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Research paper

Groundwater modeling and demarcation of groundwater protection zones for Tirupur Basin – A case study

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Abstract

Groundwater is a renewable resource and has to be protected from contamination. The concept of a zone of protection for areas containing groundwater has been developed and adopted in a number of countries. One such area is Tirupur, (Tamil Nadu, India) which is an arid region and rapid expansion of the textile industry has taken place with no associated development of supporting infrastructure or institutional capacity. Textile production, particularly dyeing and bleaching is water intensive and generates large quantities of effluent. One of the most significant challenges for the Tirupur textile industry today is water for bleaching and disposal of effluent. Demarcation of groundwater protection zones has become necessary to facilitate recharging of the aquifer to meet the water demand. These zones are considered sensitive zones and should be free from activities such as the groundwater over exploitation, effluent discharge and construction of barriers. Groundwater flow for Tirupur Block was simulated using visual MODFLOW version 4.1. The model was run for the year 1998–99 with transient flow condition. Taking June 1998 water level as initial head, the model was run to simulate water level up to May 1999 and validated with the observed data for all the six wells which are distributed over six different zones. The results obtained from the simulation were used to assign the ranks and weights for overlay process in Geomedia environment. The consequent higher index values indicate the sensitivity zone influencing recharge to the aquifer which should be demarcated as groundwater protection zones. This groundwater protection zone will be designated as pollution free zone for better management of the aquife.

Keywords: Groundwater; Textile effluent; Demarcation of protection zone; Visual MODFLOW

1. Introduction

Groundwater is a renewable resource, hence it is not only sufficient to assess the potential of groundwater but also necessary to manage it efficiently, so that long-term benefits can be achieved (Singh, 1997). The concept of a zone of protection for areas containing groundwater has been developed and adopted in a number of countries. Many have developed guidelines for water resource managers who wish to delineate protection areas around drinking-water abstraction points (e.g. Adams and Foster, 1992; NRA, 1992; US EPA, 1993). Historically, groundwater protection zones were developed using a variety of concepts and principles. Although some include prioritization schemes for land use, all aim is at controlling polluting activities around abstraction points in order to reduce the potential for groundwater contamination. Criteria commonly used for these include the following: distance, drawdown, time of travel, assimilative capacity and flow boundaries.

Many countries have developed and implemented policies for preventing the pollution of groundwater. These commonly involve regulatory control of activities which generate or use

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polluting materials or control of the entry of potential pollutants into vulnerable surface and underground waters. However, protection zones are not applied in all countries, despite recognition of their desirability (Bannerman, 2000). This may be due to a number of factors, including the lack of sufficiently detailed information regarding the hydro-geological environments (Taylor and Barrett, 1999; Bannerman, 2000) or existing land uses that impede enforcement of such a concept. Furthermore, poverty, uncertain tenure and limited capacity to provide compensation packages suggest that such approaches may be difficult to be implemented particularly in developing countries.

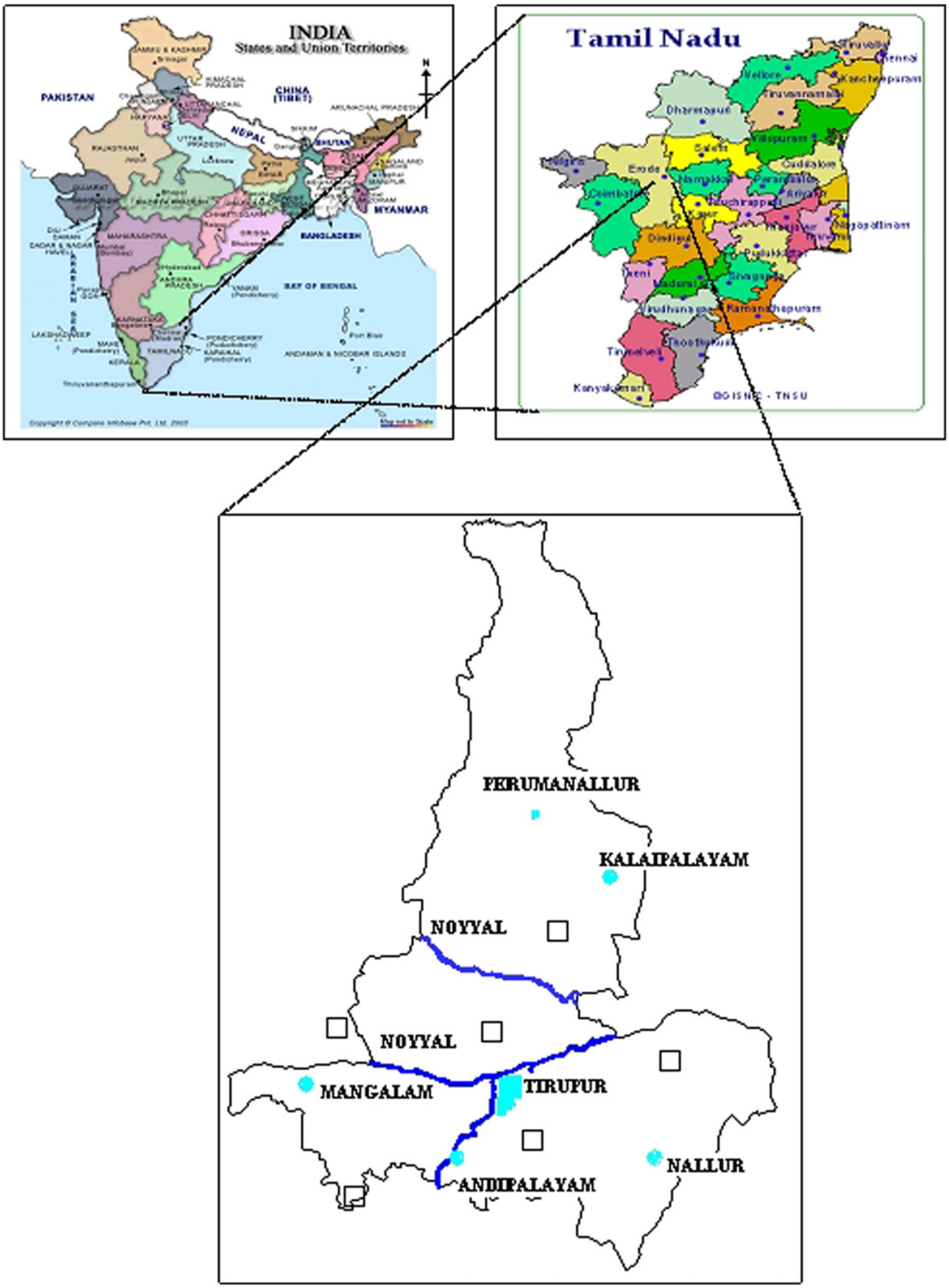

Fig. 1. Index map of Tirupur Block.

Protection zones are particularly effective to control pollution from diffuse sources (e.g. agriculture or traffic), while the prevention or control of point sources of pollution may be achieved through rather straight-forward approaches such as permit systems or other legal controls on the quantity, types of substances and places where discharges may take place. The prevention of groundwater pollution from diffuse sources is more problematic because the sources are less easy to identify and the impact is more difficult to control. Thus effective regulatory control of diffuse pollution often relies upon prohibition or restriction of polluting activities in specific protected areas where impacts on groundwater sources are likely to be serious.

The application of existing groundwater model helps in gaining knowledge about the quantitative aspects of the unsaturated zone and simulation of water flow in the saturated zone including river–groundwater relations (Richard, 2002). The quantum of groundwater flow to a horizontal or slanted well in an unconfined aquifer has to be assessed accurately for its optimum extraction and utilization (Hongbin, 2001). GFLOW (Analytic Element Model with Conjunctive Surface Water and Groundwater Flow) is an efficient stepwise groundwater flow modeling system. GFLOW supports some local transient and three-dimensional flow modeling. It is particularly suitable for modeling regional horizontal flow (Haitjema, 1992). MODPATH (3-D Particle Tracking Program for MODFLOW) is a widely used particle-tracking program (Kumar, 2002). To improve the understanding of hydro-geologic framework of Delaware County, Indiana, Arc View GIS 3-D and Spatial Analysis along with visual MODFLOW were used to study the groundwater flow patterns (Samuelson, 2004). The results of the modeling study can be used as a predictive tool for long-term management and monitoring of water resources. The simulated groundwater flow is subject to a nonlinear moving boundary resulting from periodic recharge and significant vertical hydraulic gradients (Sergio, 2003). Also the groundwater protection zones can be demarked using MODFLOW by dividing the total area into a number of grids (Rahman and Shahid, 2004). From groundwater flow model, protection area was demarcated. Mark et al. (1997) have adopted methodology for the study of integrated information from multiple hydro-geologic mapping through review of site-specific literature and documents obtained from state, federal agencies and local universities. Based on this model, potential groundwater flow controls were identified. Beckers and Frind (2000) have simulated groundwater flow and runoff for the Oro moraine aquifer system. The model was developed to account for situations where recharge was significantly affected by heterogeneity above the water table. The flow simulations showed that near-surface heterogeneity had a profound impact on the sustainable capacity of a groundwater system and location of sensitive recharge areas. But the determination of spatially and temporally varied groundwater recharge in any porous medium is essential for better prediction of groundwater system (Armbruster and Leibundgut, 2001). The objectives of this study are as follows; (i) to characterize the hydro-geological conditions of study area (ii) to estimate the groundwater potential of the study area and (iii) to demarcate the groundwater protection zones.

2. Study area

The study area, Tirupur Block, is situated between 11°N to 11°20′N Latitude and 77°10′E to 77°30′E Longitude with an extent of 27.20 km^2. The study area comprises of 23 villages with a population of about 0.7 Million. The water level in the study area varies from 3.08 m to 31.9 m from ground level during winter and summer respectively. In general, the quality of groundwater in the study area has large variation of TDS concentration. The TDS of water quality ranges from 3445 mg/l to10,938 mg/l around the dam and 350 mg/l to 3500 mg/l in other places of the basin. The index map of the study area is shown in Fig. 1. The terrain slope varies from 0 to 3% and drains toward Noyyal River and Nallar River.

2.1. Hydro-geological characteristics

The study area is composed of highly and partially weathered rocks and ends up with hard rock areas. The depth of aquifer is taken up to the hard rock areas and varies from 1 to 25 m underneath the area. This formation was deeply weathered in the tertiary period. The deep pediment exists along Noyyal River course from Sulur to Tirupur and shallow pediment along the stream courses joining Noyyal River. The geomorphologic set up in this area varies from dissected hilly regions in the west to undulating plains with residual hills in the middle portion and gently sloping ground toward coast. Buried pediments (deep and shallow), pediments with low lineament density exist in this hard rock region as shown in Fig. 2. The major soil types in Tirupur Block are Red Calcareous soil (51.71%), black soil (7.33%) and Red non calcareous soil (40.96%). The range of infiltration values of these major soils are 4–48.3 mm/h for

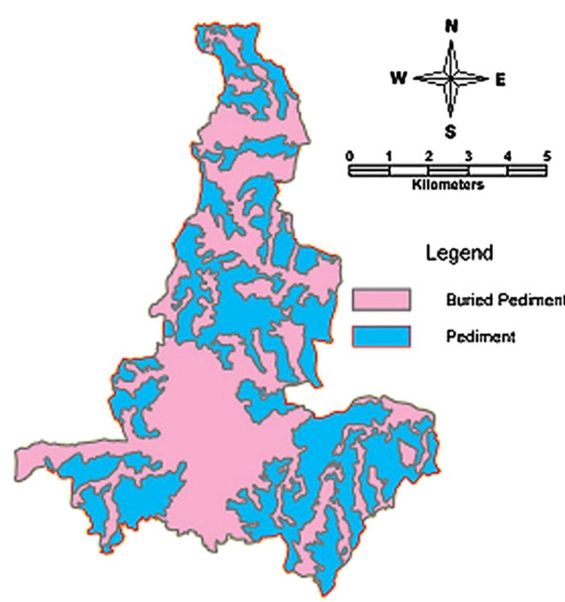

Fig. 2. Study area map with soil formation.

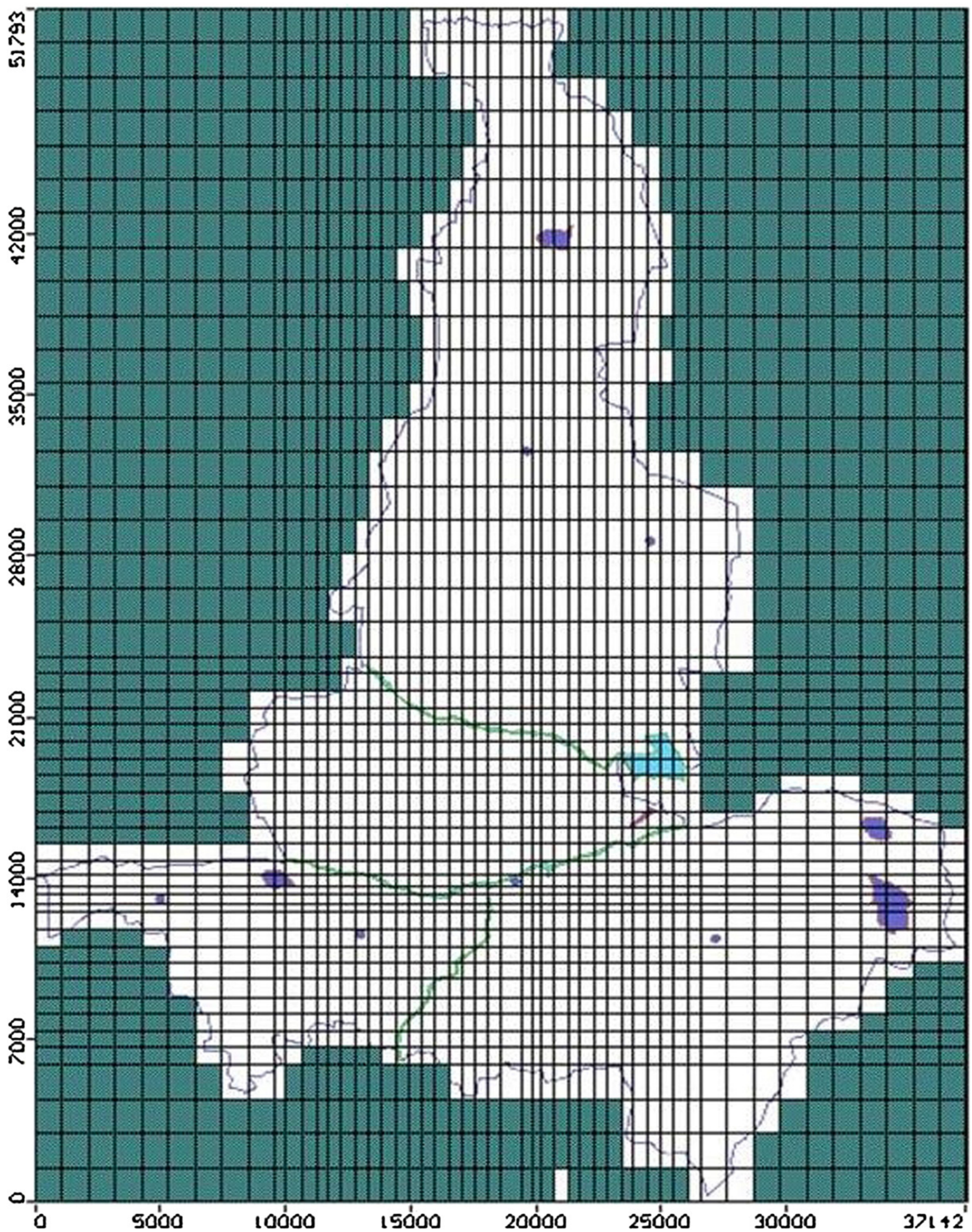

Fig. 3. Model Grid of the Study Area.

Black soil, 17–60.3 mm/h for Non calcareous red soil and 13.2–90.3 mm/h for Red calcareous soil. Typic Ustorthents in combination with Typic Ustropepts is the predominant soil type in the study area. The hydrological soil group 'B' with moderate infiltration and moderate runoff potential is comparatively found in larger areas of the block. The hydrological soil group 'C' with slow rate of infiltration and moderate runoff potential is also found in the block. The soil texture ranges from loamy sand to gravelly sandy clay loam. The common color of soil found in the study area is reddish brown. Rainfall during the southwest monsoon period (June to September) is 25% less than that during the northeast monsoon period (October to December). The annual rainfall varies from 394 mm to 921.5 mm in the study area.

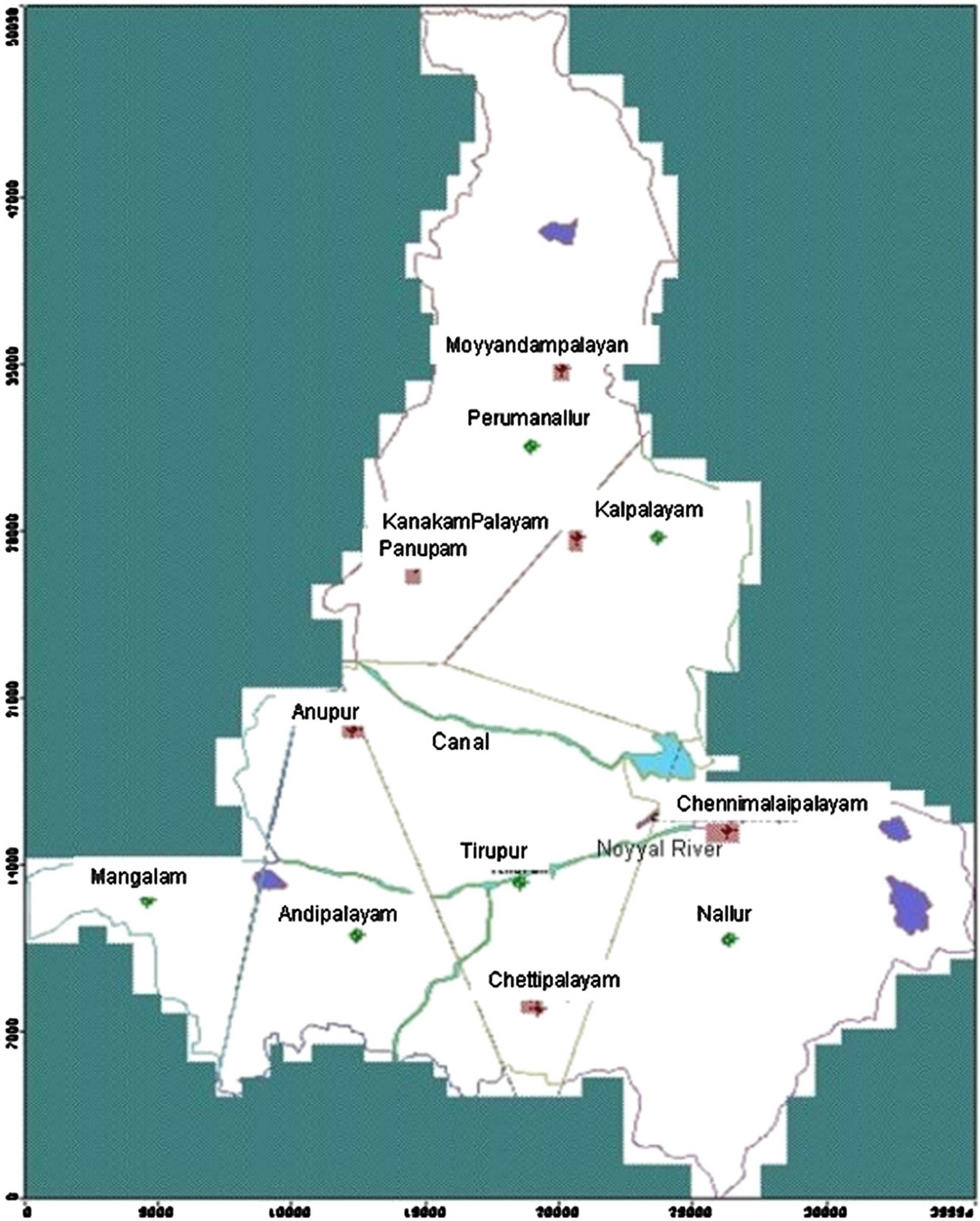

Fig. 4. Theissen polygon map.

3. Methodology

The methodology adopted in this study consists of the following phases: The first phase deals with characterization of hydro-geological boundary condition using borehole lithology and preparation of various thematic maps. In the second phase, the aquifer properties were assigned for flow and transport model to simulate the groundwater flow direction and estimate the groundwater potential. Finally the result obtained from the simulation model and map digitization such

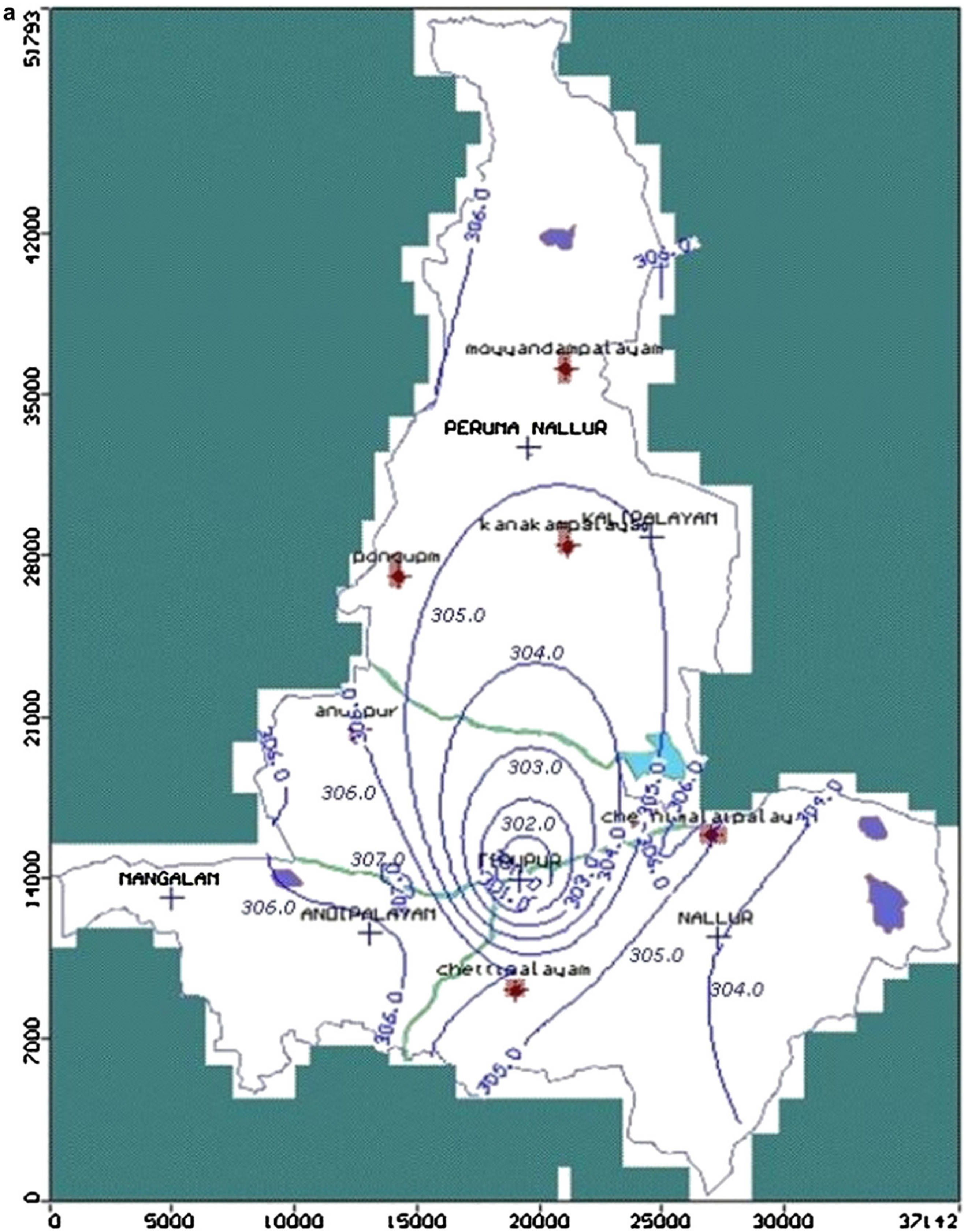

Fig. 5. (a) Water level contour for June 1999. (b) Calculated Vs Observed Head for June 1999.

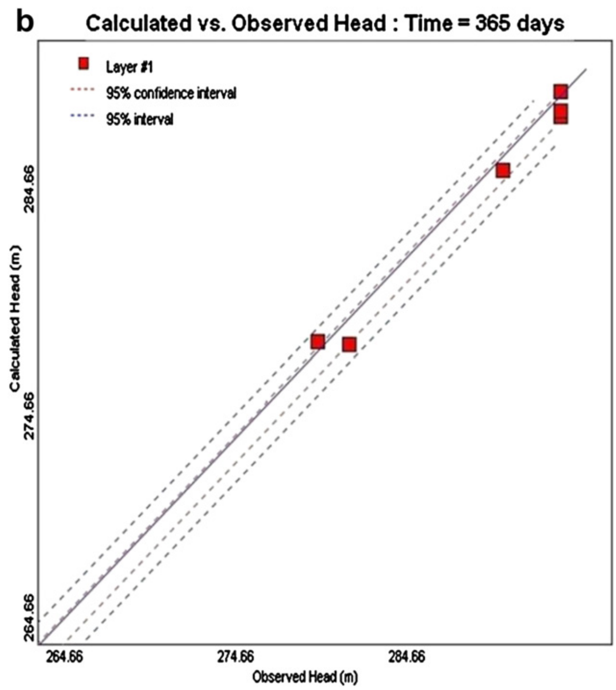

Fig. 5. (*Continued*).

as water table depth and geological features were used to assign the ranks and weights for overlay process in Geomedia environment. The higher rank and weight indicates more sensitivity to vulnerability. The higher index values obtained from the overlay process indicates the sensitivity zone influencing recharge to the aquifer and was demarcated as groundwater protection zones.

3.1. Database

Database on aquifer characteristics such as borehole details, soil type, details of wells, hydraulic conductivity, porosity and storativity were generated based on borehole lithologic data collected from Central Groundwater Board (CGWB). The time series data such as rainfall and water level data for the period from 1988 to 2003 were obtained from Institute for Water Studies (IWS) and Tamil Nadu Water Supply and Drainage (TWAD) Board. The base map was digitized in GeoMedia environment and different layers were created. It includes block boundary layer, layer of geology pattern, layer of soil and layer of the study area. Land use layer was digitized using MAP INFO and the following data were used in this study: (i) Remote Sensing Data such as IRS I-C, LISS-III data of scale 1:50,000 were collected and used to study the soil type, geology and land use of the block (ii) Daily rainfall data for the period of twelve years (1992–2003) was used in the analysis of hydrologic characteristic of the study area and to find the annual recharge and (iii) About six wells in the study area were considered for the study and the information of these wells such as groundwater level, well location in terms of latitude–longitude and mean sea level were collected.

3.2. Assessment of groundwater quantity

The assessment of groundwater is essential to maintain a proper balance between its quantity and exploitation. A standardized and simple methodology is required to achieve sustainable groundwater resources and hence the “Groundwater Estimation Methodology – 1997” (GREM, 1997) was used. The observation wells are the indicators to measure the periodical changes in groundwater level. Long term data of 12 years (1992–2003) were used to find the groundwater trends in and around the observation wells. Quantum of recharge/discharge that had taken place in the aquifer was assessed from the monthly water level fluctuation data. Dynamic groundwater potential of the study area was computed using water level fluctuation approach for the year 1992. The groundwater potential is estimated by using the following relationship;

$$\begin{aligned}\text{Groundwater potential} = {} & \text{Rise or fall in water level}(\text{m}) \\ & \times \text{Polygon area}\left(\text{m}^2\right) \\ & \times \text{Specific yield}\end{aligned} \tag{1}$$

3.3. Numerical modeling of groundwater flow and solute transport

In recent decades, numerical models have become dispensable tools for studying groundwater flow, contaminant transport and water resources management. The importance of such models has increased dramatically with the greater dependence on groundwater for irrigation and domestic use. Groundwater is tapped by wells for various purposes such as irrigation, industrial and domestic uses. The complicated flow problems can be solved by applying proper mathematical methods. MODFLOW is a computer program that simulates three-dimensional groundwater flow through a porous medium by using a finite-difference method (McDonald and Harbaugh, 1988). MODFLOW was designed to have a modular structure where similar program functions are grouped together and scientific computational and hydrologic options are constructed in such a manner that each option is independent of other options. MODFLOW 2000 (Harbaugh et al., 2000) was used in this study.

3.4. The governing groundwater flow

The governing groundwater flow equation given below is restricted to fluids with a constant density or in cases where the differences in density or viscosity are extremely small or absent (Barends and Uffink, 1997). This equation is derived mathematically by combining a water balance equation with Darcy’s law.

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}-W^* \tag{2}$$

Where, K_x, K_y, K_z = components of the hydraulic conductivity tensor [LT^{-1}]; S_s = specific storage [L^{-1}]; W^* is the general sink/source term that is intrinsically positive and defines the volume of inflow to the system per unit volume of aquifer per unit of time [T^{-1}]; h = is the groundwater head [L]; x, y, z = Cartesian coordinates [L]; t = time [T].

3.5. Model input

The inputs for MODFLOW for each cell within the volume of the aquifer system and its properties were specified. Also, details pertaining to wells, rivers, other inflow and outflow features for cells were specified for model run. The total study area

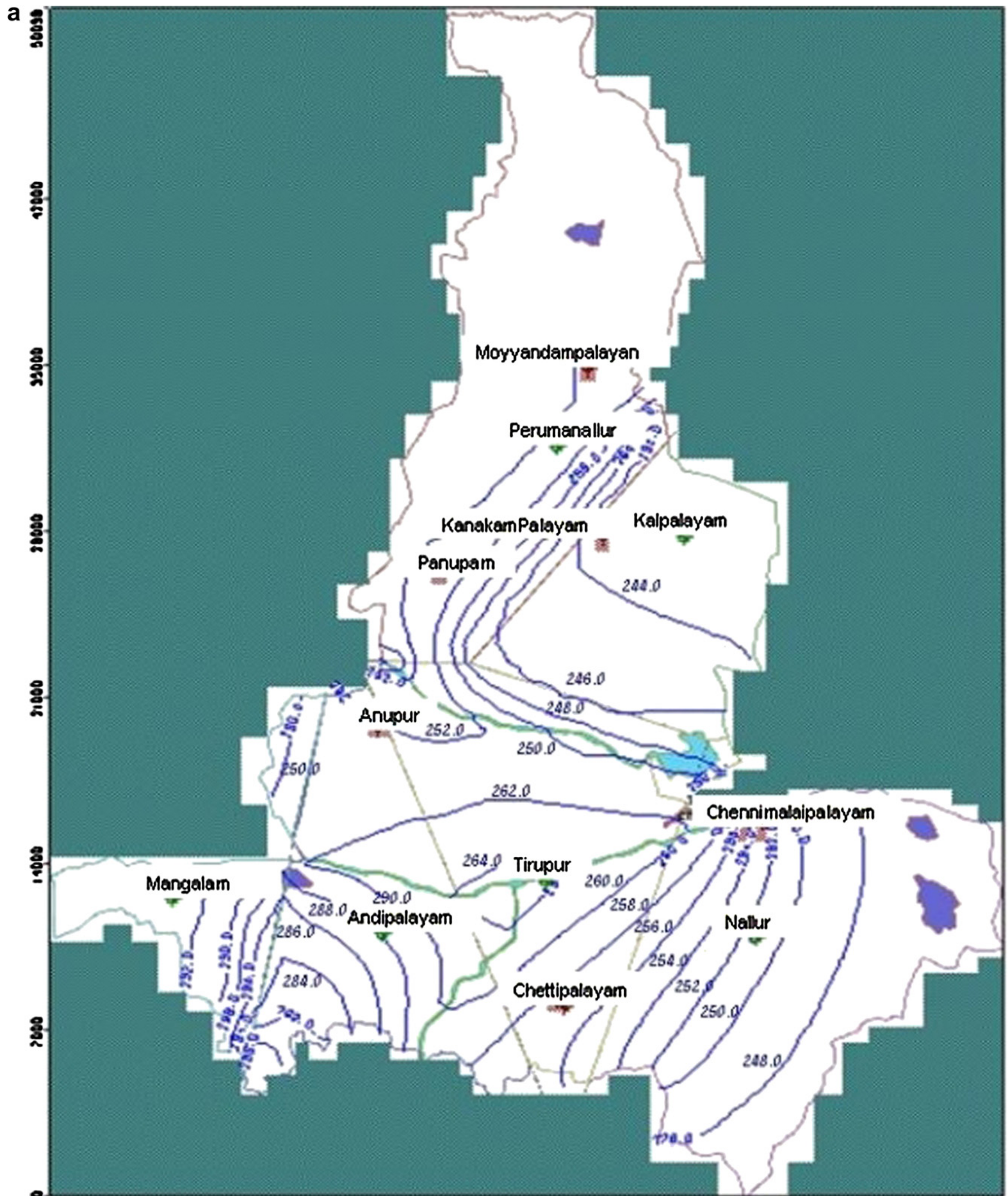

Fig. 6. (a). Water level contour for March 2003. (b) Calculated Vs Observed Head for March 2003.

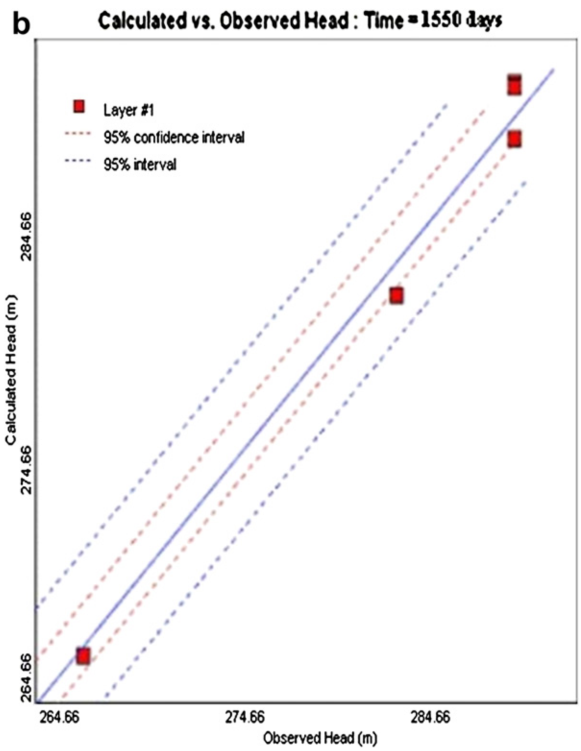

Fig. 6. (*continued*)

considered for the model was divided as 50 rows and 47 columns with cell size 1000 m × 800 m and single layer unconfined aquifer consisting of Biotite Gneiss with a thickness of 25 m. The model grid of the study area is shown in Fig. 3. The hydrogeological input parameters pertaining to the study area such as hydraulic conductivity, specific yield, porosity, hydraulic conductance and recharge were collected for all the zones and the values varies from 1.62×10^{-04} to 8.11×10^{-06} m/s, 0.13 to 0.16, 0.33 to 0.40, 1000 m^2/day and 100 mm/year respectively (CWADP, 1977). Model was carried out by assuming horizontal isotropy ($K_x = K_y$) and the value of vertical conductivity was taken as 0.1 times of K_x. The Noyyal River was taken as river boundary. The river stage elevation (free water surface elevation) is 16 m and river bottom elevation is 15 m therefore thickness of river bed was given as 1 m for river boundary condition. The initial hydraulic head for the starting time period June 1998 was taken as the initial condition and the model was simulated up to June 1999. The hydraulic heads were observed in the wells, water level is high in the western part and low in the eastern part near the river boundary. Most commonly, recharge refers to areal recharge which occurs as a result of precipitation that percolates into the groundwater system. Since natural recharge enters the groundwater system at the ground surface, visual MODFLOW only allows recharge values to be assigned to top layer. The recharge was computed based on the three methods (Kumar, 1997), namely Water level fluctuation method, Chaturvedi formula and Krishna Rao formula. The average value of each method works out to 92 mm/yr, 134 mm/yr and 86 mm/yr respectively which is because of heterogeneity in the land use pattern. The recharge value estimated based on the above methods vary from 9% to 14% of annual average of rainfall. Therefore, for the model input, the percentage of recharge was estimated as 10%, 9%, 14%, 11%, 13% and 12% for zones 1–6 respectively.

3.6. Zone budget

For the specified sub-regions zone, budgets can be computed using the cell-by-cell flow option with transient simulation. Flow observations, such as base flow to a stream, or flux across a boundary, are very useful for calibrating a groundwater flow model against data than head measurements. Theissen polygon was constructed using Geomedia Professional, keeping the well locations as a base point. The base map with the boundaries for determining the area of influence of each well is shown in Fig. 4. These areas were assigned as individual zones and the flow observed from these zones were used for model calibration.

3.7. Flow model

MODFLOW simulates groundwater flow in aquifer systems using block centered finite-difference method. Aquifer properties and information related to wells, rivers and other inflow and outflow features were specified for each cell within the volume of the aquifer system. The groundwater potential was computed using Theissen polygon method and the above input parameters were fed to the model. A stress period is defined as

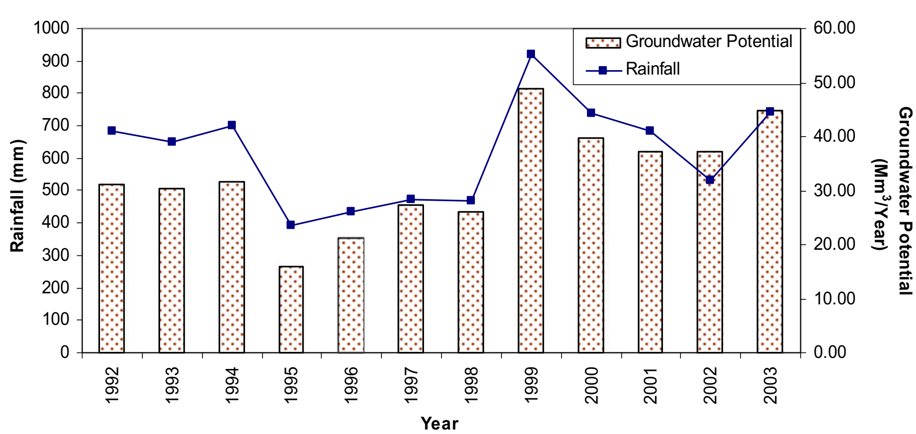

Fig. 7. Rainfall vs groundwater potential from 1992 to 2003.

a time period (monthly time step) in which all the stresses on the system are constant. The model was run with the monthly input data for the year 1998–99 by specifying Transient flow condition. Taking June 1998 water level as initial head, model was run to simulate water level upto May 1999 and validated with the observed data for all the six wells which are distributed over six different zones. In general, for unconfined aquifer condition, number of observation well required for every 100–200 km^2 is one (Ragunath, 2000). Since the model area is 27.20 km^2, six number of observation wells are sufficient for model calibration. The influence area of each well was considered as a zone and the zone budget was run for the

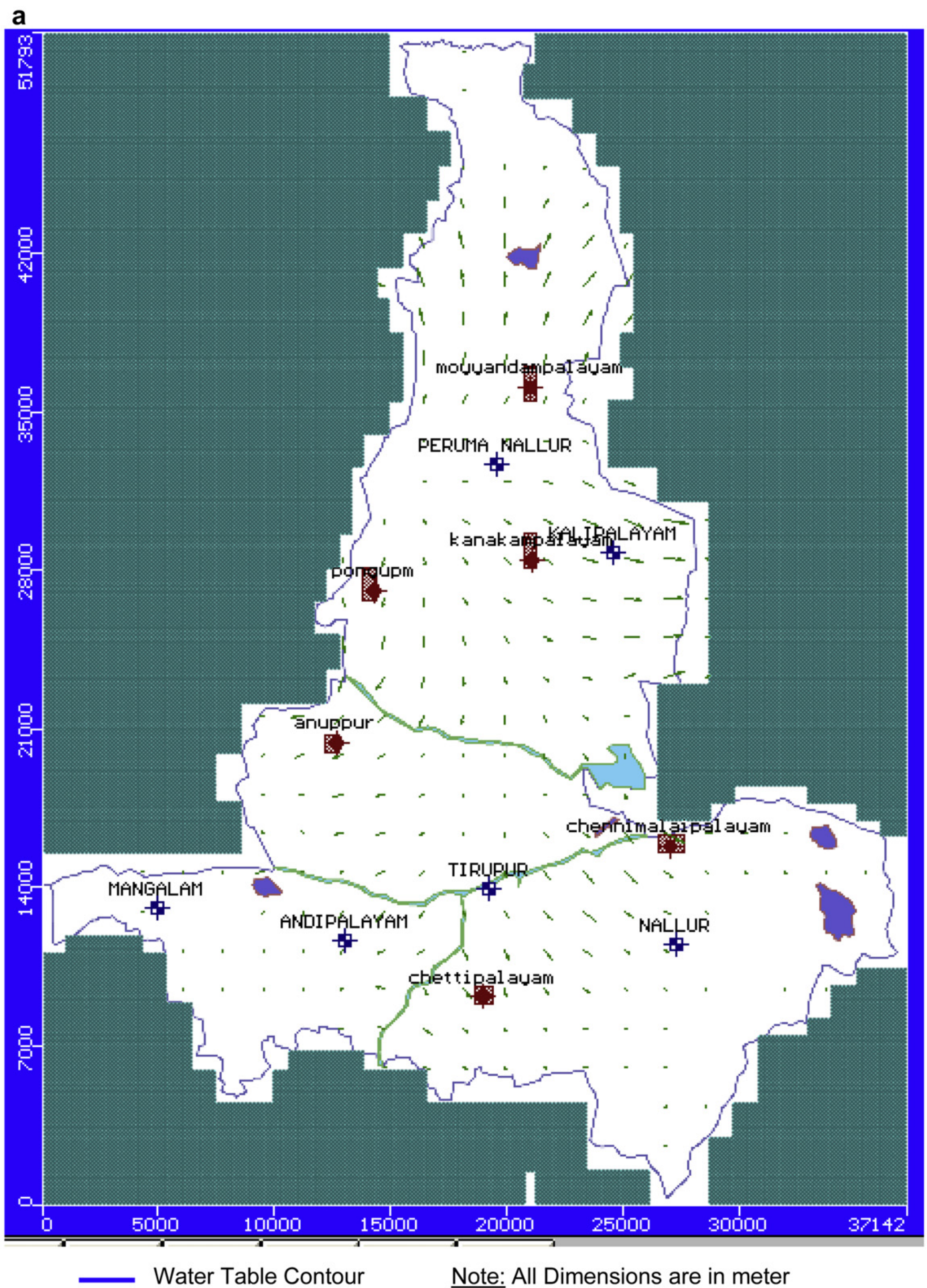

Fig. 8. (a) Groundwater flow directions (1999). (b) Groundwater flow directions (2003).

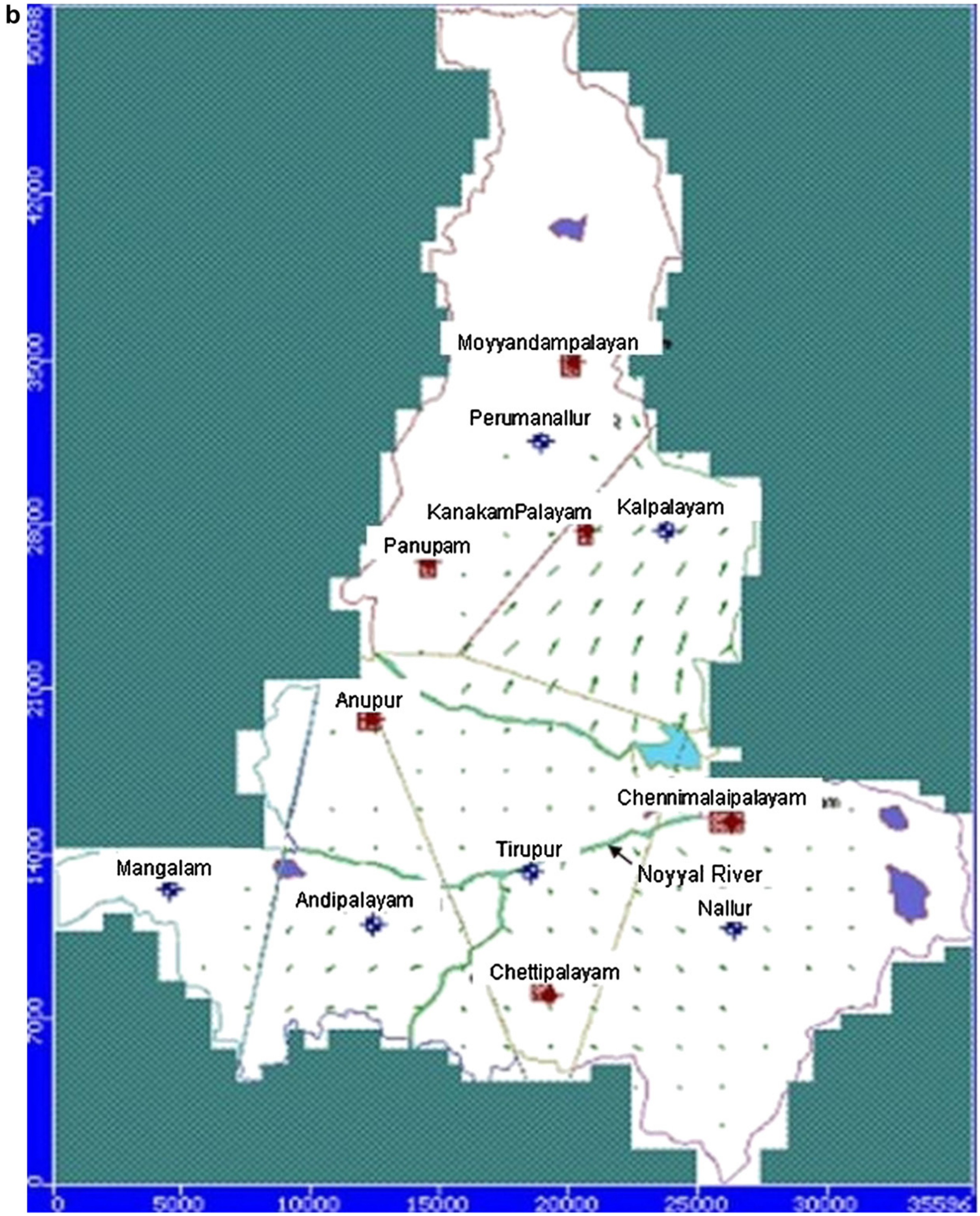

Fig. 8. (*continued*)

same period. The zone budget output was compared with groundwater storage computed by Theissen polygon method.

3.8. Model output

Water levels obtained from simulated model were used to construct contour maps for comparison with similar maps drawn from field data. The water levels were compared with measured water levels from wells at corresponding locations to determine model error. The process of adjusting the model input values to reduce the model error is referred as model calibration. The calibration value (0.9) indicates that there is a good agreement between observed and simulated values. It was found that the model was more sensitive to hydraulic conductivity than other aquifer parameters. The parameters such as heads, drawdown, water table elevations, head difference between layers, layer elevations (top, bottom and thickness) and net recharge were selected to prepare the contour maps. The flow velocity vectors provide an important representation of the groundwater flow direction in a particular layer and row or column. It provides information about both velocity and flow direction. The mass balance results and zone-to-zone flow exchanges provide important information on the quantity and reliability of the groundwater model. The visual MODFLOW uses zone budget to provide a detailed summary of the inflows and outflows from specified zones throughout the model domain.

3.9. Demarcation of groundwater protection zones

The groundwater flow model computes the protection area around the well through three main steps, (i) compute the zone of influence, (ii) compute the zone of contribution for a user-defined time period and (iii) combine both zones to demarcate

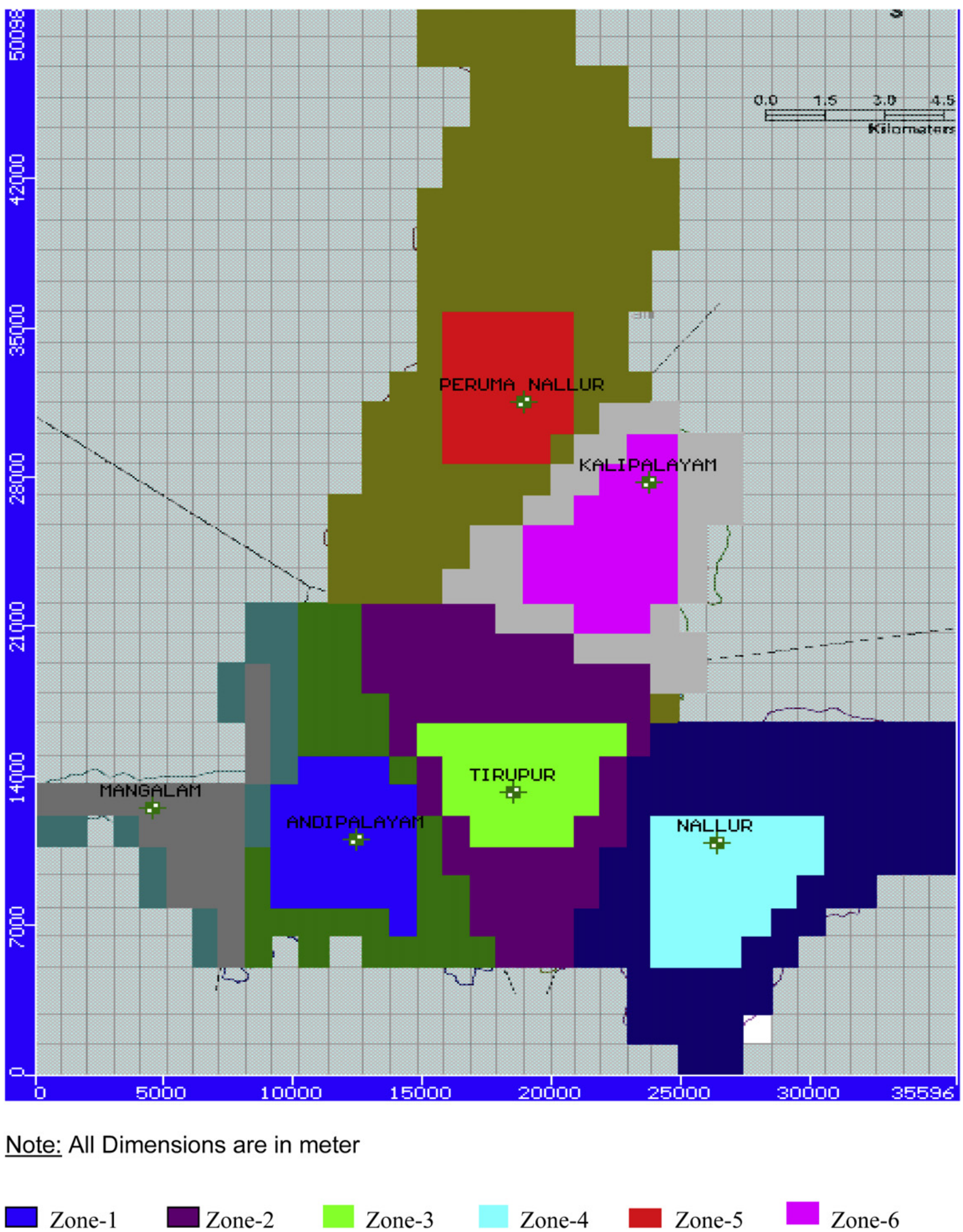

Fig. 9. Suitable recharge zones.

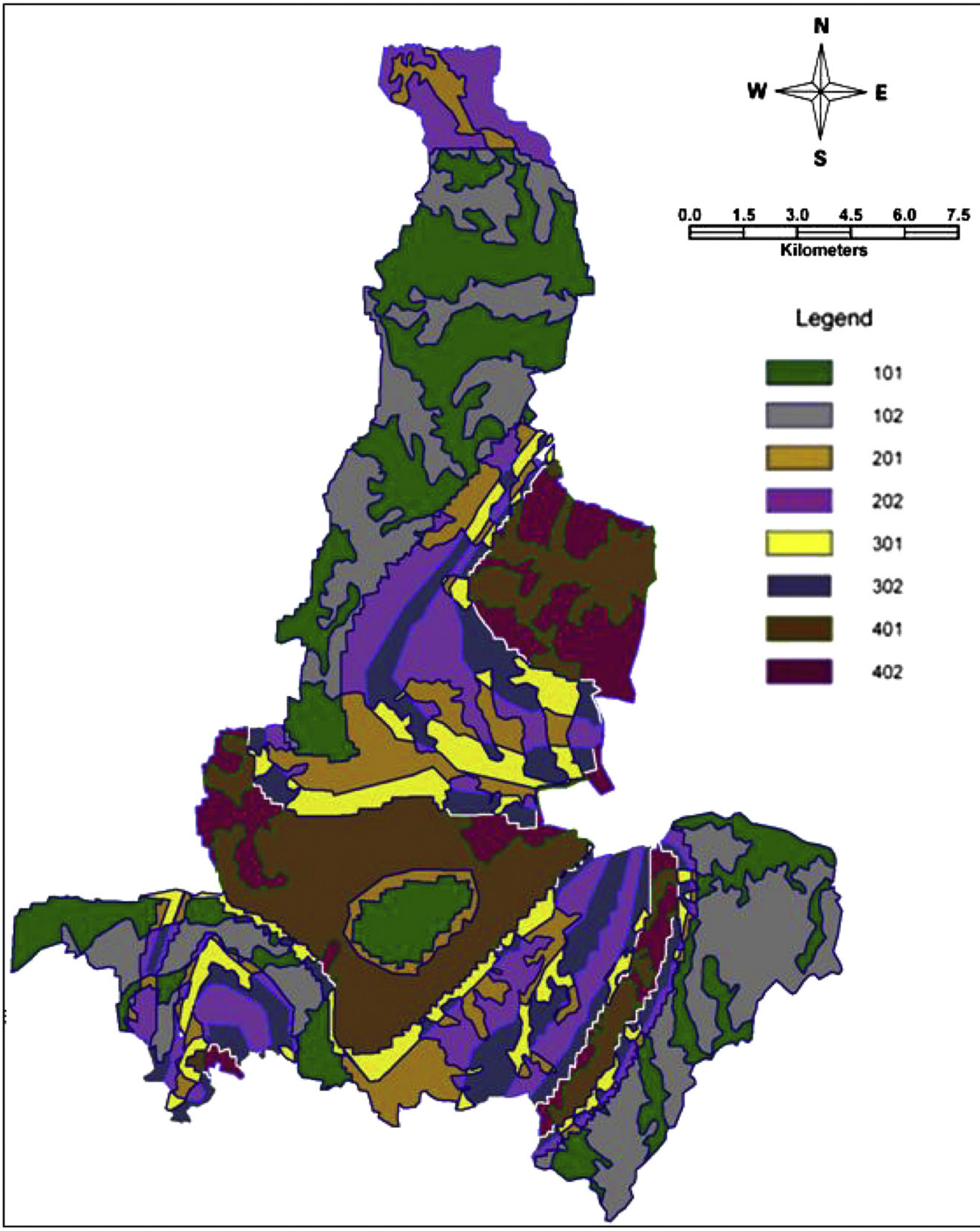

Fig. 10. Groundwater protection zones of Tirupur Block.

the groundwater protection area. The model was simulated and the heads observed in the wells were compared with the model result. The head contours and the velocity vectors were obtained as the output. The model was run for different recharge locations (i.e., zones) for 9%–14% of annual rainfall as recharge and integrating with water table level as well as lithology to find out suitable location for recharge (GREM, 1997).

Table 1
Estimation of groundwater potential for 1992.

Well No.	Village name	Area(km^2)	Average GWL(m)			Groundwater potential Mm^3/year
			High	Low	Diff.	
1	Mangalam	18.52	20.44	16.32	4.12	1.14
2	Andipalayam	40.15	39.7	32.4	7.3	10.25
3	Tirupur	53.78	20.46	16.32	4.14	3.76
4	Nallur	63.58	26.6	22.4	4.2	8.01
5	Perumanallur	79.37	20.46	16.88	3.58	4.97
6	Kaliyapalayam	34.64	44.6	41.1	3.5	3.03
Total						31.16

4. Results and discussion

4.1. Water level

Using June 1998 water level data as initial head, model simulated the heads for May 1999. Maximum and minimum deviations in water level were observed for wells at Kalipalayam and Andipalayam respectively. The water level contour for May 1999 is shown in Fig. 5(a). The Root Mean Square (RMS) error between the predicted and observed is 0.776 m and shown in Fig. 5(b). After validation, model was simulated up to March 2003 and the water level is shown in Fig. 6(a). The RMS error between the predicted and observed is 0.658 m and it is shown in Fig. 6(b). Maximum and minimum deviation was observed for wells at Mangalam and Nallur respectively.

4.2. Groundwater quantity

The groundwater potential for the year 1992 was computed by considering the Theissen polygon area, water level fluctuation and the specific yield for each well. The minimum and maximum rainfall was observed as 394 mm and 921 mm for the year 1995 and 1999 respectively. The total groundwater potential of six wells for the year 1992 works out to be 31.16 Mm^3/year as shown in Table 1. In the same way, groundwater potential of the entire Tirupur Block was also estimated for the year 1992–2003. The minimum and maximum groundwater potential was observed as 16.04 Mm^3/year and 48.79 Mm^3/year for the years 1995 and 1999 respectively. The relationship between the rainfall and groundwater potential as plotted in Fig. 7 justifies that the groundwater potential has direct relation with the rainfall. The consistency of above normal rainfall results in continuous increase of groundwater potential even when rainfall decreases as seen in the year 2002.

Table 2
Validation of zone budget.

Sl. No.	Area (km^2)	Groundwater potential in m^3/yr		
		November 1999		
		Water level fluctuation method	Simulated model output	% Error
1	18.52	5,194,202	5,294,252	0.21
2	40.15	10,889,939	10,265,990	−1.29
3	53.78	133033.1	144419.6	0.02
4	63.58	16,784,789	17,351,370	1.17
5	79.37	9,886,046	9,186,685	−1.44
6	34.64	5,910,850	5,828,685	−0.17
Total	290.04	48,798,859	48,071,402	−1.50

Table 3
Groundwater potential for optimal recharge location.

Zone/Well	Groundwater potential for 25% of total rainfall (Mm^3/yr)		
	Simulated model output	Improved recharge	% Increase
1	45.893	0.84	1.86
2	45.885	0.82	1.85
3	45.830	0.77	1.72
4	45.874	0.79	1.82
5	45.900	0.85	1.88
6	46.000	0.94	2.10

4.3. Groundwater flow

The flow directions of the simulated outputs are discussed with reference to the Noyyal River, canal and wells. The canal is located in Northern side and ends in a pond. The Noyyal River and its tributary are located in the Southern side of the canal. The flow direction is described with respect to the Noyyal River and canal. Generally the groundwater flow pattern is toward east in the surrounding areas of the river. It tends toward the northern end and southern end on either extreme. The area between the river and canal as seen from the direction and magnitude of the flow indicates that all the wells fall within this region. The magnitude of the velocity of flow in the groundwater is proportion to the size of the arrow, the southern side of the river has a lower velocity compared to the velocity of flow between the river and canal. This can be presumed as a reason for the wells to have a potential to recharge the groundwater and therefore can be demarcated as protection zones. The groundwater flow direction for the year 1999 and 2003 are shown in Fig. 8(a) and (b) respectively.

4.4. Zone budget

The groundwater storage obtained for the specified individual zones in the zone budget of MODFLOW were compared with the groundwater potential computed by Theissen polygon method for June 1999 as shown in Table 2. The error computed in groundwater potential for the individual zones varies from −1.44% to 1.17% but in total the error

Table 4
Demarcation of protection zones.

Sl. No.	Index value	Overlaid themes
1	101	Wt_a-Buried Pediment
2	102	Wt_a-Pediment
3	201	Wt_b-Buried Pediment
4	202	Wt_b-Pediment
5	301	Wt_c-Buried Pediment
6	302	Wt_c-Pediment
7	401	Wt_d-Buried Pediment

is −1.50%. It is observed that the wells located in area 1, 3 and 4 at higher elevation shows the maximum groundwater potential and the other wells in lower elevation shows the minimum groundwater potential.

4.5. Suitable recharge location

An area of 6000 m × 6000 m for each well/zone was taken to study the suitable location for recharge. The model was simulated up to March 2003 for each location with assumed recharge of 25% of total rainfall (by creating artificial storage). The increase in groundwater potential was obtained by increasing the recharge rate for each location (zone or well) which varies from 1.72% to 2.10% as shown in Table 3. It is observed that a recharge of 25% of rainfall improves the groundwater potential to a maximum of 46.00 M m^3/yr in zone 6. Based on the above, it can be concluded that Zones 5 and 6 have high recharge potential hence they are suitable for recharge (Fig. 9).

4.6. Groundwater protection zones

Zone of influence or sensitivity zone which is considered as the source of recharge to the aquifers is known as Groundwater protection zone. The demarcation of protection zones plays an important role in preserving the available water resources. The demarcation of protection zones was done by overlaying water table depth and geological features using Geomedia environment. Water table depth was taken from the output of the visual MODFLOW for the year 2003 and it was interpolated by using Arc GIS (version 9.1). Rank was assigned to each sub zone theme of geology and water table depth. The rank 1 and 2 were given to buried pediment and pediment soils respectively, where 1 represents the higher infiltration rate than the other. Ranks 1, 2, 3 and 4 were given to water table level with respect to increase in their depth from 1 to 10 m, 11 to 20 m, 20 to 30 m and 31 to 40 m respectively. After overlaying all the themes the resulting map was obtained in Geomedia which is shown in Fig. 10. Each index obtained in the result represents the proportionalities of the overlaid zones. The results of the above overlay such as Wt_a, Wt_b, Wt_c, and Wt_d are the water table for increase in their depth from the ground level for Buried pediments and Pediments are shown in Table 4. The zone of index value 101 represents the higher rank of geology and water table depth which indicates the zone of influence contributing recharge to the aquifer having higher infiltration rate and maximum water availability. As the Groundwater protection zone is the zone of influence which contributes to the recharge, the locations represented by index value 101 was demarcated as groundwater Protection Zones which is shown in Fig. 10. These Zones has to be protected from groundwater over exploitation, disposal of effluent and construction of artificial barriers. These zones can be used to recharge the groundwater in turn, water level and quality gets improved. This technique can be considered as model and may be very useful to Asia hydro-environmental engineers for implementing into basin for macro level studies.

5. Conclusions

Groundwater is a renewable resource and has to be protected from contamination. The concept of a zone of protection for areas containing groundwater has been developed and adopted for Tirupur, (Tamil Nadu, India) which is an arid region and rapid expansion of the textile industry has taken place with no associated development of supporting infrastructure or institutional capacity. Groundwater flow for Tirupur Block was simulated using visual MODFLOW version 4.1. The aquifer characteristics, water level data for the observation wells were used as model input. The model was run to simulate water level in 1999 and validated with observed value. The validated model was again run to predict water level in 2003. The variation of predicted water level with respect to time is almost identical with that of variation of water level in the field. This could be possible only if the computed flow components are in close agreement with the actual flows hence it can be concluded that; the water level is high in central western part and declining toward the Noyyal River. Noyyal River acts as drainage during June 1999 and March 2003 (monsoon and post monsoon), the velocity increases as the flow moves toward the river. The velocity of flow is high in the central part of the basin and also in the north-east and south-west part indicating recharging in these areas may lead to groundwater movement toward river and canals. The output of groundwater flow direction for 1999 and 2003 are shown in Fig. 8(a) and (b) respectively. Based on the index value, Zones 5 and 6 were identified as suitable recharge zones and these zones were demarcated as groundwater protection zones (Fig. 9). The well/zone 6 is identified as the suitable recharge location due to an increase of 2.10% of groundwater potential for a recharge of 25% of total annual rainfall. The locations represented by index value 101 were demarcated as groundwater Protection Zones (Fig. 10) as they have favorable condition for recharge and geological formation in the aquifer. These zones can be used to recharge the groundwater leading to improvement of water level and quality. This modeling technique may be very useful to Asia hydro-environmental engineers for implementing into a basin for macro level studies because assessment and demarcation of groundwater availability is crucial for its proper planning, development and management. The study of contaminant transport modeling and suitable recharge quantity required to remediate the groundwater quality can be taken up as future study.

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