MODELING SHALLOW AQUIFER RESPONSE TO DROUGHT: CASE STUDY RAUTAHAT DISTRICT, TERAI, NEPAL[1]

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ABSTRACT

The model of the shallow ground water system of the Rautahat District was primarily made to arrive at a global water balance of the whole district and to indicate a maximum development potential for future intensive ground water exploitation. In the process, all components of the system have been verified. For the purpose of this Symposium, the existing model of Rautahat District has been expanded to check the effect of a sequence of future years with less-than-normal rainfall. Four different schemes have been tested in the future-forecasts modeling phase. Schemes are gradually made more and more severe in the sense of a drought, with final scheme testing a 50% of normal monsoon rain hypothetically occurring in four years in row, followed by the fifth year in which 30% more rain falls compared to the long-term average.

The following is concluded. In a normal year the recharge from rainfall may amount to about 105 million cubic meters (MCM). Considering the size of the model of about 1008 km² and the average annual rainfall of about 1500 mm, the percentage of recharge to the shallow system amounts to about 7. The total input to the shallow aquifer system is about 129 MCM, out of which about 24 MCM comes as boundary inflow of river underflow, entering the Terai Plain from Siwalik hills. The "future-forecast" schemes tested the pumping in amount of 87 MCM, distributed over the central and southern parts of an area of 336 km^2. The pumping from wells was simulated according to current practices in the Terai of Nepal, that is the pumping season starting in November and terminating in April/May, just prior to the onset of monsoon. The monthly pumping rates and volumes are variable, being at maximum in January through March. The total pumping rate is converted into about 260,000 m^3/season/km^2. With 10,000 m^3/ha agricultural demand, this might be sufficient to irrigate a total of about 8,700 ha. With an average well pumping sufficiently to irrigate 6 hectares, the total number of wells simulated in such a development scheme is about 1450.

The decline of water levels in shallow aquifer of Rautahat District is a sequence of "normal" years in a maximum about x meters in the central part of the district, and is approaching a steady or balanced state in most of the area. The abstraction is balanced by (a) reduced evaporation loss due to the lowering of levels, (b) induced recharge from the Bagmati River, and (c) reduced outflow down the gradient from Nepal to India.

The remaining three development schemes differ in the amount of hypothetic future recharge. In scheme B, the recharge in the monsoon season is reduced to 70% of what is believed to be an average monsoon rainfall; in scheme C, the recharge is further reduced to 60% of the normal rainfall in the years 1,2,4,5; in scheme D, the recharge is only 50% of "normal" in the first four years of simulation, followed by 130% rainfall in the monsoon season of the fifth year. The effect of the dry sequence is well documented. Less-than-normal rainfall and recharge do not create extremely adverse consequences. The levels are lowered, but for an acceptable amount. An eventual irrigation system sustained by shallow aquifer development will still have enough ground water, although the pumping may be slightly more expensive. Ground water system is normally large enough that one or more dry years will not stop the development. If a more-than-normal rainfall occurs, the system is rapidly recovering from dry spells. The overall conclusion is that development from a shallow ground water system. such as is Rautahat District, is a very viable project even under "dry" conditions. The model is a proper tool to test and quantify such a system and its input/output.

1. Introduction

The current modeling exercise was a part of the activities in an ongoing United Nations project NEP/86/025, "Shallow Ground Water Investigations in the Terai", executed by the UN Department of Technical Co-operation for Development (DTCD), and financed by the UN Development Programme (UNDP). It is designed as a four-year project primarily oriented to field-data collection, establishment of a ground water data base, and to

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[1] Presented by J.Karanjac in New Delhi, 1990 at the Symposium on "Water Resources in Drought-prone Countries".

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

2. Model Size

The modeled area is completely located in the Terai Plain. The Terai is composed of interlocked alluvial deposits of the wider Ganges Plain and that of fans, channels, floor plains of numerous rivers flowing from the Siwalik Range. The land-surface contour line of 150 m is considered to be the physical end of the Terai's Quaternary sediments. The shallow aquifer extends down to some 35 m from the land surface. The main characteristic of the climate is monsoon rainfall which occurs between June and September and which delivers an average of 85% of the total annual rainfall.

The mean annual rainfall is close to 1500 mm, and pan evaporation is also about 1500 mm. The major potential surface water source for supplementing natural rainfall is the Bagmati River which has a highly variable flow averaging annually 161 m^3/sec at the exit from the Siwalik hills. The location of the modeled district within Nepal is shown in Fig. 1.

The shallow ground water system of Rautahat District has two natural and two artificial boundaries, as shown in Fig. 2, which is in the same time the transmissivity-distribution map. The natural boundaries are the Bagmati River on the east, and the Siwalik hills on the north. The artificial boundaries are the state boundary with India in the south and the western boundary with the neighboring district Bara.
The size of the model is 34 columns by 51 rows, with equal spacing between cells of 1000 m in each direction. The total area occupied by the model is 1734 km^2, which is discretized into 1734 equal-size cells. 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. The model is two-dimensional, meaning that all lithological layers along the vertical to the depth of representation are averaged into one layer. The Rautahat model is based on 25 newly drilled "UN-project" wells, 49 existing water-supply shallow wells, about 25 pumping tests, water level observations since May 1987. The location of wells and discretization of model network is shown in Fig. 3.

3. Aquifer Geometry and Modeled Processes

The geometry of the shallow aquifer, in its north-south direction, is sketched in Fig. 4. The change of land surface slope is evident some 20 or so kilometers from the hills. Although the sketch shows the "bottom" of the shallow aquifer, it is no way an indication of the absence of permeable layers underneath. 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. The saturation line is an artificial projection onto the land surface of the line where the first permeable layer becomes fully saturated.

The shallow ground water system of the Terai is recharged directly from the surface in places in which more or less permeable layer occurs near the land surface. It receives water which infiltrates after rainfall, or which originates from rivers. Ground water, which infiltrates after rains and recharges the shallow aquifer, flows down the gradient mostly in the southern direction toward India. 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 sketch of shallow ground water system components is shown in Fig. 5.

Although the ground water system modeled in this study is two-dimensional, with only one value of hydraulic conductivity and storage coefficient representing one cell, the modeling code permits the distinction between fully saturated aquifer, and its semi- or totally confining layer above. The model also recalculates constantly the real transmissivity based on saturated thickness of the aquifer. The model distinguishes between water table and confining conditions which may switch from one to the other depending on the position of water (piezometric) head. Many pumping tests have produced a map of transmissivity which is as shown in Fig. 2. The range of values is from several hundred square meters per day to over 2,000 m^2/day.

The modeling of the Rautahat shallow ground water system was made possible by monitoring water levels in shallow tube and dug wells since May 1987.

4. Phases of Modeling

The modeling started with steady-state calibration of the model in the period of minimum levels, or maximum depths to water. The month of May 1988¸ was selected for this initial phase, which was to provide a balanced water-level configuration at the end of the dry season. The second phase of the modeling was to confirm the rise of levels over the period from May through September 1988. The third phase was the simulation of the system behavior over one year period. This was more the verification of the model than calibration. The period of simulation was between the months of May of 1988 and May of 1989. The final, fourth, phase of the modeling was to find an "optimum" distribution of hypothetical "future" shallow tube wells and their cumulative pumping rate, which could be interpreted as an "optimum yield" of the shallow aquifer system. For the sake of this presentation, there was one more phase added later, that of hypothetic aquifer behavior under stress in a sequence of dry years. Only the last phase shall be documented herein.

5. Input Data

The modeling process can be thought of a black box such as the following sketch:

INPUT DATA	OUTPUT
Boundary data	Water balance
Land surface	Map of levels
Top of	Hydrographs
Bottom of aquifer	Depth to water
Permeability	Saturated thickness
Storage coefficient	
Effective porosity	Evaporation
Recharge	Permeability
Evaporation	Storage coeff. and eff. por.
Bagmati river	
Initial levels	Declines of levels, etc.

Between the input and output, there is a solution program. This is a mathematical modeling code.

Two of input data files are shown in Fig. 6. The role of input data cannot be overemphasized. A model is only as good as the data used to make it. The program for solution was the UN/DTCD proprietary ground water software, recently developed under the Bermuda project BER/86/001[2].

6. Results of Model Calibration and Verification

The years 1988· and 1989¸ were above-average wet, with annual rainfall reaching over 1800 mm in the low part of the district. In a "virgin" state, that is under current "non-pumping" conditions, the water balance may look as follows:

Rain Recharge	+	Inflow	=	Evaporation	+	Outflow	+	Contr. to River
141	+	67·	=	71	+	3	+	134

All values are in million cubic meters per year. In a typical year there is very little change of cumulative storage, implying that the May levels at the end of the year are close to the May levels one year before. From this water balance one may conclude that a future ground water development from shallow aquifer may come mostly on expense of reduced evaporation and outflow into the Bagmati River. The evaporation loss can be reduced by lowering water levels to a depth that will prevent the losses. The outflow into the river can be reduced by pumping from shallow wells located along a stretch parallel to the river course. The sketch of the water balance in 1988/89 is shown in Fig. 7.

[2] The author of the software package used in this model is J. Karanjac.

7. Forecast of Future Development

Once the model is sufficiently successful in calibrating the past record of evolution of water levels, it can be used for future predictive purposes. The Rautahat model was found to correctly duplicate the behavior of shallow water table in the period from May 1988 through May 1989. The final modelling attempt was made to find out a future potential development potential by locating shallow wells near the river and in areas in which the water table comes closest to the surface. In the context of this Symposium, the model's predictive capability was used to demonstrate the effect of a sequence of more or less dry years on the shallow ground water system. The wells were hypothetically distributed as shown in Fig. 8. The total volume in each of tested schemes was equal to 87 million cubic meters, covering an area of development of 336 km^2. The monthly pumping is as shown in Fig. 9. The tested schemes differ only in the amount of effective rainfall that may produce the recharge to the shallow aquifer. The differences in monthly effective rainfall are shown in Fig. 10 and in table here below.

Scheme	A	B	C	D	D
Years	1-5	1-5	1-5	1-4	5
May	54	38	32	27	70
June	120	84	72	60	156
July	210	147	126	105	273
August	270	189	162	135	351
September	120	84	72	60	156
October	90	90	54	45	117
November	30	30	30	30	30
December	15	15	15	15	15
January	15	15	15	15	15
February	15	15	15	15	15
March	15	15	15	15	15
April	30	30	30	30	30
	984	752	638	552	1243 mm/yr

Extremely high rainfall in the monsoon peak, i.e. in July and August, is reduced to more meaningful values on the grounds that excessive rainfall is not synonymous with effective rainfall because of oversaturation of soils after heavy monsoon rains. The computer model keeps an account of water balance. In this hypothetic exercise the balance is as shown in table here below.

	Rainfall Recharge	Return Irrigation	Evap.	Pumping Wells	Inflow B'dries	Outflow B'dries
SCHEME A	ALL VALUES IN MILLION CUBIC METERS PER MONTH					
YEAR= 1	-102.	-17.	62.	87.	-24.	3.
YEAR= 2	-105.	-17.	67.	87.	-24.	3.
YEAR= 3	-105.	-17.	67.	87.	-24.	3.
YEAR= 4	-105.	-17.	67.	87.	-24.	3.
YEAR= 5	-102.	-15.	63.	77.	-22.	3.
SCHEME B						
YEAR= 1	-80.	-17.	50.	87.	-24.	3.
YEAR= 2	-80.	-17.	58.	87.	-24.	3.
YEAR= 3	-105.	-17.	61.	87.	-24.	3.
YEAR= 4	-83.	-17.	59.	87.	-24.	3.
YEAR= 5	-80.	-15.	54.	77.	-22.	3.
SCHEME C						
YEAR= 1	-69.	-17.	47.	87.	-24.	3.
YEAR= 2	-69.	-17.	52.	87.	-24.	3.

YEAR= 3	-69.	-17.	53.	87.	-24.	3.
YEAR= 4	-69.	-17.	53.	87.	-24.	3.
YEAR= 5	-66.	-15.	48.	77.	-22.	3.

SCHEME D

YEAR= 1	-58.	-17.	46.	87.	-24.	3.
YEAR= 2	-58.	-17.	49.	87.	-24.	3.
YEAR= 3	-58.	-17.	49.	87.	-24.	3.
YEAR= 4	-58.	-17.	48.	87.	-24.	3.
YEAR= 5	-125.	-15.	53.	77.	-22.	3.

COMMENTS.
Scheme A: Normal rainfall ... Effective rainfall 984 mm/yr
Scheme B: 70% of normal rainfall in years 1,2,4,5; 100% rainfall in yr 3.
Scheme C: 60% of normal rainfall in all five years
Scheme D: 50% of normal rainfall in first 4 years, 130% of normal rainfall in 5th year.

--REDUCED EFFECTIVE RAINFALL ONLY IN MAY-OCTOBER PERIOD!

8. Effect of Dry Years on Water Levels

The results are shown in Figures 11 through 18. The first four figures are maps of decline of water levels after the fifth year in each of the tested schemes (A,B,C,D). The decline is not excessive. It reaches a maximum in the central part of about 7 meters in Scheme A, 7.5 meters in Scheme B, 8 meters in Scheme C and D. The evolution of levels throughout the µ-year simulation period is shown in Figures 15. The levels are not steady and the system is not in balance in either of tested schemes. The effect of dry years is clearly shown. One should note the recovery of levels in Scheme D in the fifth year, in which the rain was 30% above the average after a prolonged severe drought. The presentation would not be adequate without a map of remaining saturated thickness of shallow aquifer after the final simulated month (April of the fifth year in Scheme D). This is shown in Fig. 16. Clearly, there remains sufficient saturated thickness all over the model to make either of tested schemes acceptable even in the case of a severe drought. The final two presentations (Fig. 17 and 18) are water levels (heads) after five years, in Schemes A and D, respectively. The flow pattern is the same, from north to south. The recharge from the Bagmati River (eastern model boundary) is evident from the row 21 to 51.

9. Conclusions

The model of the shallow ground water system of the Rautahat district proved that the ground water development and irrigation with ground water is a viable undertaking even under severe drought conditions. The aquifer can sustain several years of drought without being depleted under the tested scenario. The negative effect is the higher cost of pumping due to higher pumping lift. Yet the aquifer remains more than 50% saturated and recuperates rather quickly after the dry sequence is over.

This modeling is a kind of processing a very specific management scenario. This exercise provides quantitative answers to the specific question of reliability of a shallow ground water system development in an environment which is normally believed to heavily depend on the regularity of rainfall events. However, this last statement may be true for surface water sustained irrigation systems, which go almost completely dry if monsoon is late or weak. The ground water system of the Terai of Nepal is extensive enough to act as a regulatory storage providing enough water to compensate for reduced recharge.