444
  944444433333344444444444
  9444443333334444444444444
  94444444333111123333333444
  944444433331221133333344444
  944444444431111233333344444
 9444444444333333333334444333
 94444444433333333322222333
 944444443333333332222222333
 9444444433333333332222233333
 9444444333333333344444444444
9444444444444444444444444444
9444444444444444444444444444
9444444444444444444444444444
9444444444444444444444444444
944444444444444444444444444
944444444444444444444444444
9444444444444444444444444444
944444444    4444455555444444444
944444444    4444555555444444444
944444444     44455555544444444444
944444444     444555555444444444
944444444      55555555444444444
944444444       444444444444444444
944444444        444444444333334444
94444444         44444444433333334444
 944444           4444443334444444444
 94444            444444444444444444
 944               44444444444444
 94                 4444444444
 94                  444444444
 94                    44444
01 0.001 0.02 0.03 0.06 0.08 0.09 0.10 0.12 1E21
```

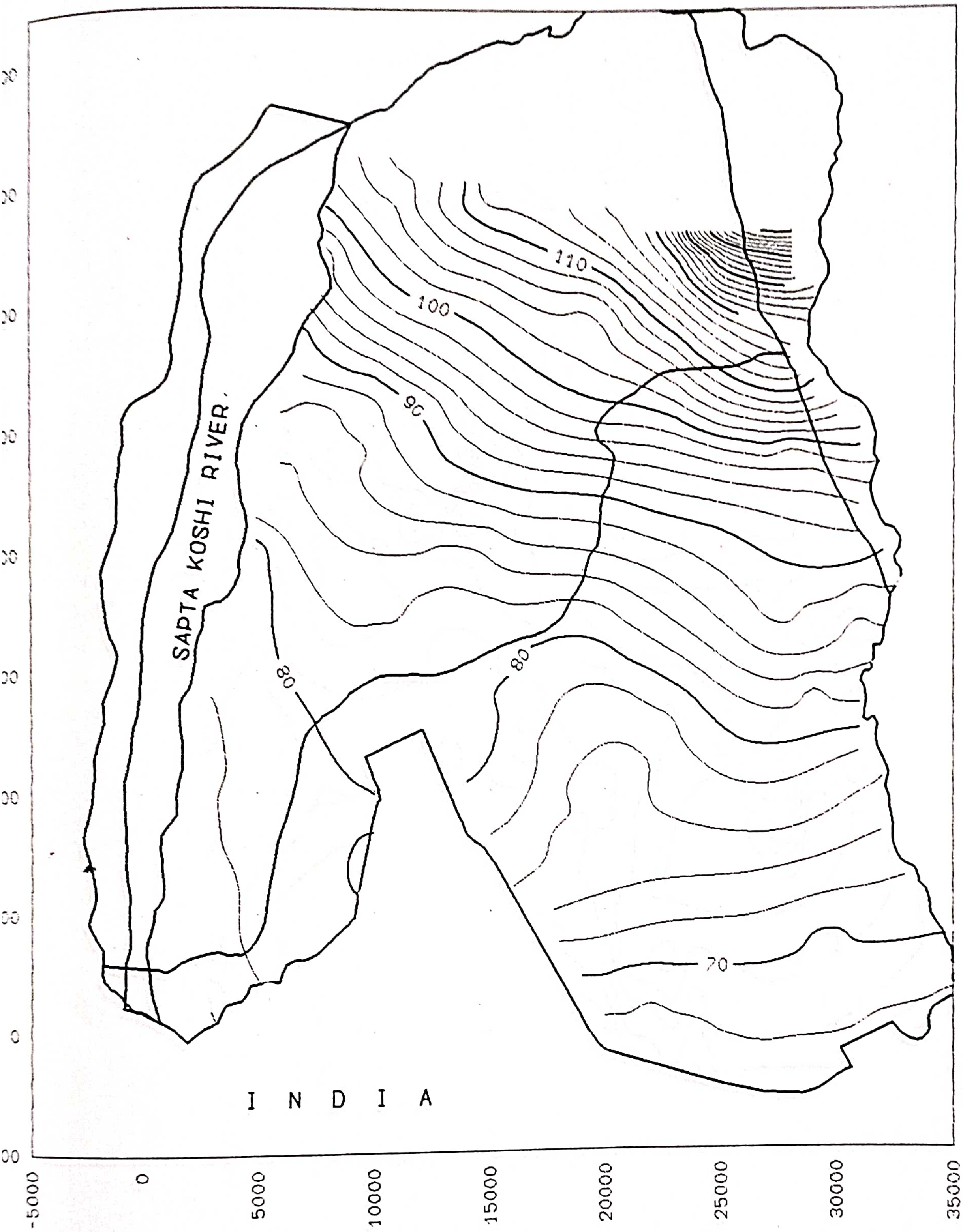
STORAGE COEFFICIENT FILE

0 or Blank:	STOR COEFF	0.001
1:		0.001
2:		0.01
3:		0.02
1E21 .. Constant Head		

APPENDIX 19

MODEL OF SUNSARI DISTRICT

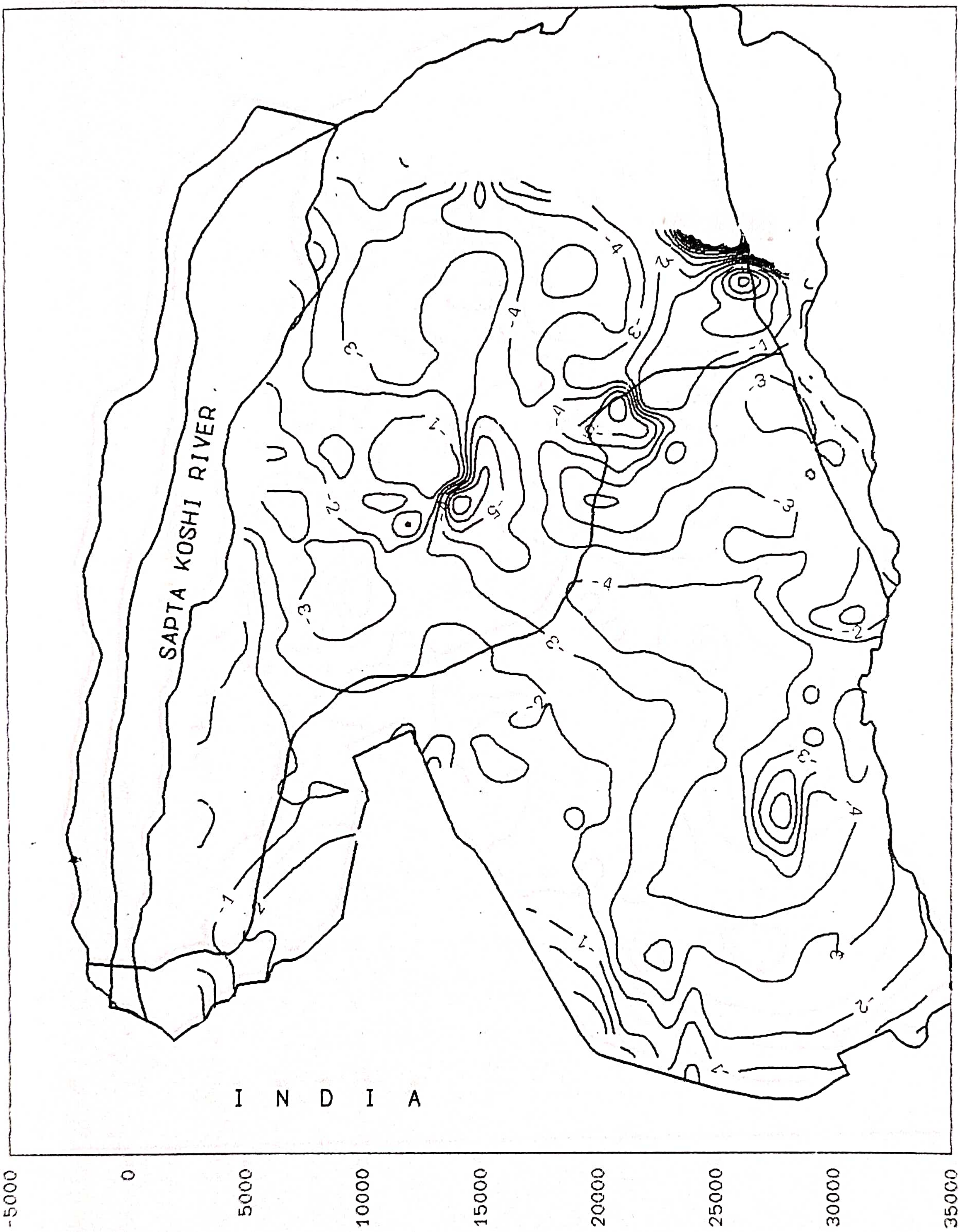
WATER LEVEL IN SEPTEMBER 1989 (M)



APPENDIX 20

MODEL OF SUNSARI DISTRICT

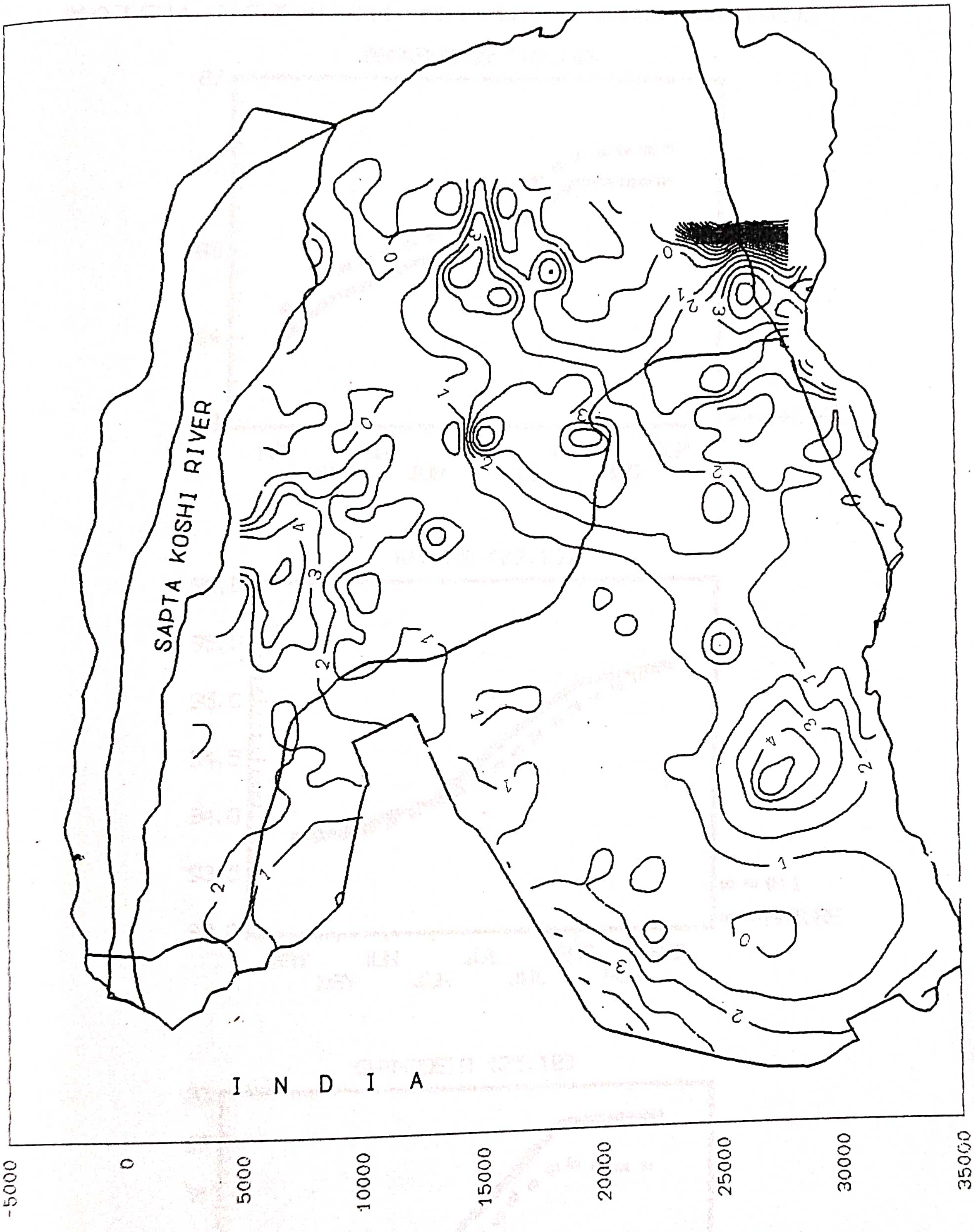
RISE OF LEVEL FROM MAY TO SEPTEMBER 1989 (- SIGN = RISE)



APPENDIX 21

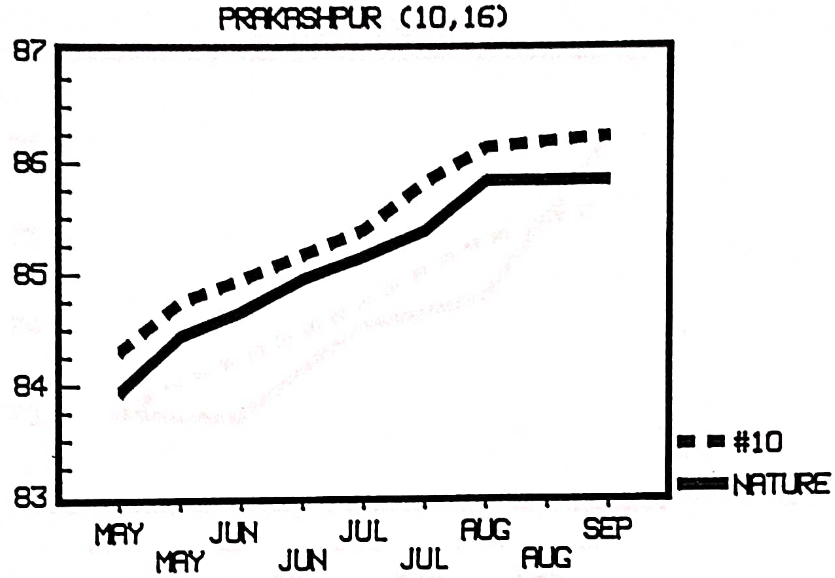
MODEL OF SUNSARI DISTRICT

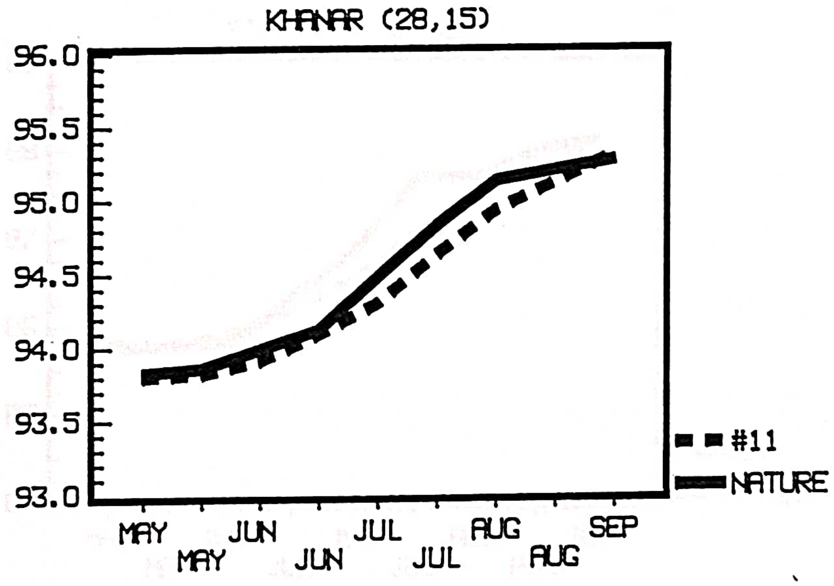
DEPTH TO WATER IN SEPTEMBER 1989 (MODEL OUTPUT)

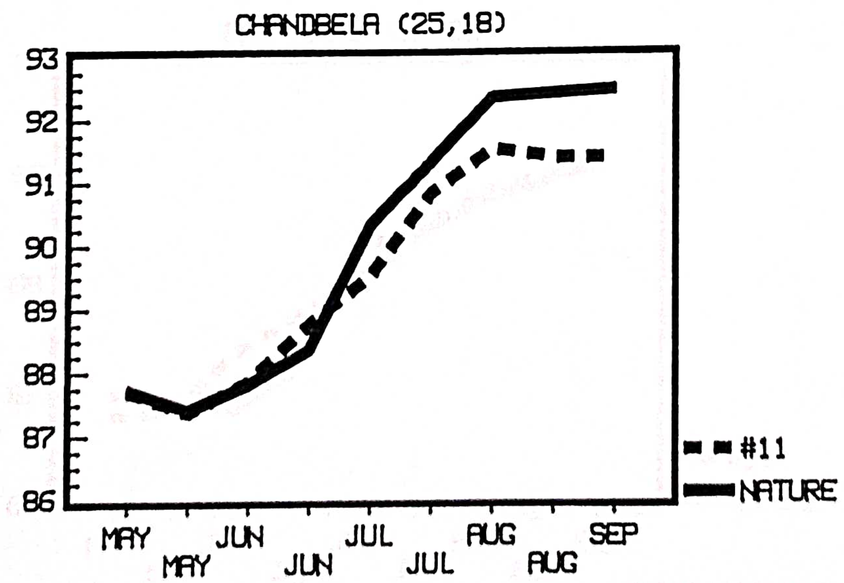


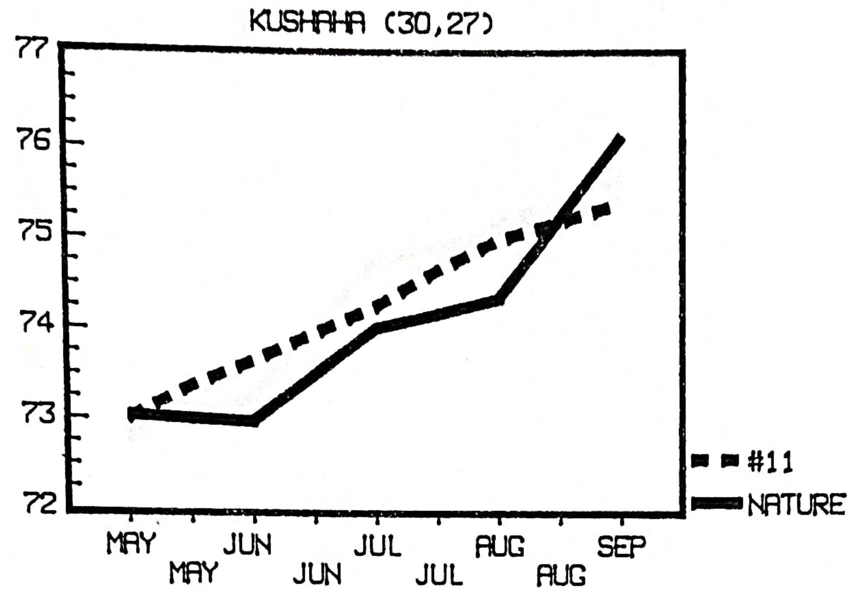
APPENDIX 22

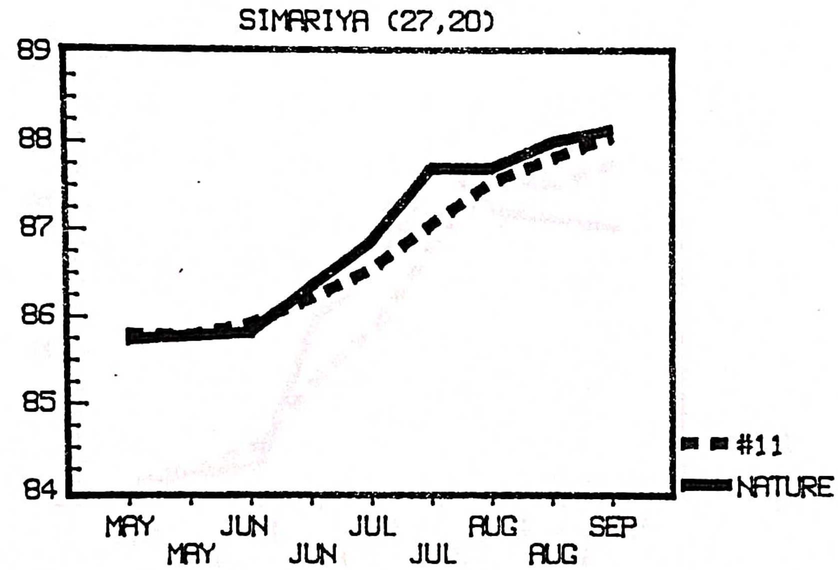
MATCH BETWEEN NATURE AND MODEL

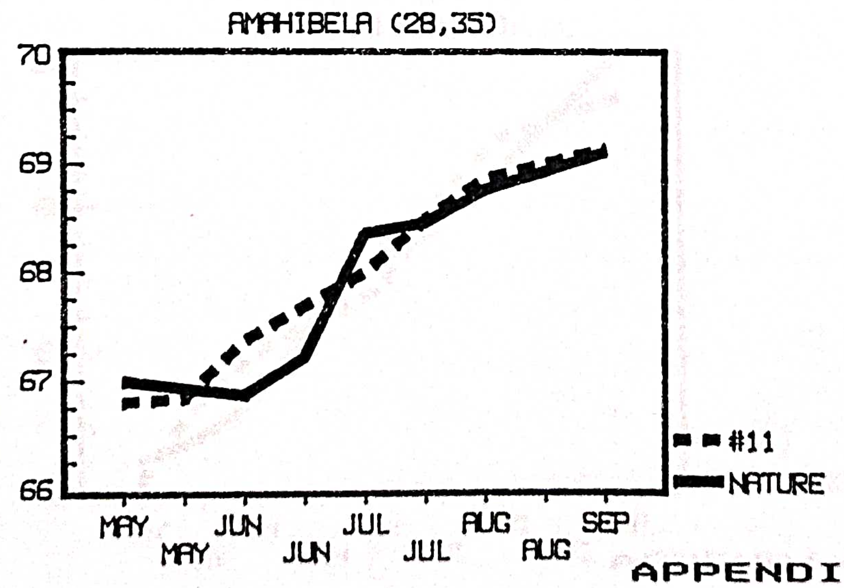


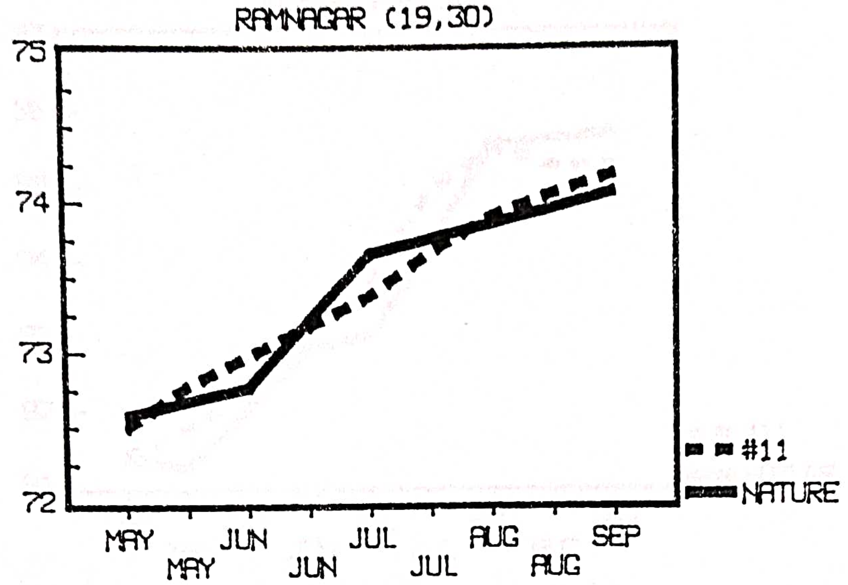


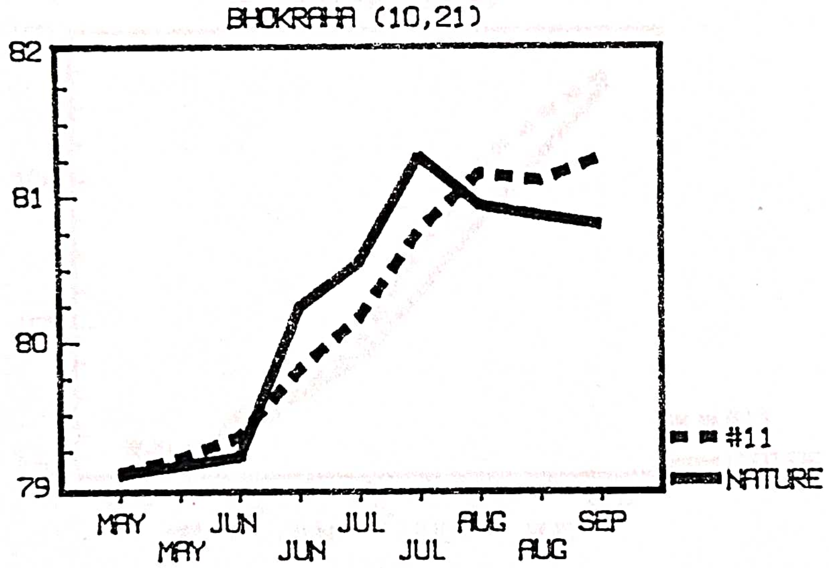


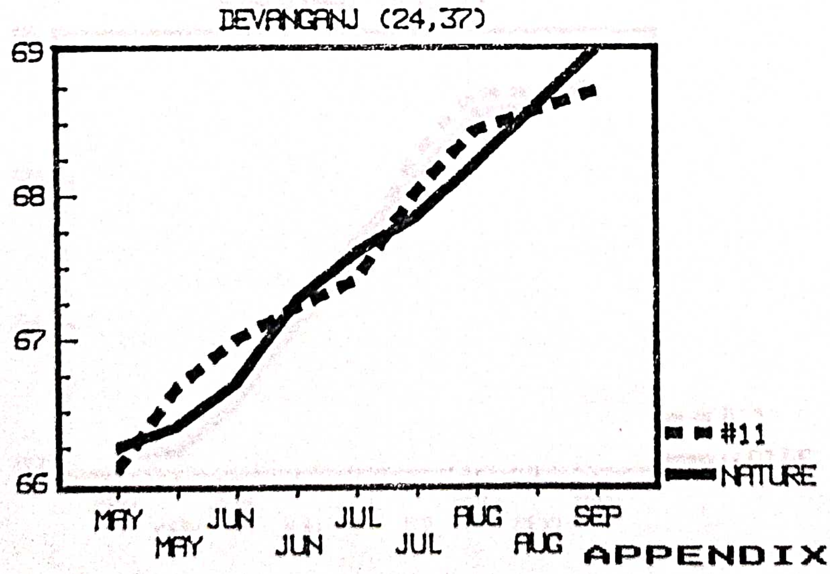

KUSHAHA (30,27)
77
76
75
74
73
72
MAY JUN JUL AUG SEP
MAY JUN JUL AUG
#11
NATURE


SIMARIYA (27,20)
89
88
87
86
85
84
MAY JUN JUL AUG SEP
MAY JUN JUL AUG
#11
NATURE

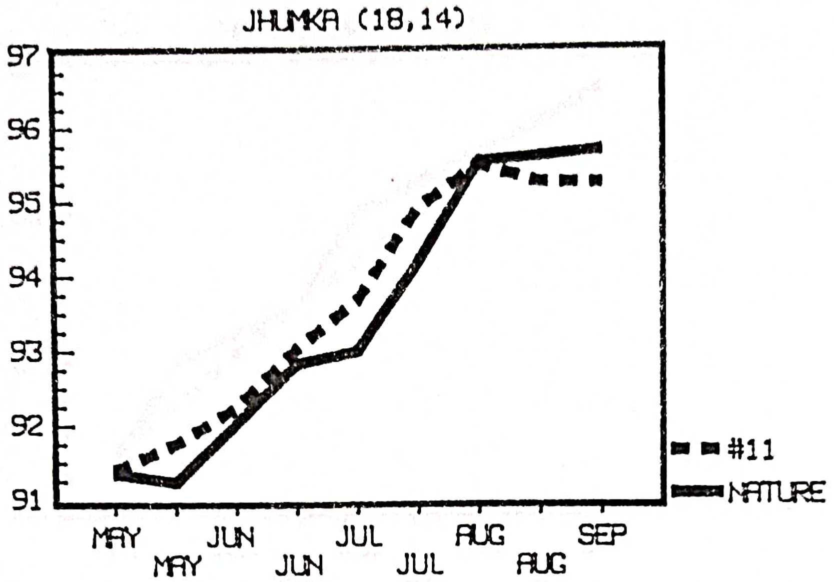

AMAHIBELA (28,35)
70
69
68
67
66
MAY JUN JUL AUG SEP
MAY JUN JUL AUG
#11
NATURE

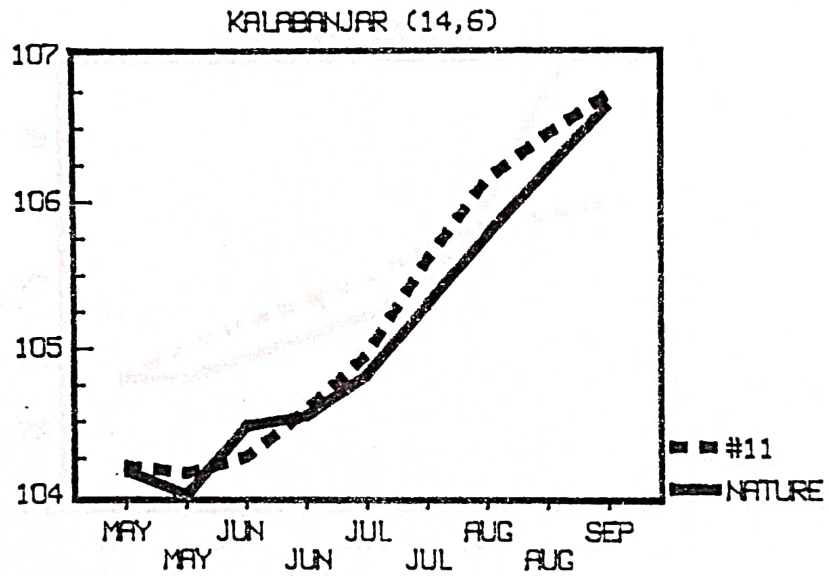


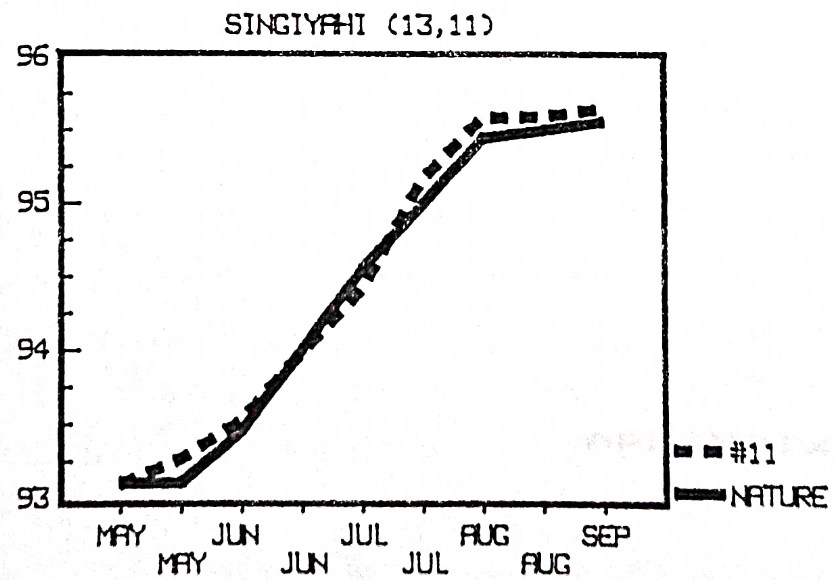


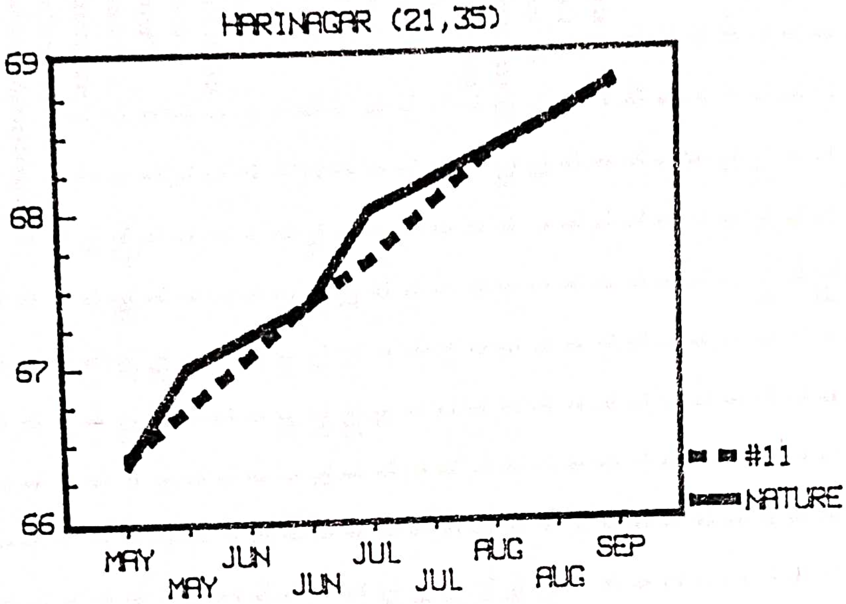


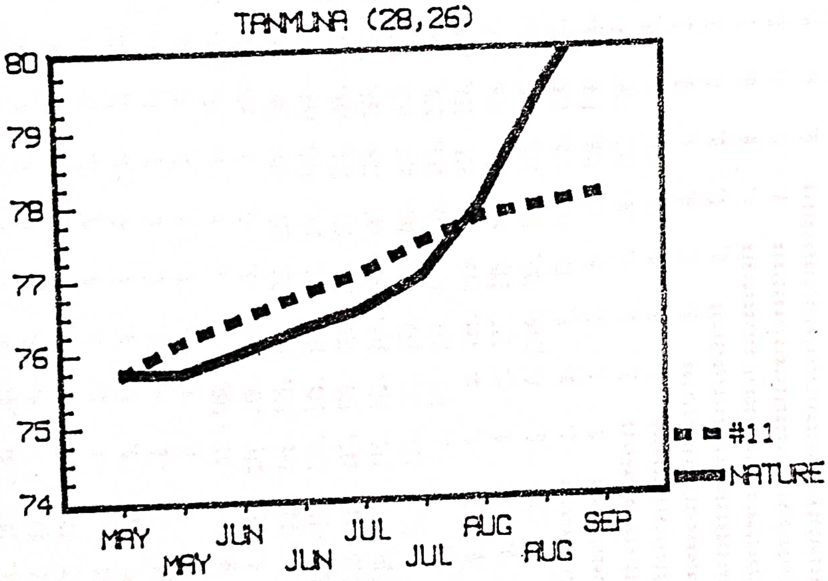
APPENDIX 23/3


JHUMKA (18,14)
97
96
95
94
93
92
91
MAY
JUN
JUL
AUG
SEP
MAY
JUN
JUL
AUG
#11
NATURE


KALABANJAR (14,6)
107
106
105
104
MAY
JUN
JUL
AUG
SEP
MAY
JUN
JUL
AUG
#11
NATURE


SINGIYAHI (13,11)
96
95
94
93
MAY
JUN
JUL
AUG
SEP
MAY
JUN
JUL
AUG
#11
NATURE

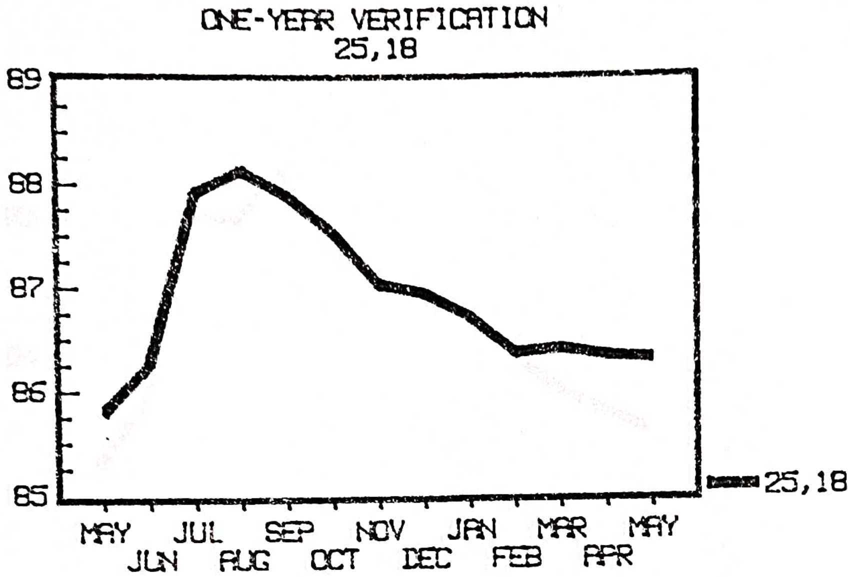

HARINAGAR (21,35)
69
68
67
66
MAY
MAY
JUN
JUN
JUL
JUL
AUG
AUG
SEP
#11
NATURE

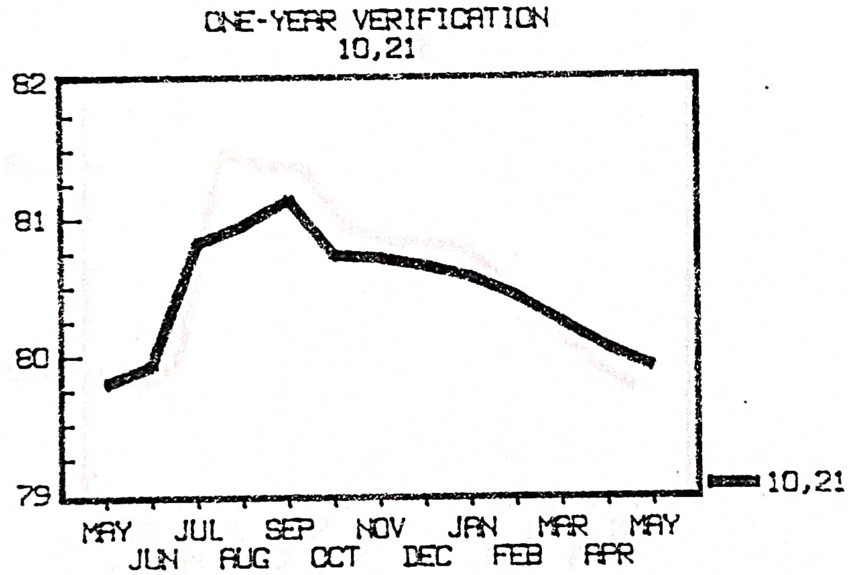

TANMUNA (28,26)
80
79
78
77
76
75
74
MAY
MAY
JUN
JUN
JUL
JUL
AUG
AUG
SEP
#11
NATURE

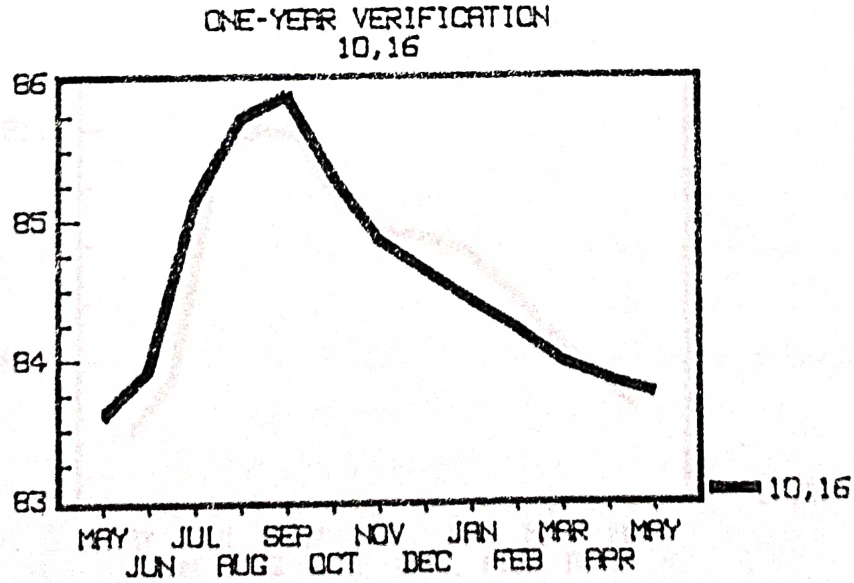
EVAPORATION LOSS

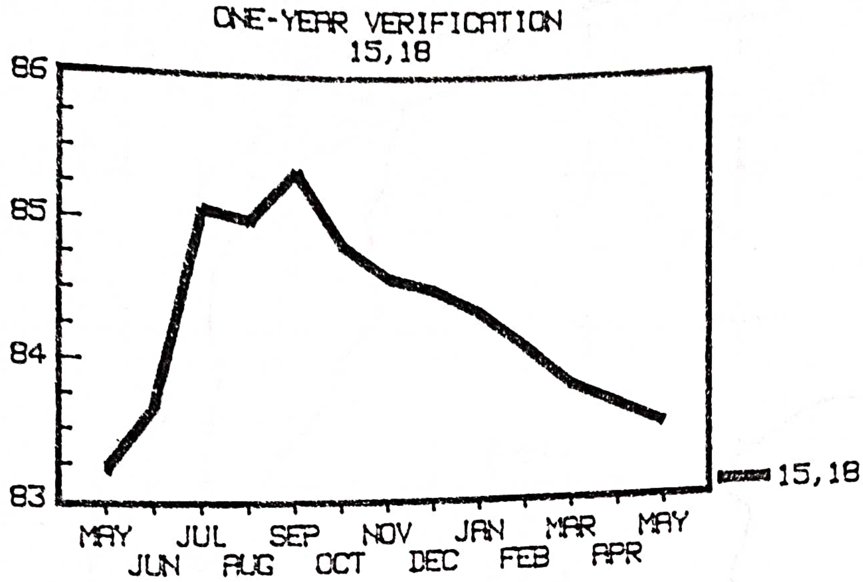
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
2	####	####	####	####	####	####	####	0.	182.	115.	87.	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####
3	####	####	####	####	####	####	0.	252.	153.	97.	82.	98.	127.	0.	82.	0.	0.####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####
4	####	####	####	####	####	####	0.	188.	110.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####
5	####	####	####	####	####	####	0.	132.	83.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####	####	####
6	####	####	####	####	####	####	0.	92.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####	####	####
7	####	####	####	####	####	0.	91.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####	####
8	####	####	####	####	####	0.	122.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	113.	110.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####	####
9	####	####	####	####	####	0.	128.	102.	0.	0.	0.	0.	0.	0.	0.	0.	0.	92.	89.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####	####
10	####	####	####	####	####	0.	172.	140.	0.	0.	181.	161.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####	####	####
11	####	####	####	####	0.	289.	260.	219.	192.	111.	163.	238.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####	####
12	####	####	####	####	0.	397.	360.	309.	382.	267.	252.	174.	125.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####
13	####	####	####	####	0.	411.	4300.	229.	293.	158.	226.	166.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	85.	0.	0.####	####	####	####	####	####
14	####	####	####	####	0.	420.	122.	334.	189.	0.	173.	92.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	133.	116.	180.	130.	0.	0.	0.####	####	####	####	####
15	####	####	####	####	0.	204.	96.	106.	0.	0.	89.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	84.	82.	160.	0.	0.	0.	0.	0.####	####	####	####	####
16	####	####	####	0.	146.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####
17	####	####	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	87.	110.	0.	0.	0.	0.	155.	119.	117.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####
18	####	####	####	0.	0.	0.	0.	0.	0.	0.	0.	358.	234.	149.	83.	0.	0.	0.	90.	106.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####
19	####	####	####	0.	0.	0.	0.	0.	0.	136.	85.	239.	198.	159.	139.	123.	123.	129.	108.	0.	0.	0.	0.	0.	366.	164.	100.	0.	0.	0.	0.	0.####	####	####	####
20	####	####	####	0.	0.	0.	0.	0.	284.	215.	228.	171.	178.	175.	188.	207.	258.	337.	294.	164.	84.	0.	0.	99.	366.	165.	173.	144.	0.	0.	0.	0.####	####	####	####
21	####	####	0.	915.	0.	0.	0.	0.	102.	149.	112.	140.	157.	179.	224.	293.	221.	252.	256.	249.	132.	0.	0.	0.	169.	123.	97.	81.	0.	0.	0.	95.####	####	####	####
22	####	####	0.	0.	0.	0.	0.	0.	900.	970.	1030.	0.	146.	179.	240.	340.	247.	326.	267.	145.	162.	80.	0.	0.	86.	0.	0.	0.	0.	0.	80.####	####	####	####	####
23	####	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	116.	133.	190.	336.	261.	289.	269.	188.	115.	96.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####
24	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	173.	236.	317.	222.	260.	270.	236.	155.	152.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####
25	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	122.	173.	242.	325.	357.	342.	226.	142.	108.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####
26	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	137.	235.	227.	300.	356.	347.	235.	206.	122.	0.	0.	0.	0.	0.	131.	200.####	####	####	####	####	####
27	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1118.	0.	0.	1129.	155.	176.	219.	247.	231.	167.	176.	0.	0.	0.	0.	0.	0.	83.	109.	109.####	####	####	####	####
28	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	0.	0.	0.	87.	138.	175.	154.	152.	110.	0.	0.	0.	0.	0.	0.	0.	0.	0.	95.####	####	####	####	####
29	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	0.	0.	0.	0.	147.	198.	116.	156.	124.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####
30	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	0.	0.	0.	138.	217.	133.	106.	96.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####
31	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	0.	0.	0.	81.	106.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####
32	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	0.	0.	0.	0.	0.	0.	94.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####
33	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####	0.	0.	0.	0.	0.	90.	0.	0.	0.	0.	0.	0.	0.	87.	0.	0.	0.	0.	0.####	####
34	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	111.	90.	888.	0.	0.	0.	0.	0.####	####
35	0.	0.	0.	0.	0.	0.	0.	883.####	####	####	####	####	####	####	####	####	0.	0.	0.	0.	883.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
36	####	0.	0.	0.	0.	0.	0.####	####	####	####	####	####	####	####	####	####	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	803.	0.	0.	0.	0.	0.	0.	0.	0.
37	####	0.	0.	0.	0.	0.####	####	####	####	####	####	####	####	####	####	####	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
38	####	0.	0.	0.####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####
39	####	0.	0.####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####
40	####	0.	0.####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.####	####	####	####	####	####
41	####	0.	0.####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	####	0.	0.	0.	0.	0.	0.####	####	####	####	####	####

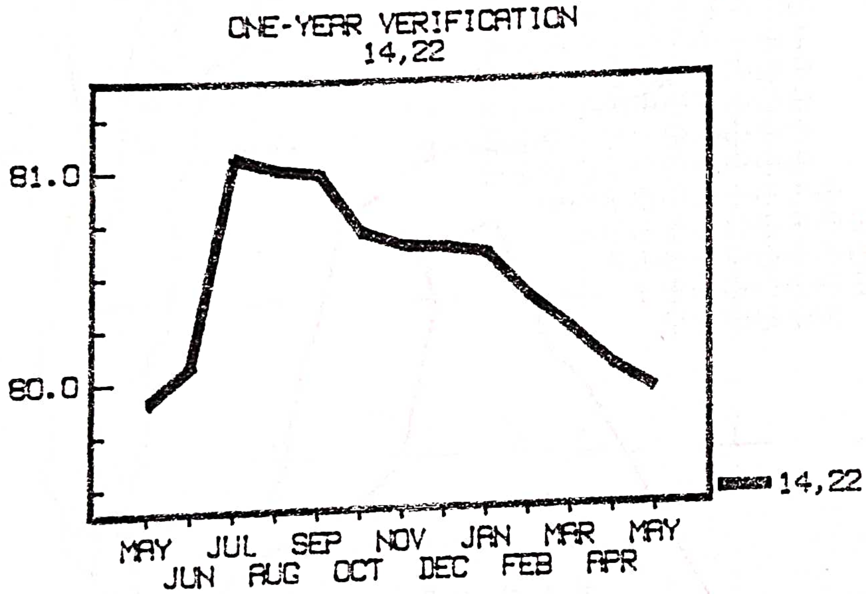
COMMENTS:
Evaporation is in [m3day
Time Step = 8
Time elapsed - 0.1200E+03 [day]

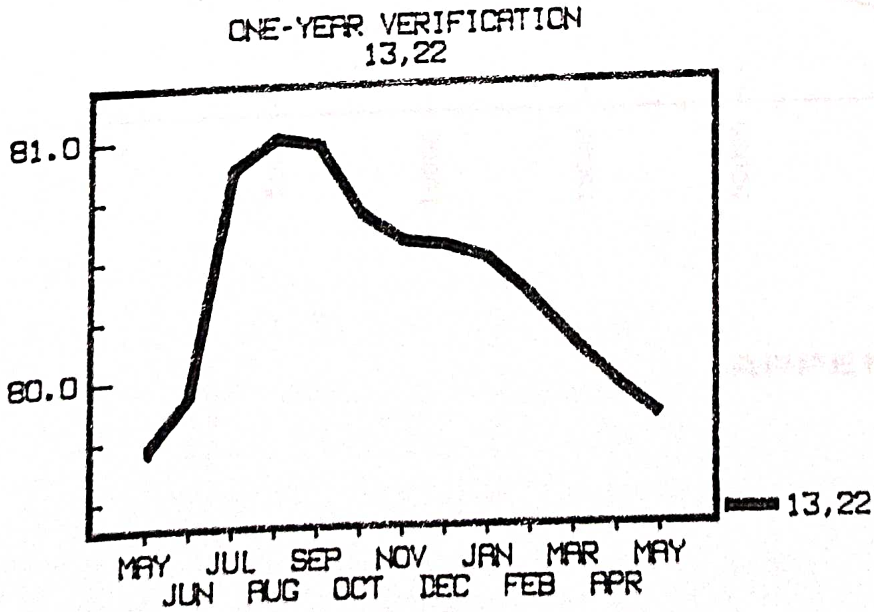

ONE-YEAR VERIFICATION
25,18
89
88
87
86
85
MAY JUL SEP NOV JAN MAR MAY
JUN AUG OCT DEC FEB APR
25,18


ONE-YEAR VERIFICATION
10,21
82
81
80
79
MAY JUL SEP NOV JAN MAR MAY
JUN AUG OCT DEC FEB APR
10,21

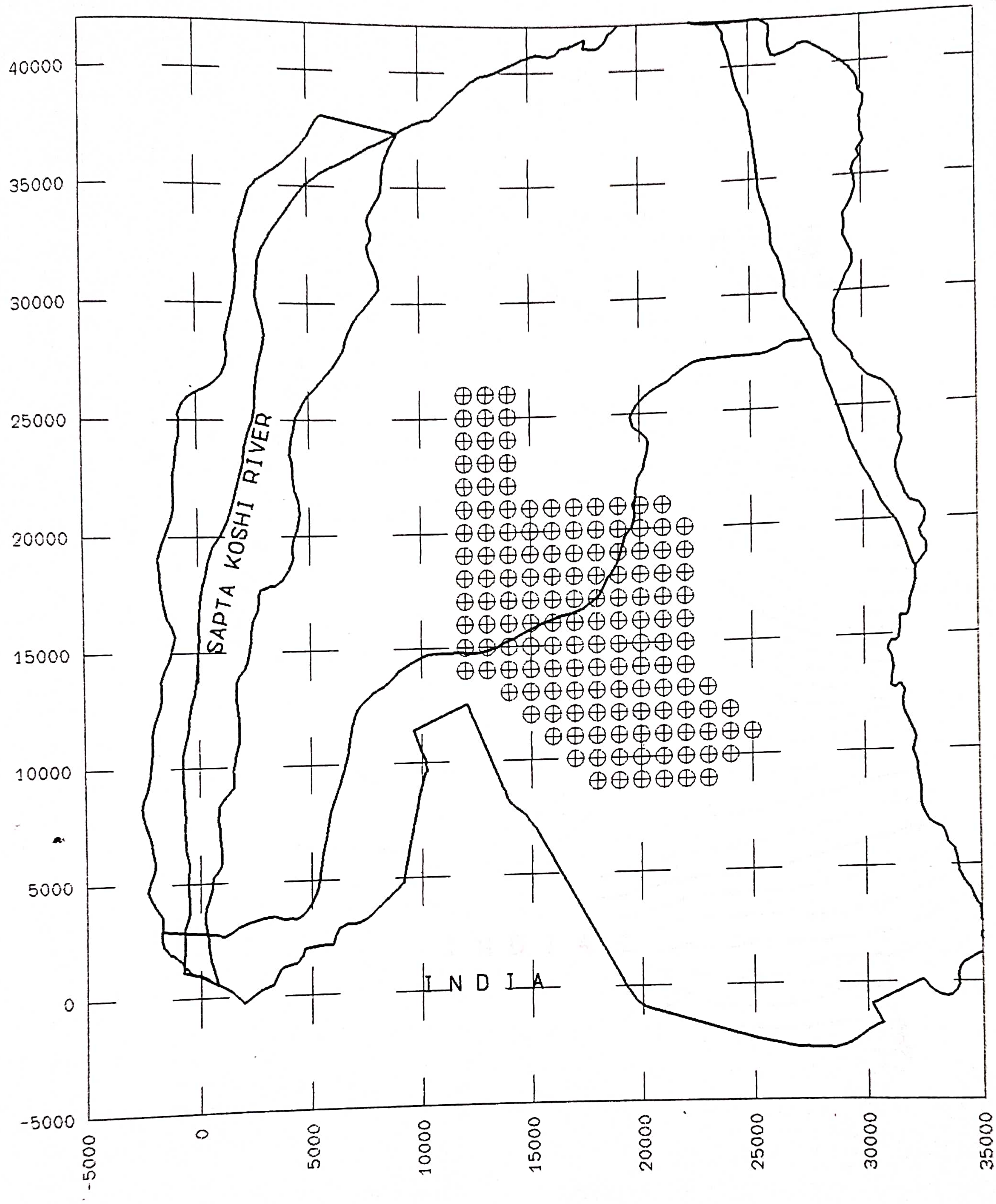

ONE-YEAR VERIFICATION
10,16
86
85
84
83
MAY JUL SEP NOV JAN MAR MAY
JUN AUG OCT DEC FEB APR
10,16


ONE-YEAR VERIFICATION
15,18
86
85
84
83
MAY JUL SEP NOV JAN MAR MAY
JUN AUG OCT DEC FEB APR
15,18


ONE-YEAR VERIFICATION
14,22
81.0
80.0
MAY JUL SEP NOV JAN MAR MAY
JUN AUG OCT DEC FEB APR
14,22


ONE-YEAR VERIFICATION
13,22
81.0
80.0
MAY JUL SEP NOV JAN MAR MAY
JUN AUG OCT DEC FEB APR
13,22

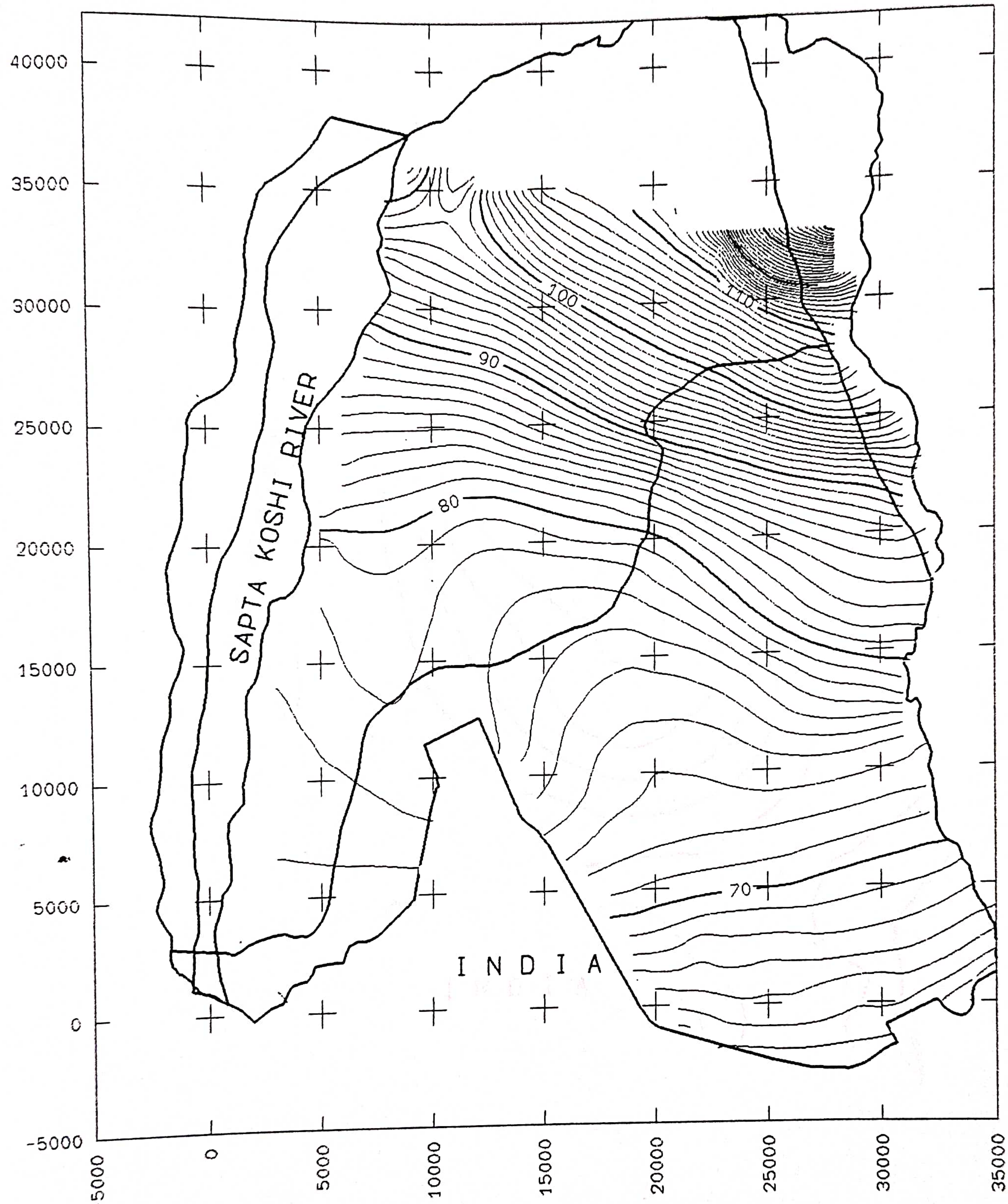
SCHEME A: DISTRIBUTION OF WELLS



APPENDIX 26

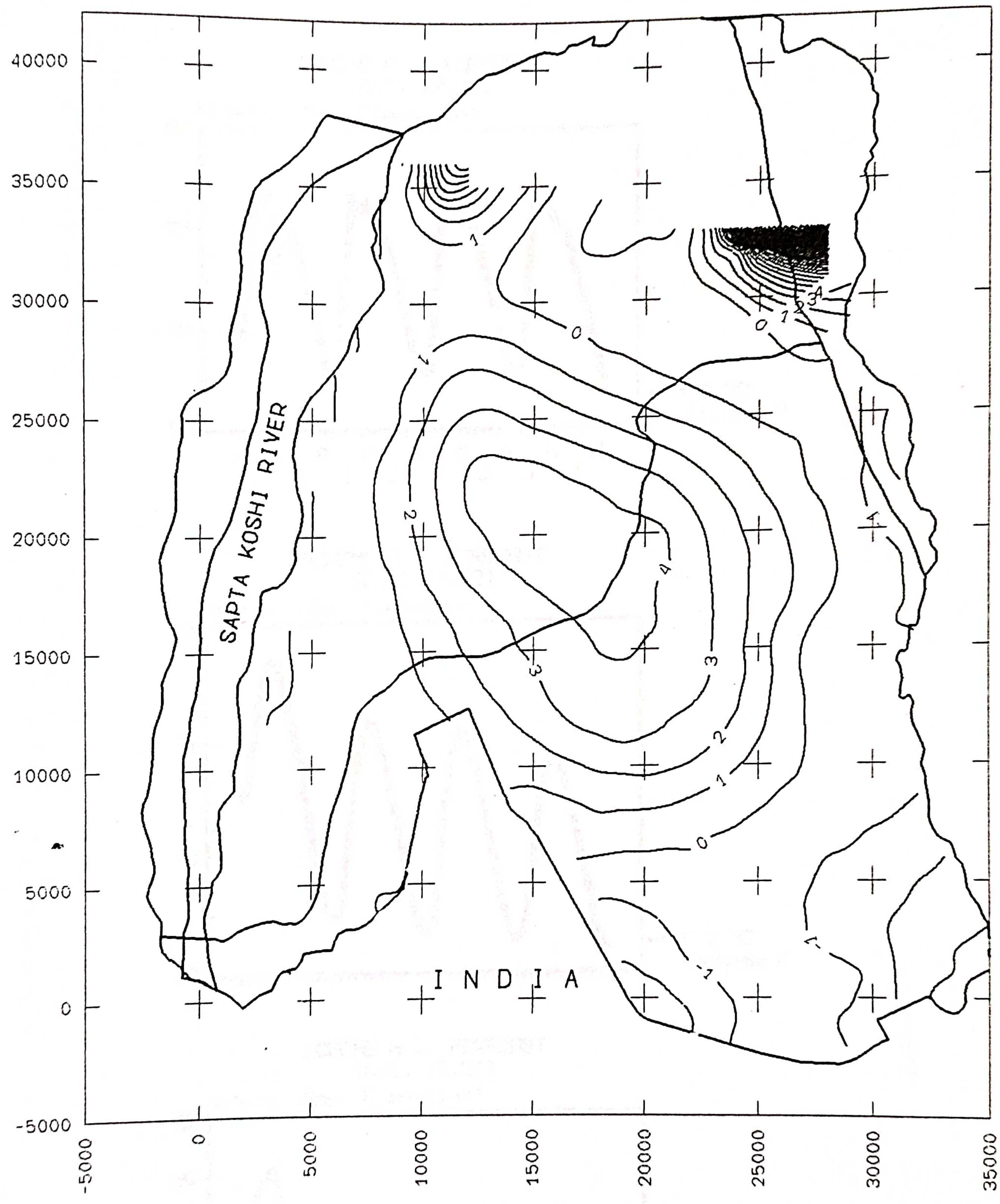
WATER LEVEL CONTOUR MAP

AFTER 4 YEARS OF PUMPING

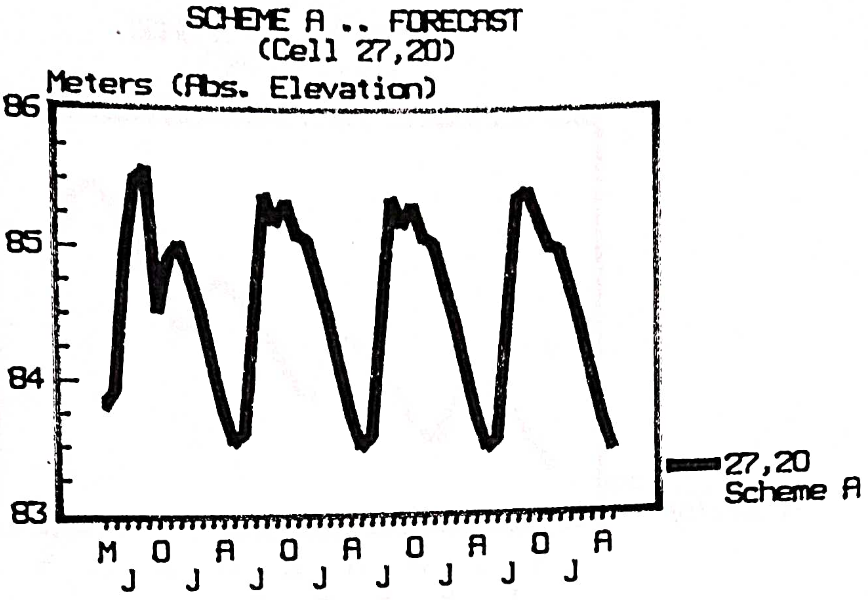


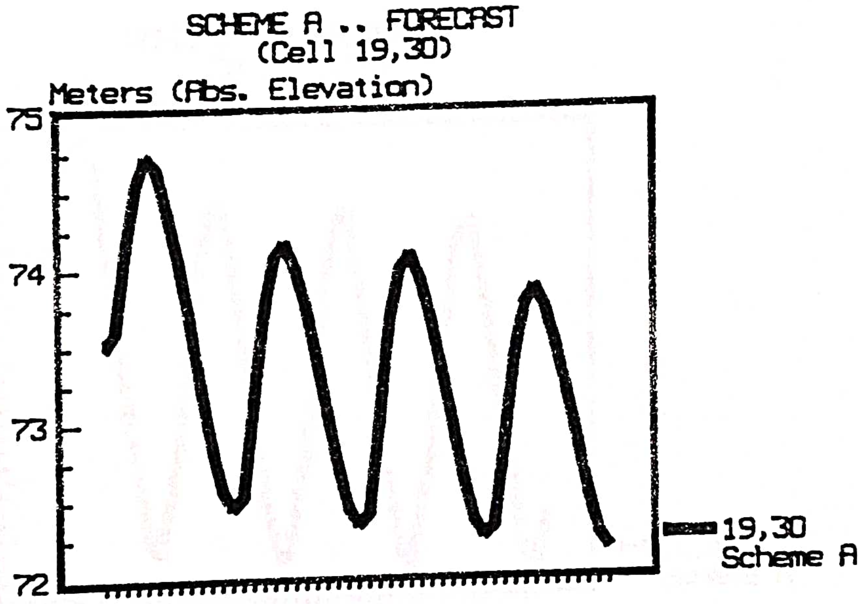
APPENDIX 27

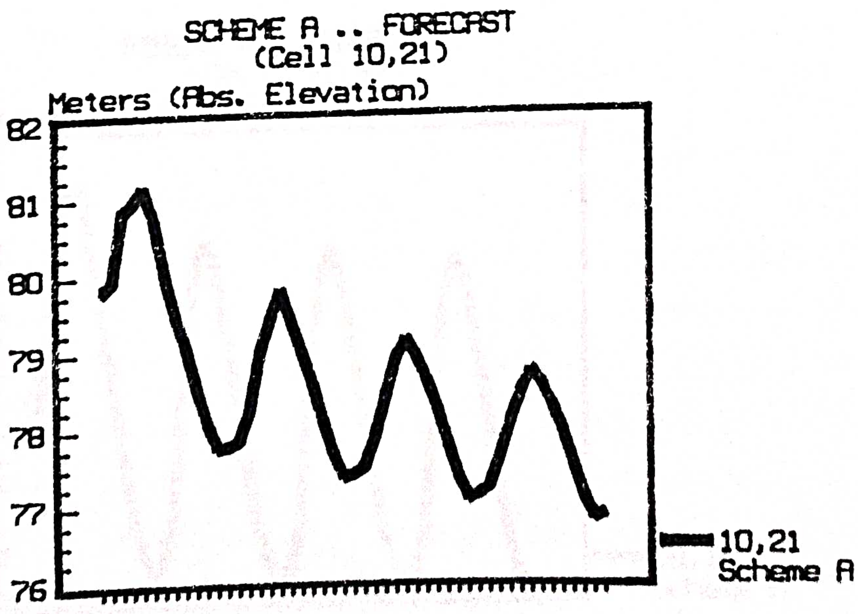
SCHEME A: DRAWDOWN AFTER 4 YRS

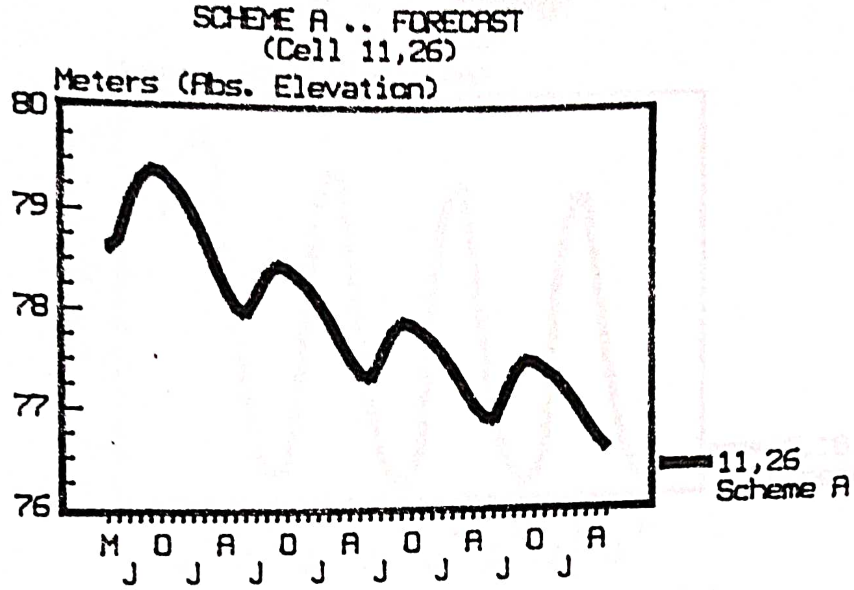


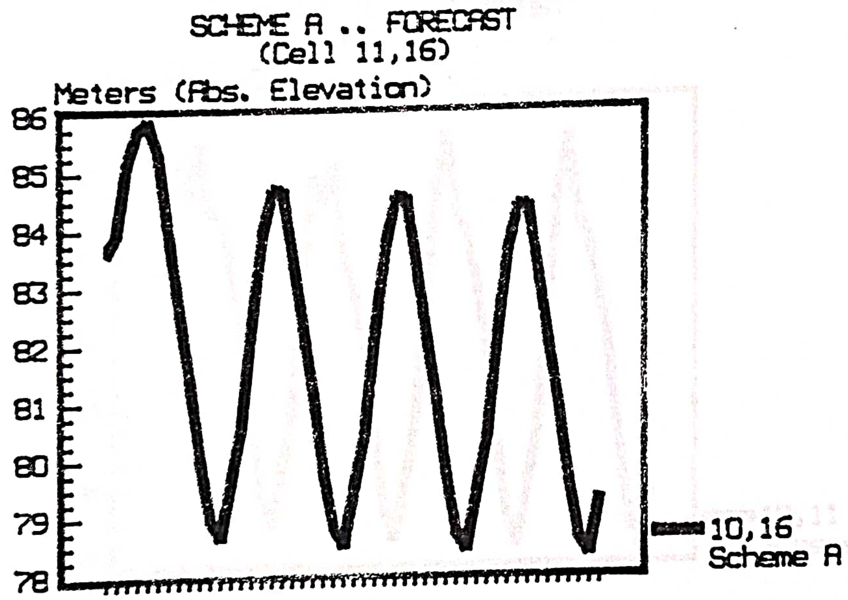
APPENDIX 28

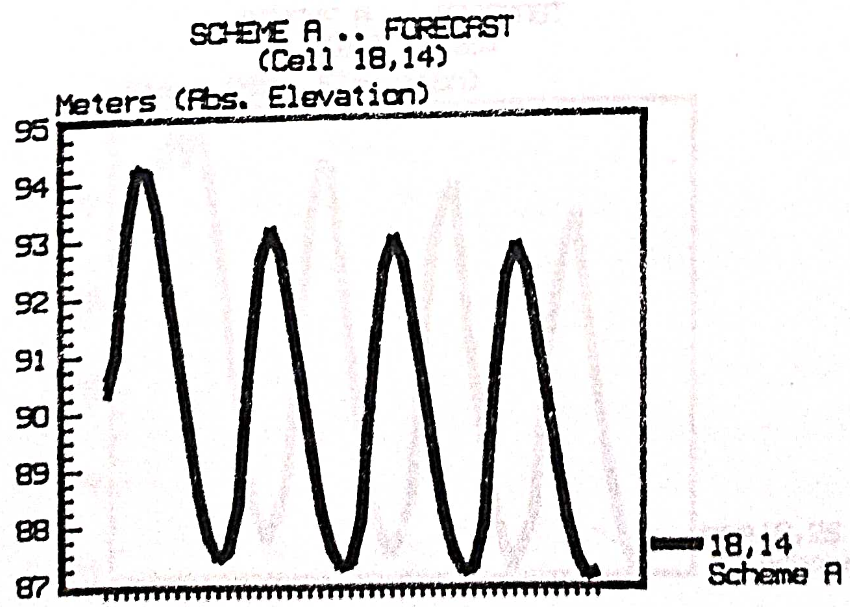

SCHEME A .. FORECAST
(Cell 27,20)
Meters (Abs. Elevation)
86
85
84
83
M O A O A O A O A
J J J J J J J J
27,20
Scheme A

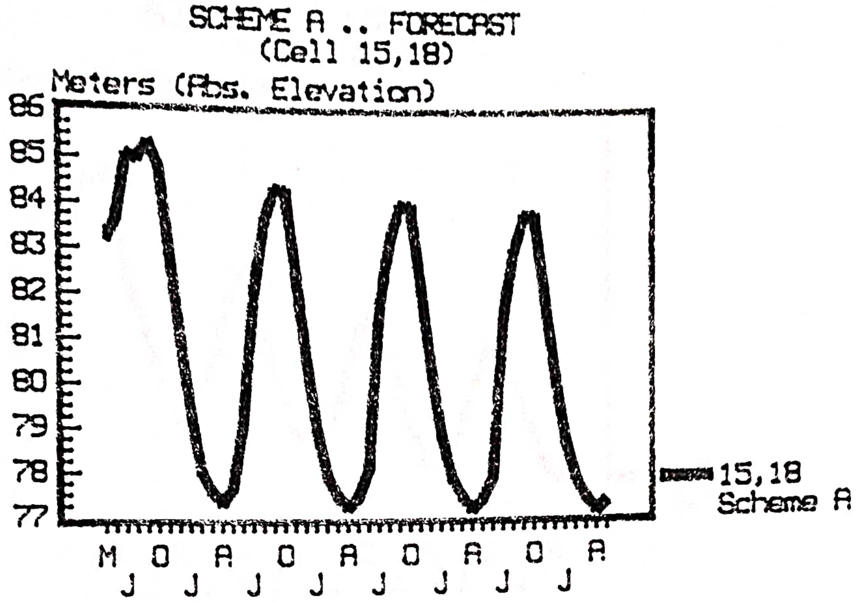

SCHEME A .. FORECAST
(Cell 19,30)
Meters (Abs. Elevation)
75
74
73
72
19,30
Scheme A

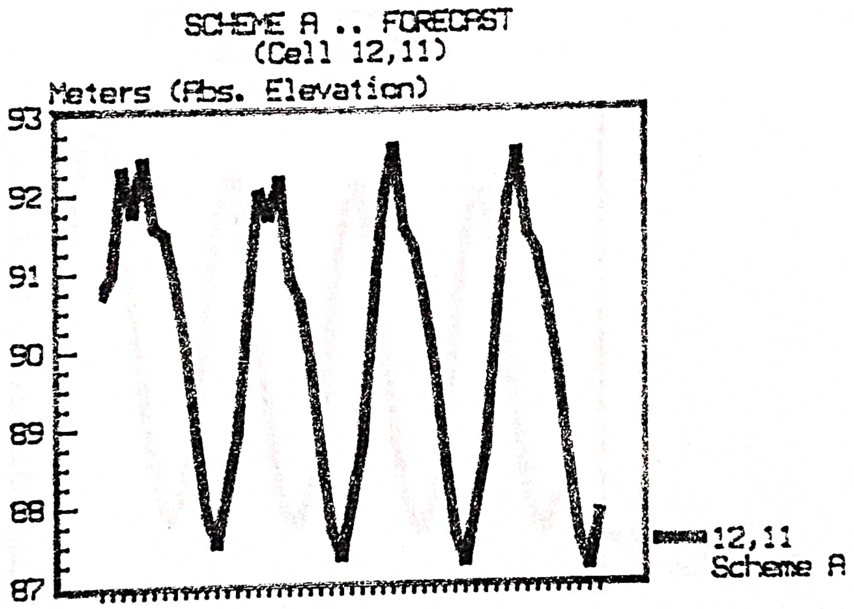

SCHEME A .. FORECAST
(Cell 10,21)
Meters (Abs. Elevation)
82
81
80
79
78
77
76
10,21
Scheme A

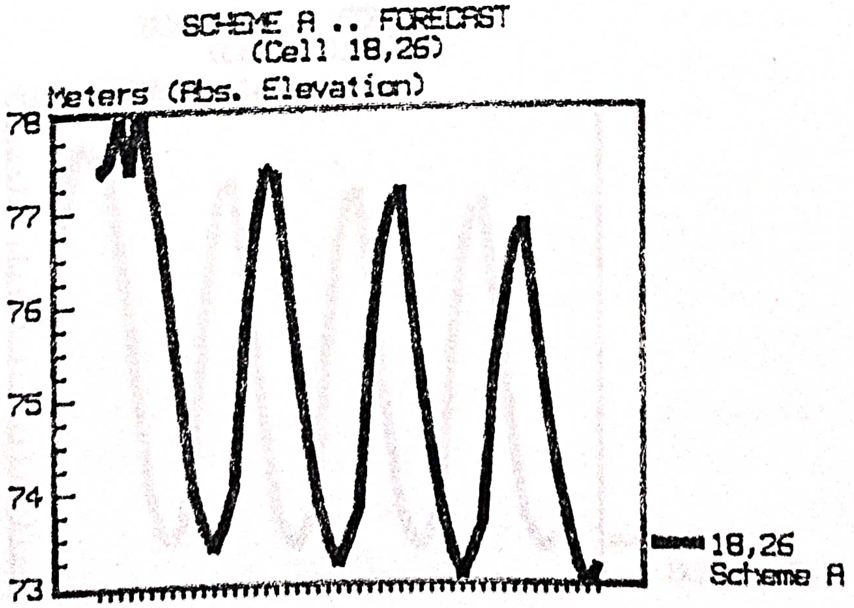

SCHEME A .. FORECAST
(Cell 11,26)
Meters (Abs. Elevation)
80
79
78
77
76
M O A O A O A O A
J J J J J J J J
11,26
Scheme A

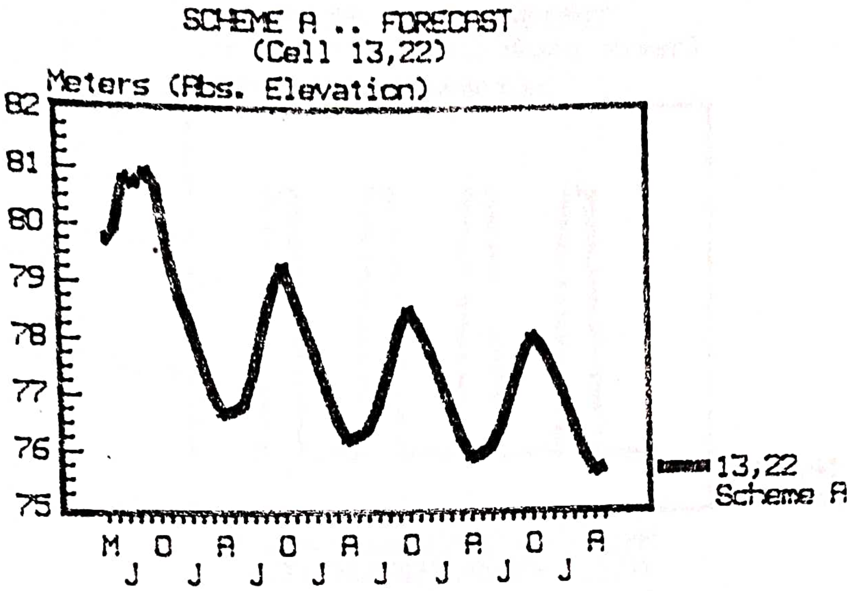

SCHEME A .. FORECAST
(Cell 11,16)
Meters (Abs. Elevation)
86
85
84
83
82
81
80
79
78
10,16
Scheme A

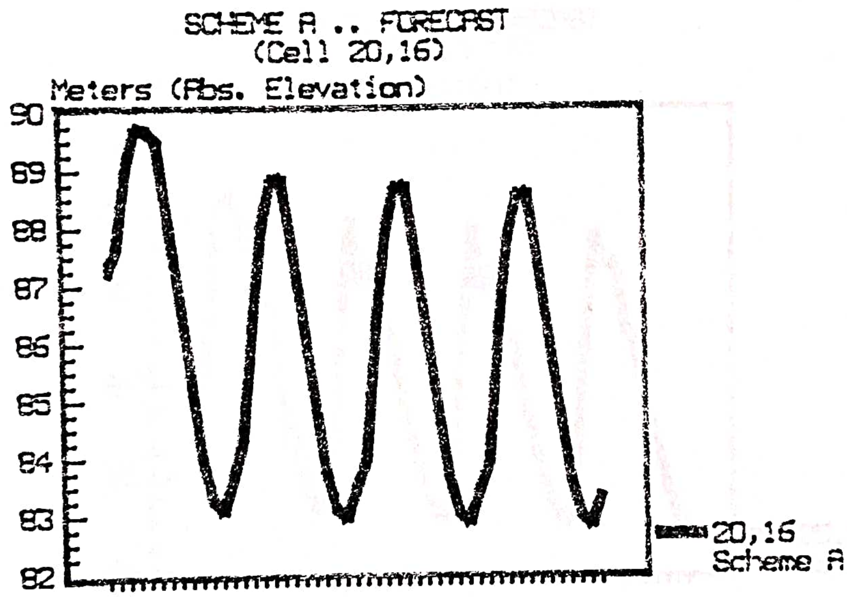

SCHEME A .. FORECAST
(Cell 18,14)
Meters (Abs. Elevation)
95
94
93
92
91
90
89
88
87
18,14
Scheme A

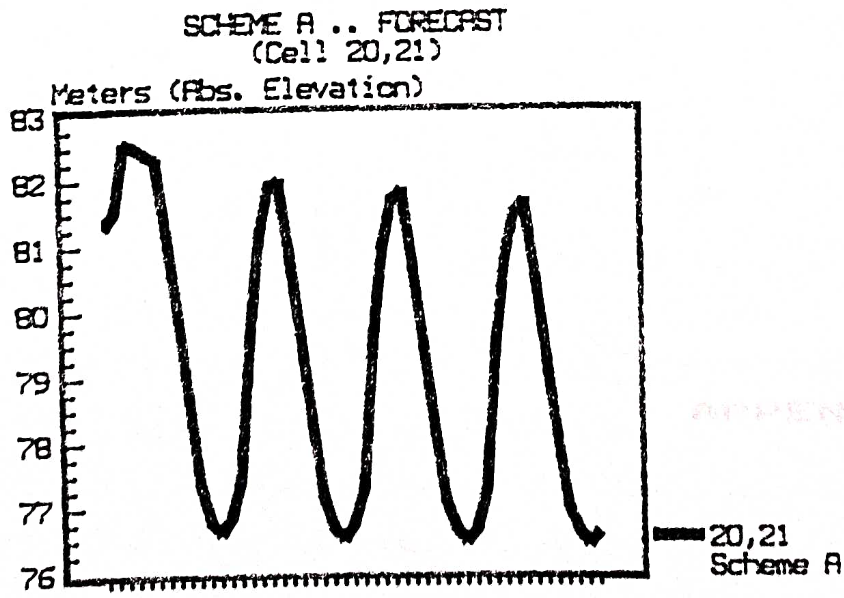

SCHEME A .. FORECAST
(Cell 15,18)
Meters (Abs. Elevation)
86
85
84
83
82
81
80
79
78
77
M O A O A O A O A
J J J J J J J J
15,18
Scheme A

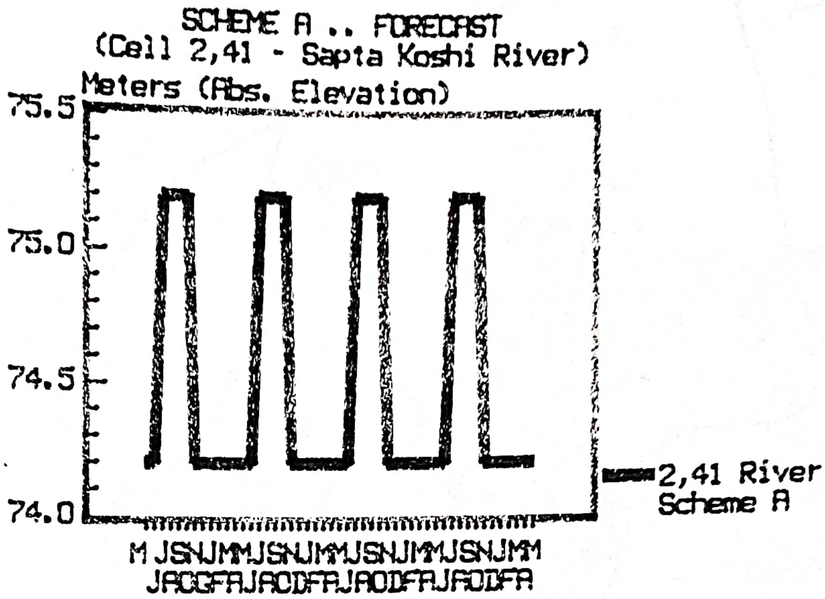

SCHEME A .. FORECAST
(Cell 12,11)
Meters (Abs. Elevation)
93
92
91
90
89
88
87
12,11
Scheme A


SCHEME A .. FORECAST
(Cell 18,26)
Meters (Abs. Elevation)
78
77
76
75
74
73
18,26
Scheme A

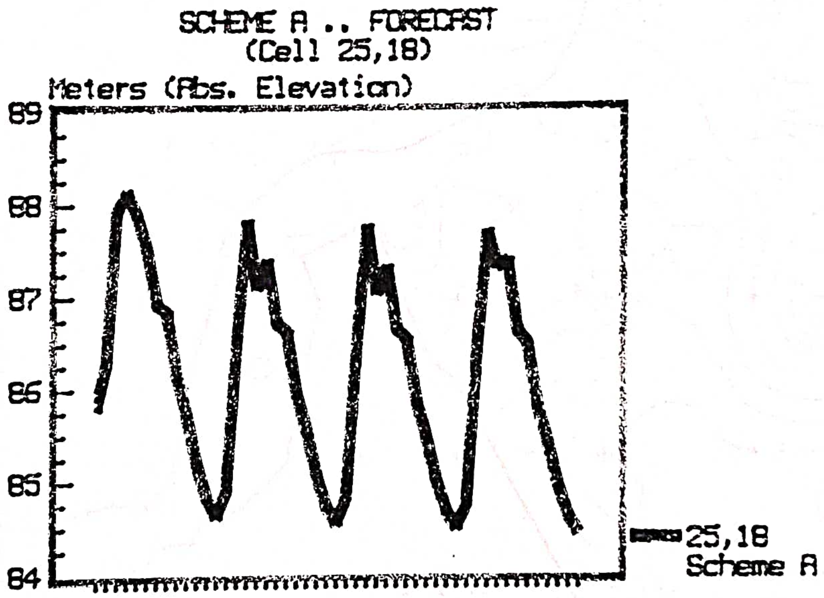

SCHEME A .. FORECAST
(Cell 13,22)
Meters (Abs. Elevation)
82
81
80
79
78
77
76
75
M O A O A O A O A
J J J J J J J J
13,22
Scheme A


SCHEME A .. FORECAST
(Cell 20,16)
Meters (Abs. Elevation)
90
89
88
87
86
85
84
83
82
20,16
Scheme A


SCHEME A .. FORECAST
(Cell 20,21)
Meters (Abs. Elevation)
83
82
81
80
79
78
77
76
20,21
Scheme A



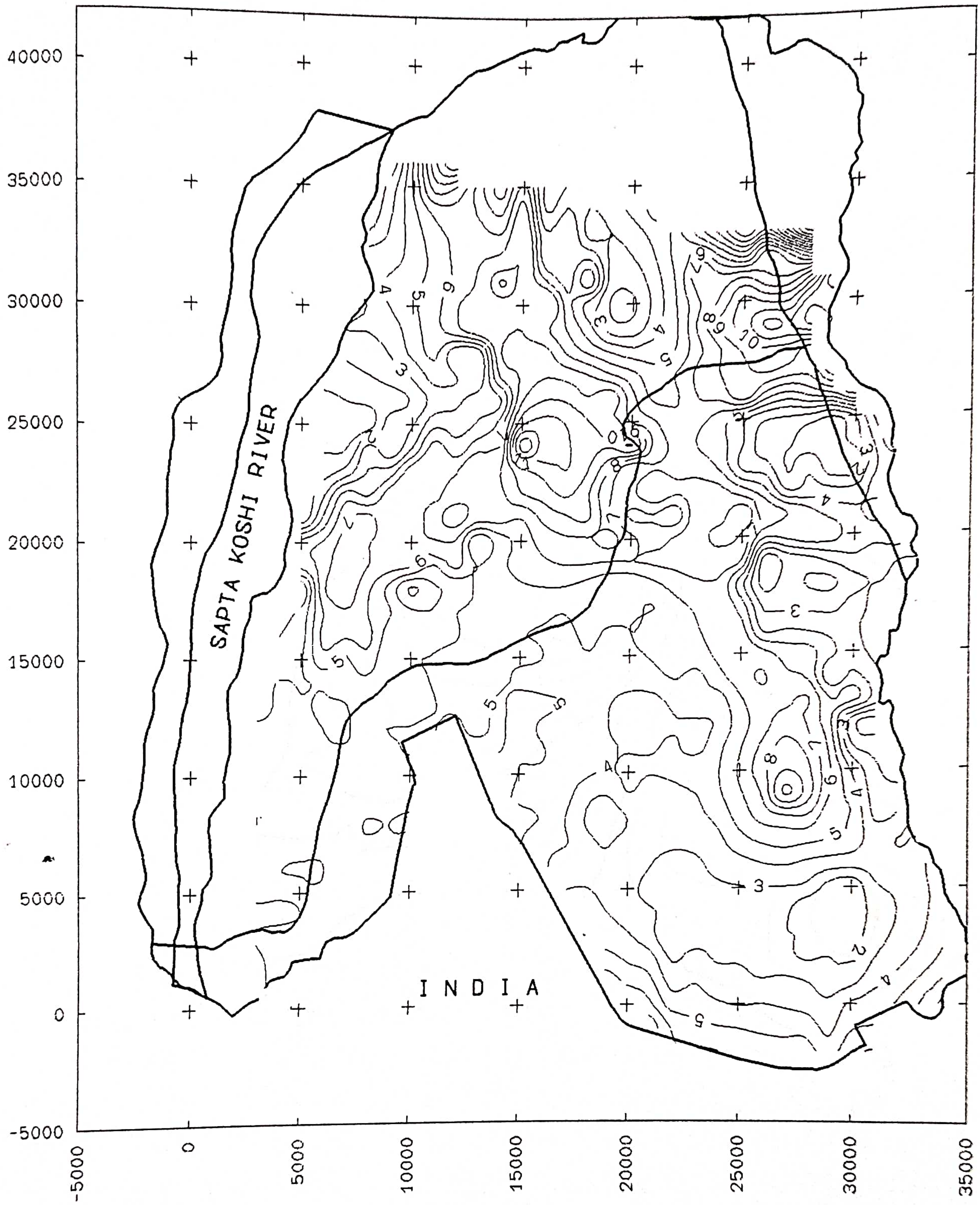
SCHEME A .. FORECAST
(Cell 2,41 - Sapta Koshi River)
Meters (Abs. Elevation)
75.5
75.0
74.5
74.0
2,41 River
Scheme A
M JSNJMMJSNJMMJSNJMMJSNJMM
JAOGFAJAODFAJAODFAJAODFA



SCHEME A .. FORECAST
(Cell 25,18)
Meters (Abs. Elevation)
89
88
87
86
85
84
25,18
Scheme A

SCHEME A: DEPTH TO WATER

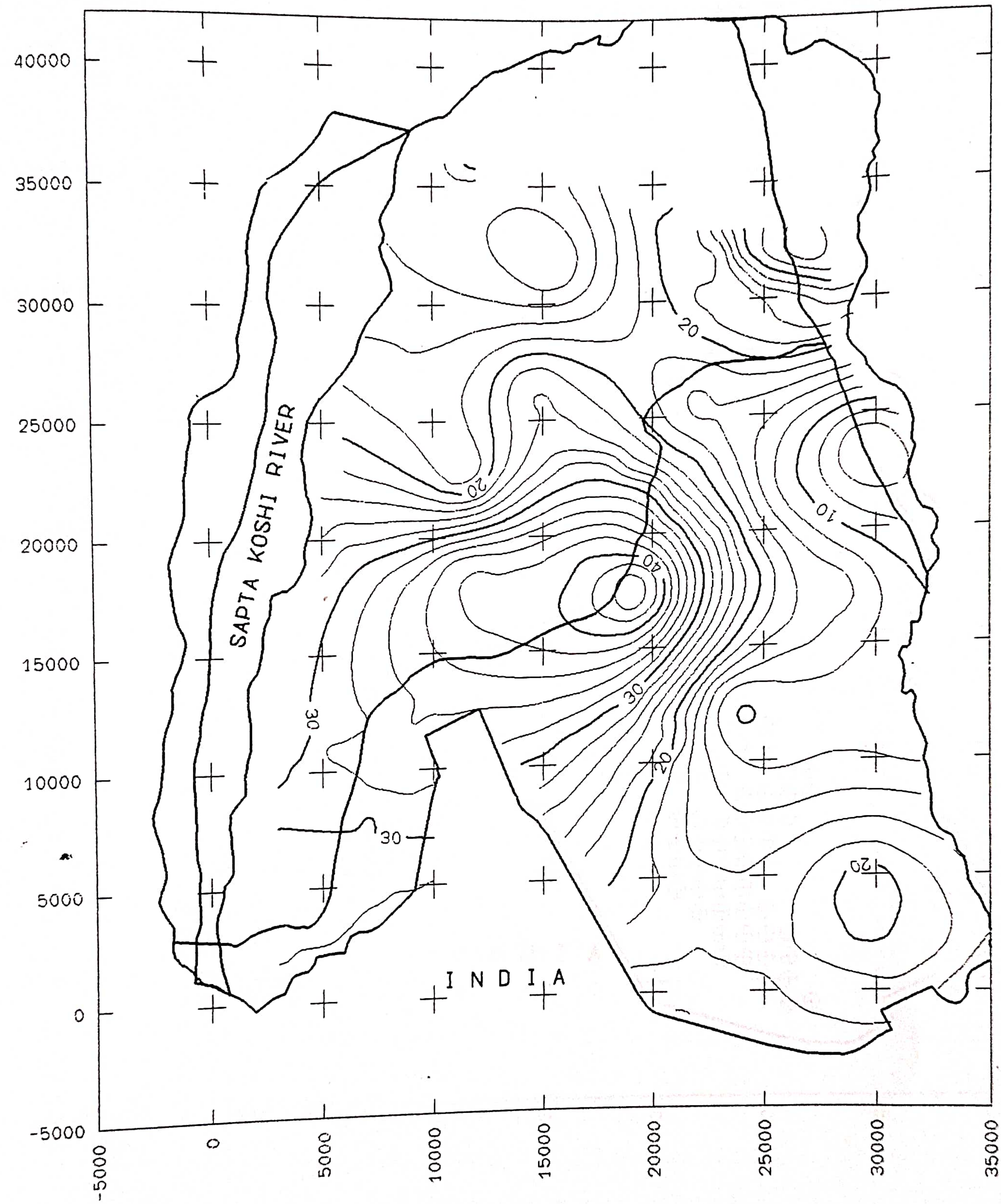
AFTER 4 YEARS OF PUMPING



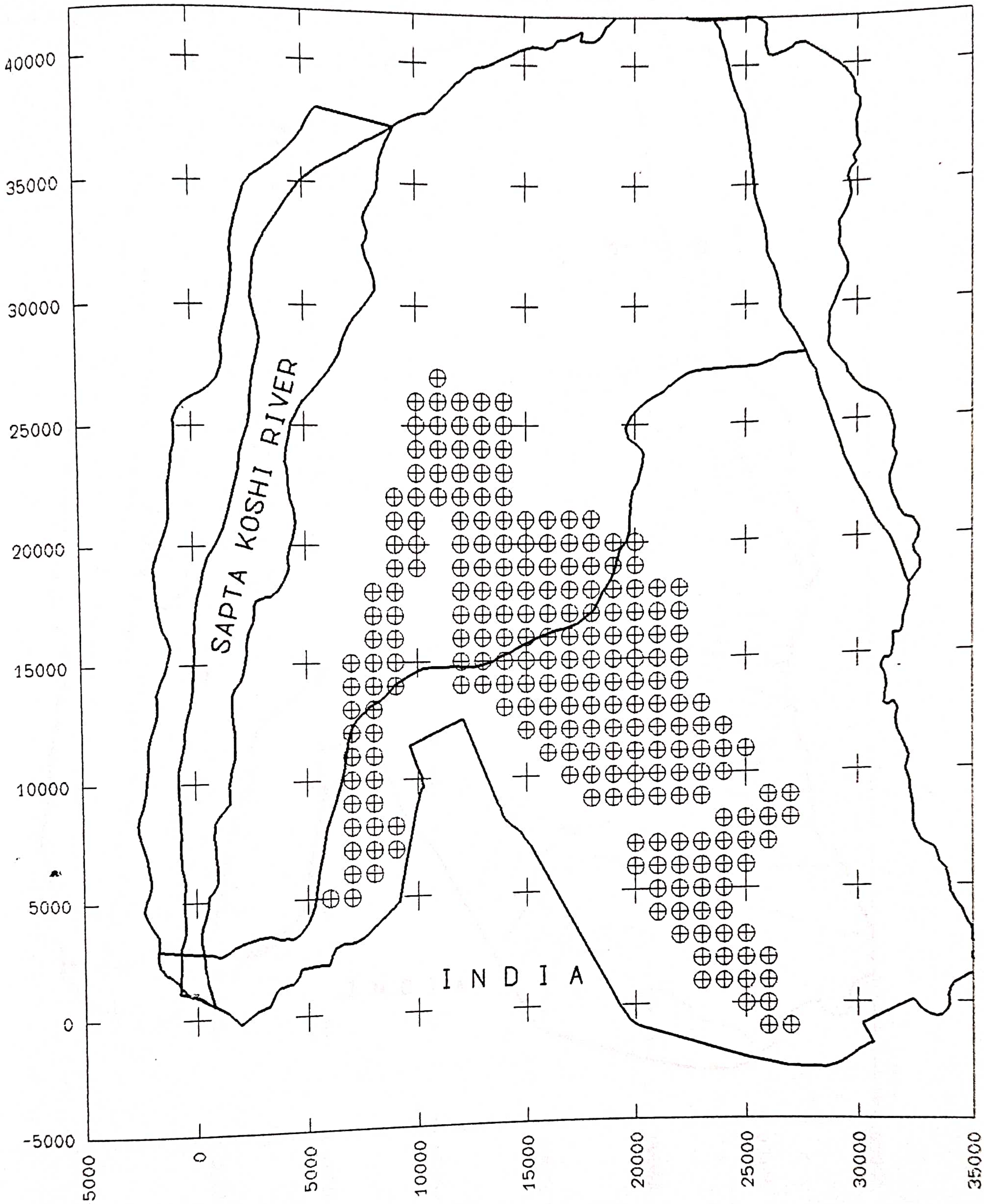
APPENDIX 30

SCHEME A: SATURATED THICKNESS

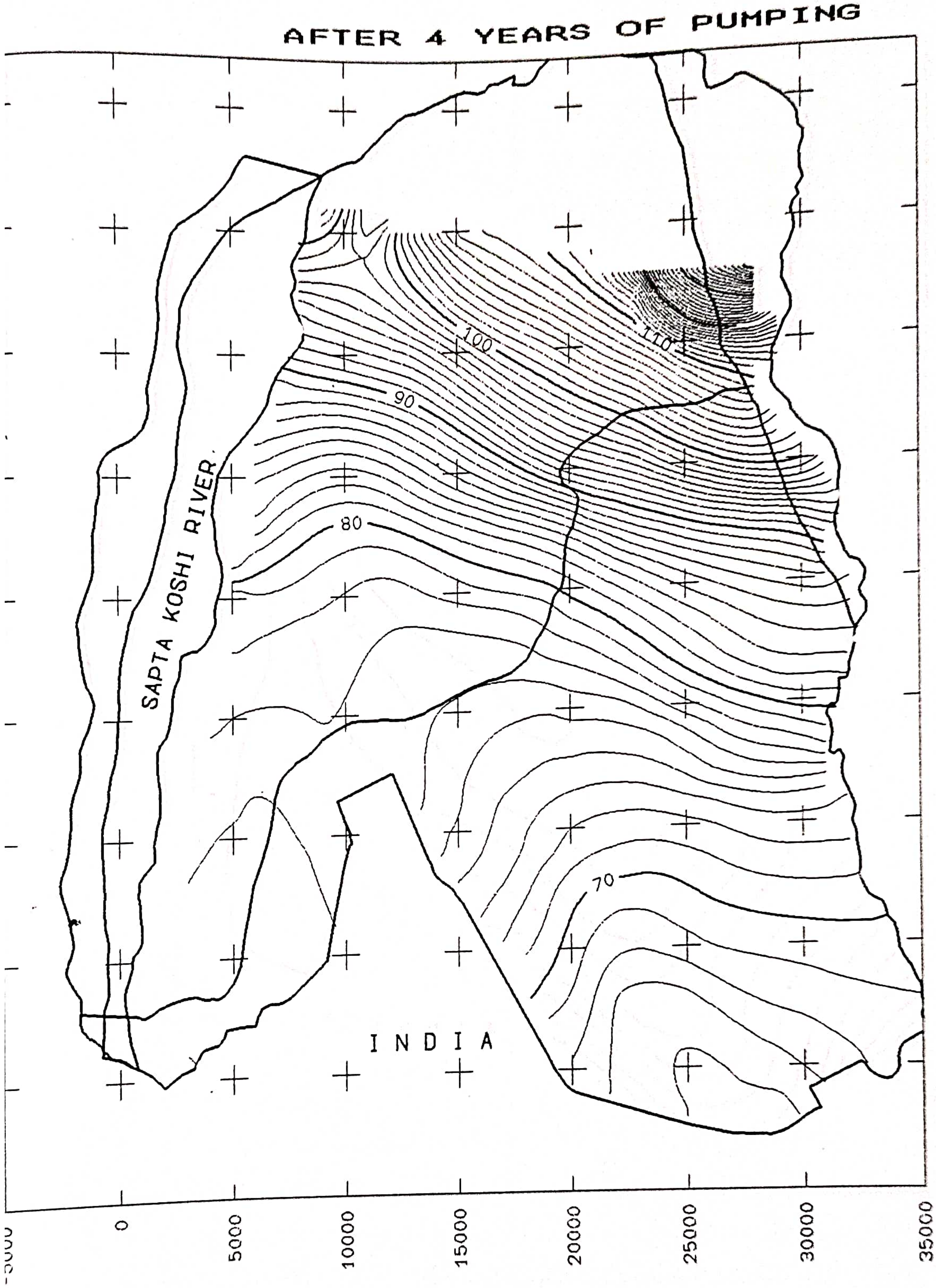
AFTER 4 YEARS OF PUMPING



SCHEME B: DISTRIBUTION OF WELLS

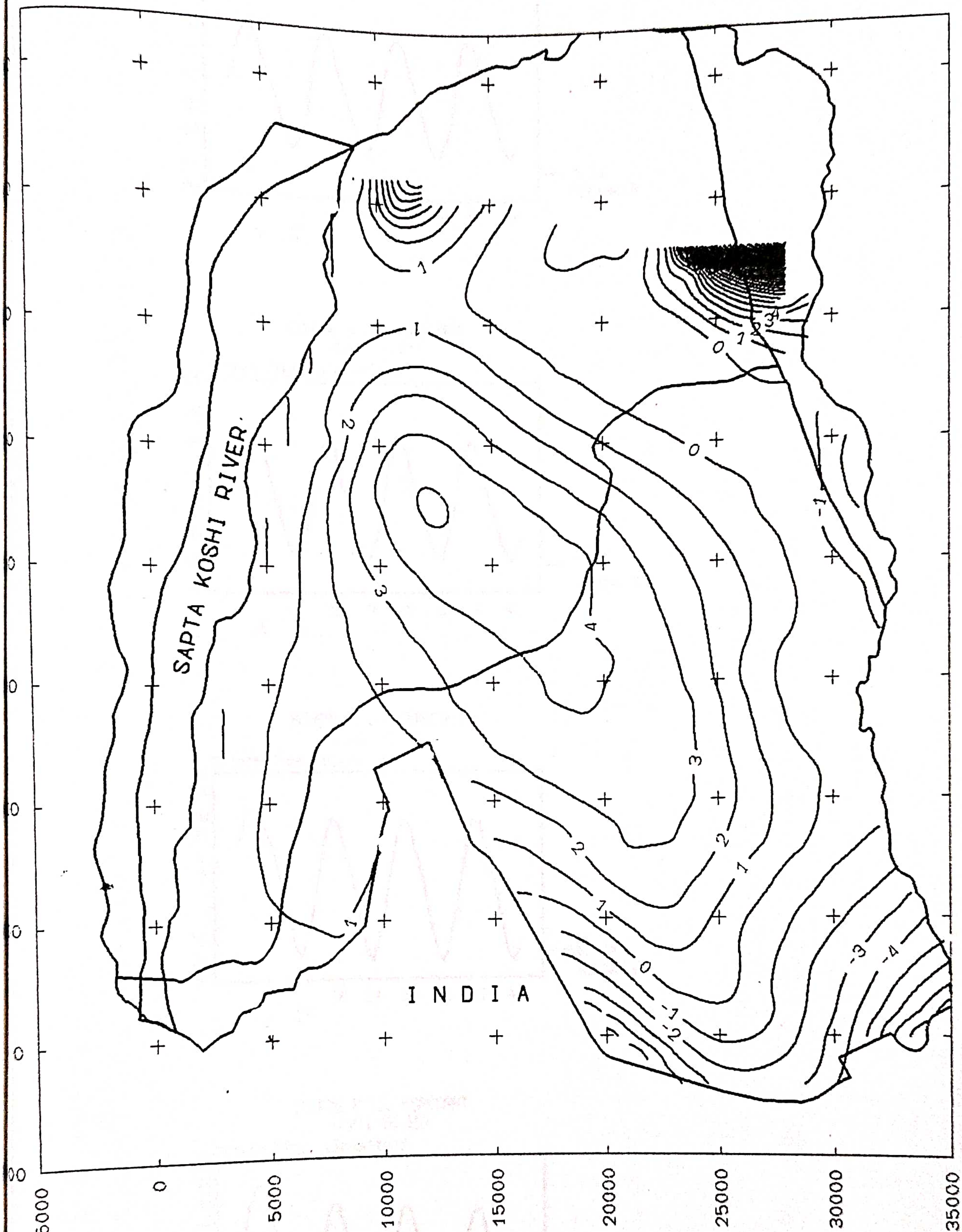


SCHEME B: WATER LEVEL MAP



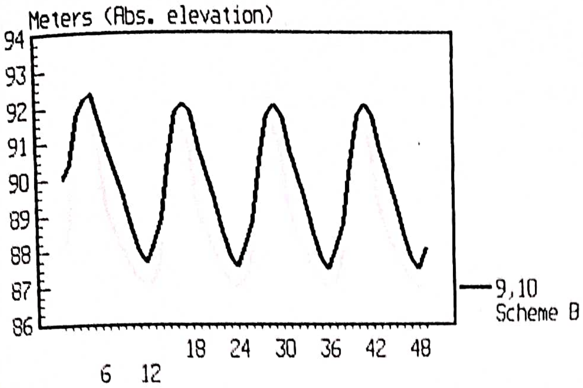
APPENDIX 33

SCHEME B: DRAWDOWN AFTER 4 YRS

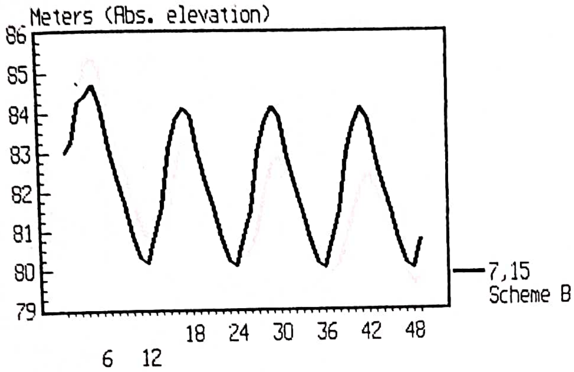


APPENDIX 34

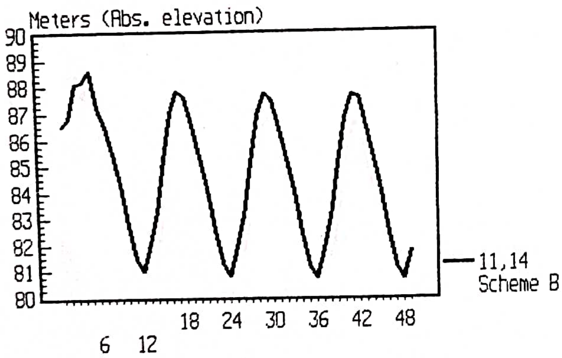
SCHEME B ... FORECAST
(Cell 10,9)



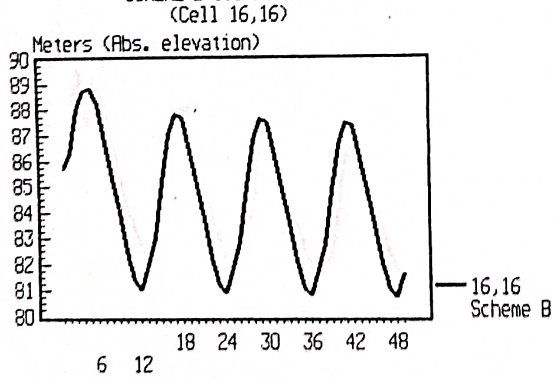
SCHEME B ... FORECAST
(Cell 7,15)



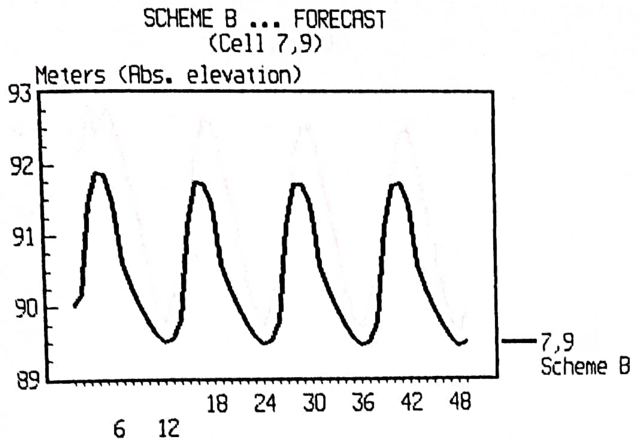
SCHEME B ... FORECAST
(Cell 11,14)

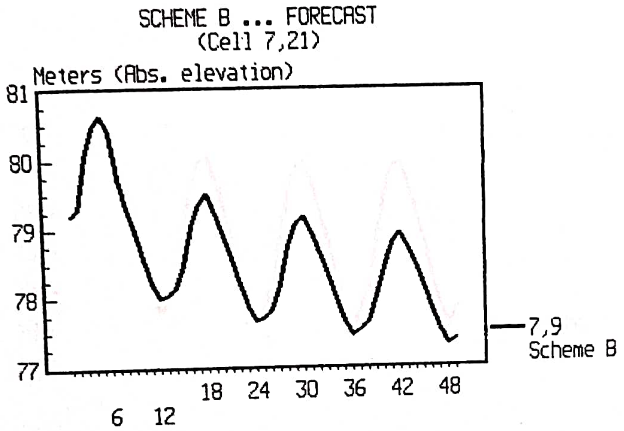


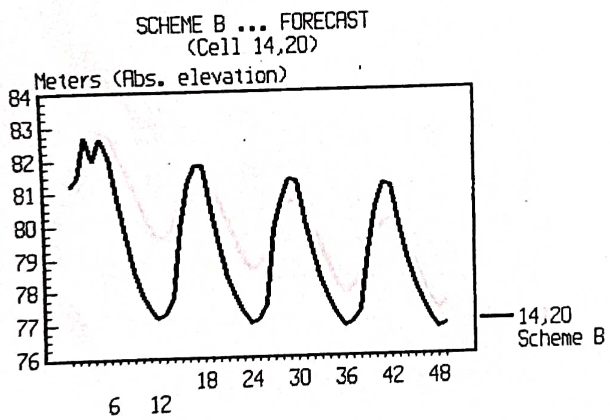
SCHEME B ... FORECAST
(Cell 16,16)

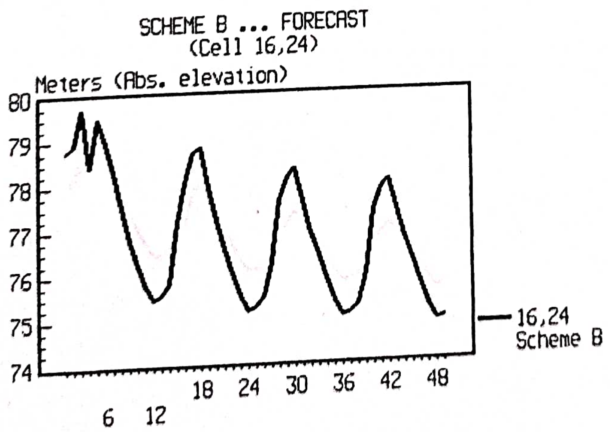


APPENDIX 35/1



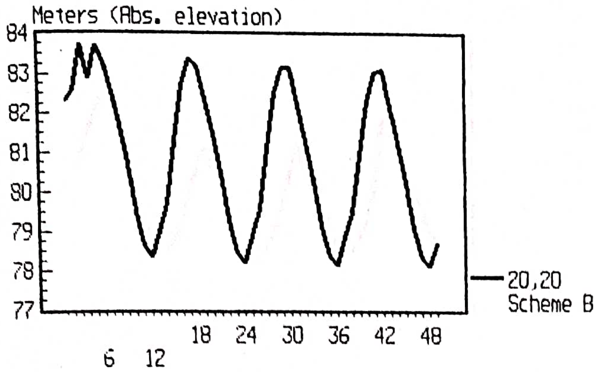




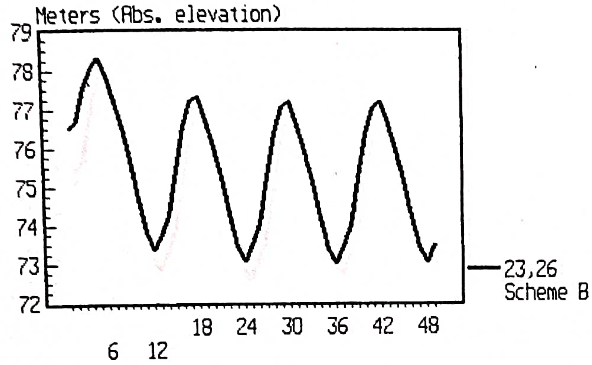


APPENDIX 35/2

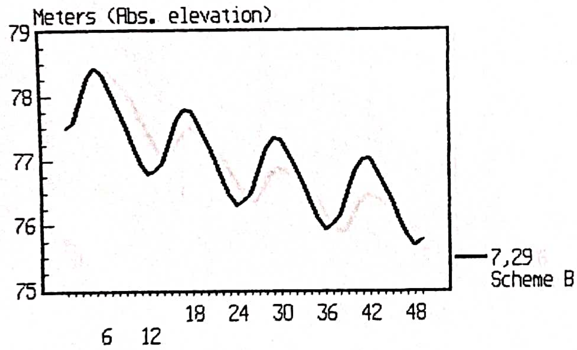
SCHEME B ... FORECAST
(Cell 20,20)



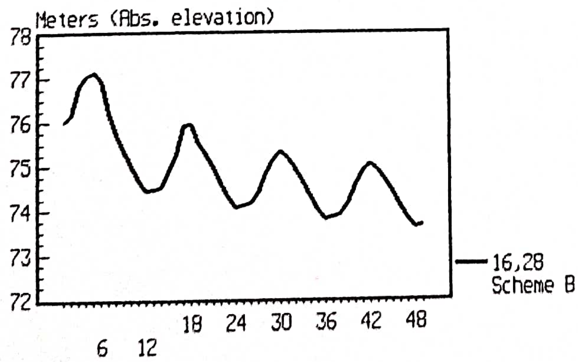
SCHEME B ... FORECAST
(Cell 23,26)



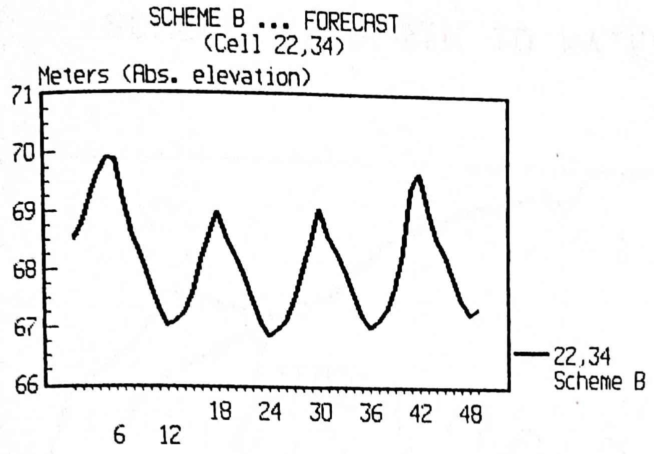
SCHEME B ... FORECAST
(Cell 7,29)



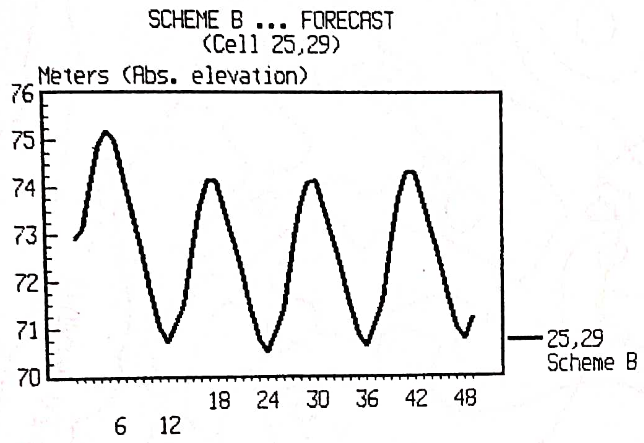
SCHEME B ... FORECAST
(Cell 16,28)



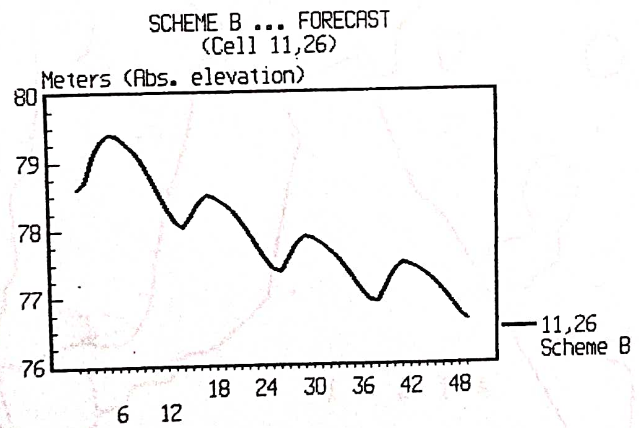
APPENDIX 35/3



SCHEME B ... FORECAST
(Cell 22,34)
Meters (Abs. elevation)
71
70
69
68
67
66
6
12
18
24
30
36
42
48
22,34
Scheme B

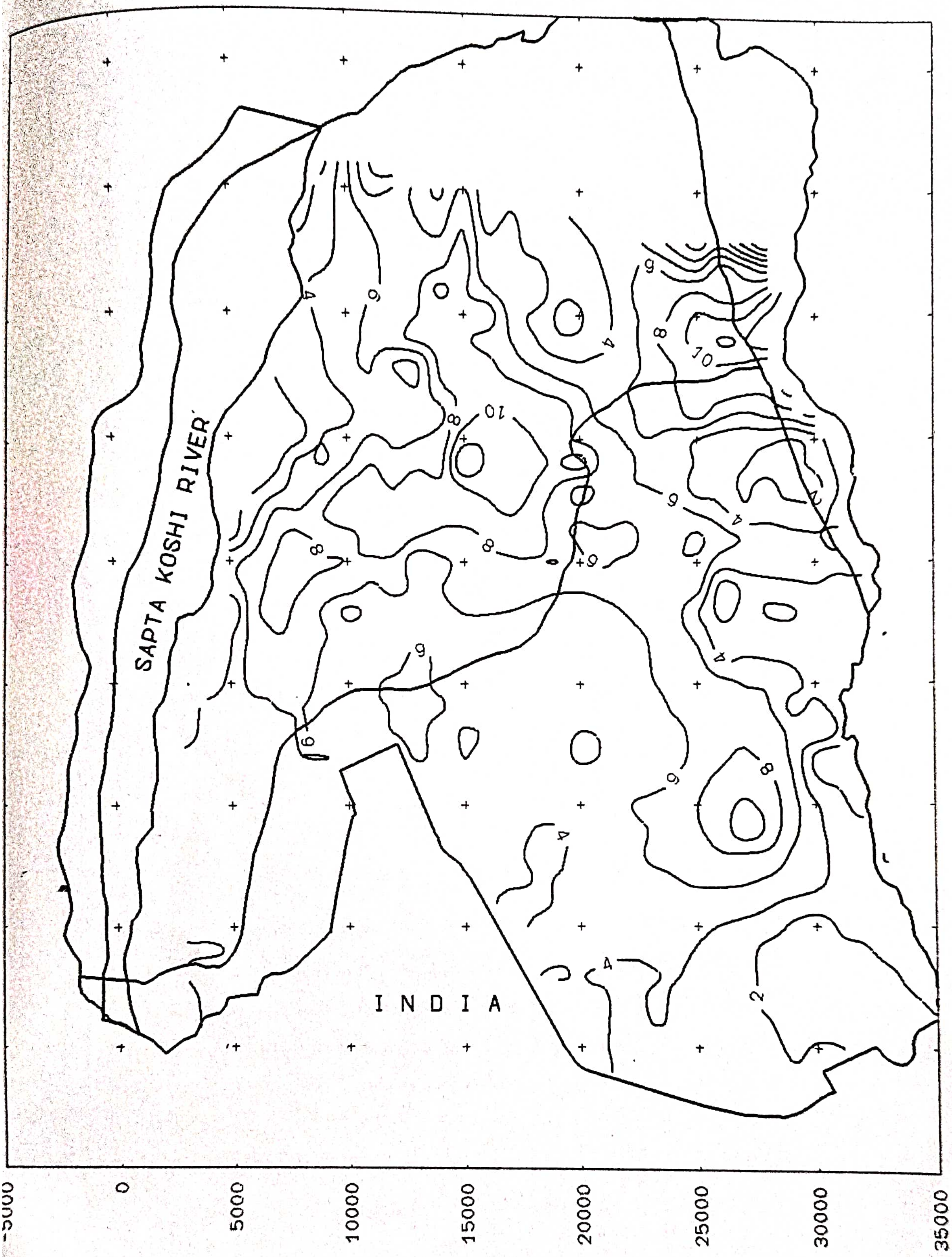


SCHEME B ... FORECAST
(Cell 25,29)
Meters (Abs. elevation)
76
75
74
73
72
71
70
6
12
18
24
30
36
42
48
25,29
Scheme B



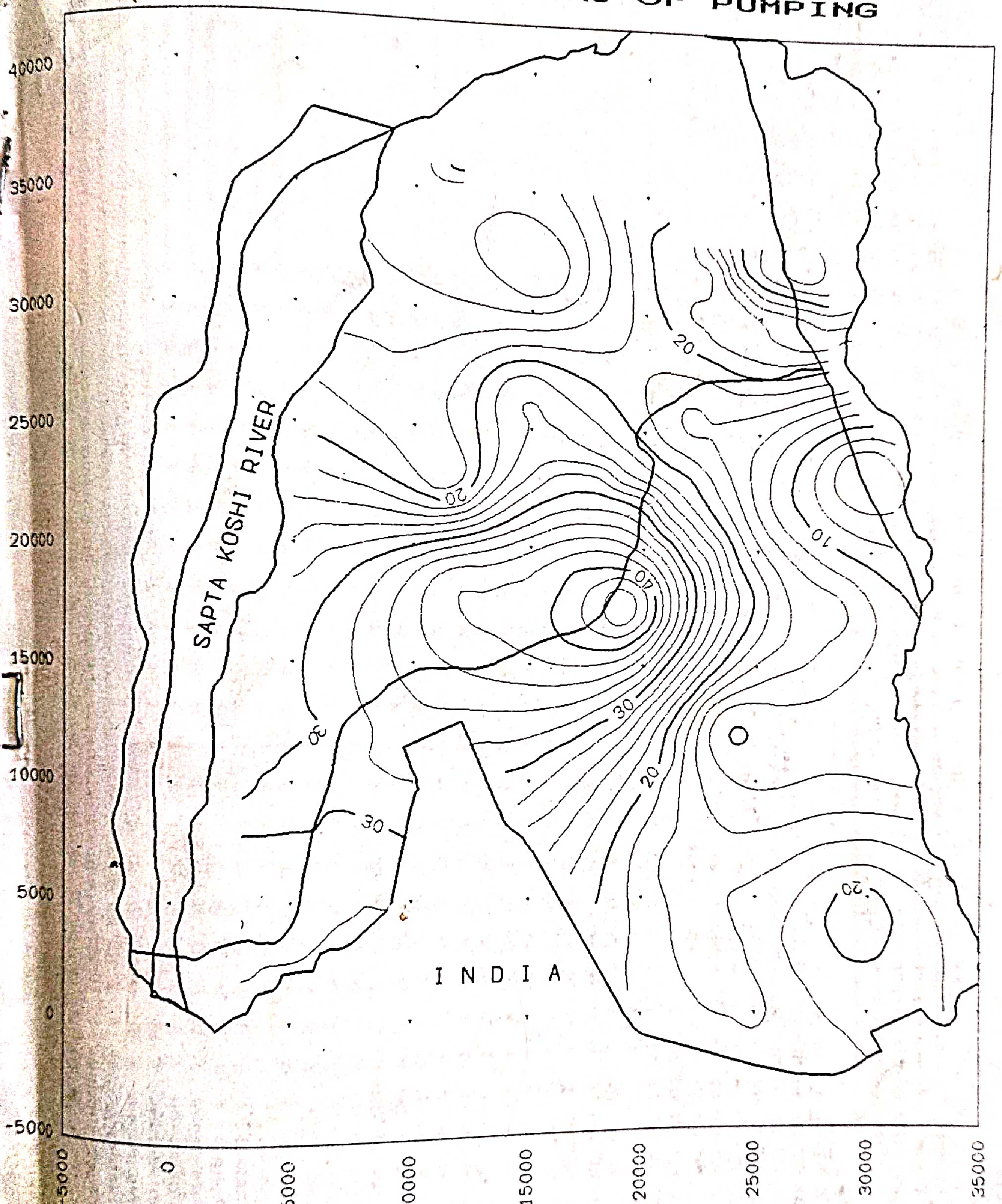
SCHEME B ... FORECAST
(Cell 11,26)
Meters (Abs. elevation)
80
79
78
77
76
6
12
18
24
30
36
42
48
11,26
Scheme B

SCHEME B: DEPTH TO WATER (4 YR)



SCHEME B: SATURATED THICKNESS

AFTER 4 YEARS OF PUMPING



ORATION LOSS

APPENDIX 38

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
1	******	******	******	******	******	******	******	0.	64.	6500.	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
2	******	******	******	******	******	******	******	0.	70.	6500.	6500.	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
3	******	******	******	******	******	******	0.	184.	78.	6500.	68.	77.	98.	175.	186.	141.	62.	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
4	******	******	******	******	******	******	0.	144.	85.	76.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******
5	******	******	******	******	******	******	0.	54.	41.	74.	61.	61.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	******	******	******	******	******	******	******	******
6	******	******	******	******	******	******	0.	36.	46.	35.	62.	72.	0.	0.	0.	36.	34.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	******	******	******	******	******	******	******	******
7	******	******	******	******	******	0.	34.	39.	38.	38.	59.	67.	0.	0.	0.	38.	0.	214.	212.	0.	0.	0.	0.	0.	0.	64.	93.	0.	******	******	******	******	******	******	******
8	******	******	******	******	******	0.	56.	42.	39.	70.	77.	0.	0.	0.	0.	59.	126.	312.	317.	126.	0.	0.	0.	0.	0.	0.	0.	0.	******	******	******	******	******	******	******
9	******	******	******	******	******	0.	57.	46.	41.	73.	0.	0.	0.	0.	0.	68.	60.	231.	239.	92.	0.	0.	0.	0.	0.	0.	0.	0.	******	******	******	******	******	******	******
10	******	******	******	******	******	0.	98.	55.	41.	34.	96.	108.	0.	0.	0.	70.	61.	38.	57.	38.	0.	0.	0.	0.	0.	0.	0.	******	******	******	******	******	******	******	******
11	******	******	******	******	0.	261.	151.	63.	49.	47.	54.	90.	67.	0.	0.	0.	0.	0.	0.	61.	0.	0.	0.	0.	0.	0.	0.	0.	******	******	******	******	******	******	******
12	******	******	******	******	0.	350.	197.	93.	75.	57.	62.	56.	55.	0.	0.	0.	0.	0.	0.	62.	0.	0.	0.	0.	0.	0.	0.	0.	0.	******	******	******	******	******	******
13	******	******	******	******	0.	447.	266.	53.	54.	51.	48.	46.	49.	0.	0.	0.	0.	0.	0.	0.	59.	0.	59.	57.	154.	174.	200.	288.	145.	0.	******	******	******	******	******
14	******	******	******	******	0.	314.	41.	61.	57.	85.	63.	40.	44.	0.	0.	0.	0.	0.	0.	0.	62.	59.	36.	97.	284.	274.	482.	425.	209.	67.	0.	******	******	******	******
15	******	******	******	******	0.	88.	93.	105.	58.	67.	112.	63.	87.	90.	66.	0.	0.	60.	39.	72.	68.	58.	35.	158.	153.	344.	195.	530.	473.	35.	0.	******	******	******	******
16	******	******	******	0.	52.	0.	60.	78.	0.	72.	71.	83.	98.	63.	68.	68.	64.	44.	48.	59.	64.	58.	78.	72.	36.	203.	150.	165.	152.	64.	66.	******	******	******	******
17	******	******	******	0.	70.	0.	0.	72.	62.	75.	65.	76.	98.	33.	71.	61.	60.	34.	51.	51.	59.	81.	71.	0.	0.	66.	88.	34.	37.	60.	******	******	******	******	******
18	******	******	******	0.	0.	0.	0.	0.	85.	84.	60.	56.	59.	37.	93.	80.	84.	69.	41.	36.	33.	78.	0.	0.	78.	89.	108.	73.	35.	35.	65.	******	******	******	******
19	******	******	******	0.	0.	0.	0.	0.	65.	85.	63.	52.	42.	34.	138.	125.	35.	41.	39.	33.	71.	47.	67.	0.	386.	225.	175.	127.	54.	94.	141.	151.	******	******	******
20	******	******	******	0.	0.	0.	0.	36.	941.	389.	365.	92.	33.	34.	39.	47.	65.	51.	53.	37.	41.	42.	42.	43.	388.	233.	310.	317.	184.	149.	185.	225.	******	******	******
21	******	******	0.	732.	0.	0.	0.	63.	368.	587.	336.	70.	71.	97.	44.	35.	53.	37.	44.	53.	46.	37.	49.	45.	182.	183.	185.	190.	140.	178.	228.	295.	******	******	******
22	******	******	0.	605.	0.	0.	0.	367.	332.	614.	638.	95.	625.	77.	44.	42.	55.	46.	44.	47.	46.	41.	34.	62.	96.	54.	55.	86.	145.	180.	249.	******	******	******	******
23	******	******	0.	623.	0.	0.	0.	520.	347.	366.	75.	334.	676.	34.	33.	42.	55.	40.	43.	35.	43.	44.	59.	67.	71.	63.	71.	34.	94.	174.	222.	******	******	******	******
24	******	0.	0.	619.	0.	0.	0.	381.	358.	340.	335.	740.	37.	642.	400.	413.	45.	37.	44.	43.	53.	44.	71.	76.	0.	0.	0.	95.	66.	135.	234.	******	******	******	******
25	******	0.	0.	583.	633.	332.	0.	374.	358.	332.	595.	580.	623.	350.	80.	76.	49.	49.	58.	54.	46.	34.	33.	78.	0.	0.	0.	0.	0.	52.	******	******	******	******	******
26	******	0.	0.	662.	614.	354.	0.	0.	0.	0.	575.	0.	587.	358.	396.	349.	45.	45.	63.	56.	47.	49.	33.	33.	0.	0.	0.	0.	358.	577.	******	******	******	******	******
27	******	0.	668.	0.	599.	609.	333.	0.	0.	0.	553.	1335.	353.	38.	41.	597.	36.	50.	43.	43.	54.	42.	34.	68.	0.	0.	0.	0.	237.	341.	362.	******	******	******	******
28	0.	0.	678.	609.	608.	650.	666.	0.	0.	******	******	******	0.	343.	351.	62.	71.	43.	43.	46.	38.	67.	52.	0.	0.	0.	0.	0.	37.	231.	342.	******	******	******	******
29	0.	597.	594.	621.	691.	691.	673.	0.	0.	******	******	******	0.	0.	333.	39.	36.	52.	36.	38.	47.	55.	89.	0.	0.	0.	0.	0.	59.	192.	240.	******	******	******	******
30	0.	624.	0.	587.	677.	689.	352.	351.	583.	******	******	******	******	0.	0.	37.	536.	611.	40.	34.	34.	74.	101.	0.	0.	0.	0.	0.	0.	173.	159.	37.	******	******	******
31	0.	687.	606.	331.	642.	332.	346.	672.	0.	******	******	******	******	0.	587.	594.	351.	35.	64.	61.	77.	78.	68.	63.	0.	0.	0.	0.	74.	98.	85.	94.	******	******	******
32	0.	616.	636.	334.	351.	687.	0.	670.	0.	******	******	******	******	******	0.	349.	527.	58.	59.	69.	38.	38.	34.	34.	65.	62.	37.	89.	137.	144.	145.	153.	91.	******	******
33	0.	580.	598.	625.	346.	675.	1077.	663.	598.	******	******	******	******	******	******	0.	0.	0.	66.	35.	41.	38.	44.	42.	62.	99.	151.	349.	528.	243.	226.	189.	174.	133.	******
34	0.	579.	603.	338.	582.	669.	1092.	597.	520.	******	******	******	******	******	******	******	0.	0.	0.	66.	351.	37.	43.	58.	140.	185.	428.	466.	635.	357.	301.	245.	220.	186.	******
35	0.	580.	0.	0.	0.	679.	605.	526.	******	******	******	******	******	******	******	******	0.	0.	0.	582.	1294.	540.	382.	859.	161.	239.	309.	392.	577.	398.	342.	308.	252.	229.	187.
36	******	0.	0.	0.	673.	592.	665.	******	******	******	******	******	******	******	******	******	******	0.	0.	0.	890.	36.	40.	601.	1486.	229.	393.	451.	631.	384.	348.	326.	296.	260.	237.
37	******	0.	0.	0.	332.	673.	******	******	******	******	******	******	******	******	******	******	******	0.	0.	0.	966.	355.	379.	549.	1353.	1775.	281.	494.	536.	334.	332.	328.	328.	298.	267.
38	******	0.	0.	0.	******	******	******	******	******	******	******	******	******	******	******	******	******	******	0.	0.	921.	336.	351.	374.	379.	1286.	2141.	380.	249.	282.	327.	350.	340.	******	******
39	******	0.	0.	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	0.	0.	580.	588.	619.	347.	554.	1380.	2940.	196.	222.	******	******	******	******	******
40	******	0.	0.	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	0.	0.	0.	669.	664.	599.	518.	2274.	1627.	176.	******	******	******	******	******
41	******	0.	0.	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	******	1087.	1117.	1103.	586.	1353.	1573.	******	******	******	******	******
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35

COMMENTS:
Evaporation is in [m3day
Time Step = 48
Time elapsed = 0.1440E+04 [day]