Groundwater-recharge estimation using a surface electrical resistivity method in the Himalayan foothill region, India

M. Israil · Mufid al-hadithi · D. C. Singhal · Bhism Kumar

Abstract A new method for the estimation of groundwater recharge is presented using a surface resistivity method and isotope technique. A linear relationship was obtained between the resistivity of the unsaturated top layer and the recharge estimated using a tritium tagging technique for the piedmont zone in the Himalayan foothill region, India. The relation can be used for the estimation of recharge using surface electrical resistivity measurements for the same geological formation. The data used for the study are 32 vertical electrical resistivity sounding measurements at a station interval of 2 km, tritium tagging studies at six selected sites and pre- and post-monsoon water-level monitoring in the piedmont zone of the Himalayan foothill region (India). The results of this study were mapped using GIS techniques. In the study area, a well-defined empirical relationship between unsaturated zone resistivity and recharge per cent was obtained. The method suggests a new application of surface electrical resistivity data in determining recharge per cent due to infiltration. The technique of estimating groundwater recharge using surface electrical resistivity measurement is efficient, economic, less time consuming and easy to use compared with other methods used for this purpose.

Received: 9 December 2003 / Accepted: 26 August 2004
Published online: 6 November 2004

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Resumé Une nouvelle méthode permettant d'estimer la recharge des eaux souterraines a été présentée, utilisant une méthode de résistivité de surface et des méthodes isotopiques. Une relation linéaire a été obtenue entre la résistivité de la zone non saturée et la recharge estimée grâce au Tritium dans la zone du Piedmont au pied de l'Himalaya, Inde. La relation peut être utilisée pour l'estimation de la recharge en utilisant la méthode de résistivité de surface dans la même formation géologique. Les données utilisées pour l'étude sont vingt-deux sondages électriques réalisés tous les deux kilomètres, l'étude de la signature du tritium en six endroits sélectionnés, et la comparaison des niveaux piézométriques pré et post moussons. Les résultats de cette étude ont été cartographiés en utilisant les techniques SIG. Dans la zone d'étude une relation très bien définie entre la recharge (%) et la résistivité de la zone non saturée a été obtenue. La méthode suggère une nouvelle application de la résistivité de surface, pour déterminer le pourcentage de la recharge due à l'infiltration. Cette technique est efficace, économique, rapide et facile à mettre en oeuvre, en comparaison d'autres techniques utilisées pour atteindre le même objectif.

Resumen Se presenta un método nuevo para estimar recarga de agua subterránea utilizando un método superficial de resistividad y una técnica de isótopos. Se ha obtenido una relación linear entre la resistividad de la capa superior no saturada y la recarga estimada utilizando la técnica de tritio marcado etiquetado para la zona de piedemontes en la región de colinas al pie del Himalaya, India. La relación puede utilizarse para estimar recarga usando mediciones superficiales de resistividad eléctrica para la misma formación geológica. Los datos utilizados en el estudio consisten de treinta y dos mediciones de sondeos eléctricos verticales de resistividad en un intervalo de estaciones de dos km, estudios de tritio marcado en seis sitios seleccionados y monitoreo de niveles de agua, pre-monzón y post-monzón, en la zona piedemontes de la región de colinas al pie del Himalaya (India). Se mapearon los resultados de este estudio utilizando técnicas SIG. Se obtuvo para el área una relación empírica bien definida entre la resistividad de la zona no saturada y el porcentaje de recarga. El método sugiere una aplicación nueva de los datos superficiales de resistividad eléctrica en la determinación del porcentaje de recarga ocasionado

 DOI 10.1007/s10040-004-0391-8

por infiltración. La técnica de estimar recarga de agua subterránea utilizando mediciones superficiales de resistividad eléctrica es eficiente, económica, demanda poco tiempo, y fácil de utilizar en comparación con otros métodos que se utilizan para este propósito.

Keywords Electrical resistivity · Groundwater recharge · Tritium tagging technique · Water table

Introduction

Groundwater recharge takes place by various processes, viz. direct regional recharge by infiltration of rainfall, along watercourses, from lakes, return seepage from irrigation and lateral movement of groundwater through subsurface flow due to a natural hydraulic gradient. The estimation of groundwater recharge is important for groundwater-resources evaluation, budgeting, conservation and water-balance estimation. A critical review of assessment of recharge is given by Lerner et al. (1990) and Scanlon et al. (2002). The focus of this paper is the estimation of recharge by infiltration of rainfall and return seepage from irrigation fields. The common method for estimating recharge is based on monitoring water-level fluctuations and the specific yield of the aquifer. In this method the difference in water-level fluctuation is taken between the pre- and post-monsoon period. However, the estimation of specific yield is very critical in computing groundwater recharge from water-level-fluctuation data. Usually the specific yield values of the aquifer in the zone of water-level fluctuation are estimated from pumping test data. In order to have realistic values of specific yield in unconfined aquifers, long-duration pumping tests are necessary. The Central Groundwater Board (CGWB), India, based on data from some representative basins, has suggested specific yield values for common water-bearing formations, which can be used in areas where pumping-test data are not available (CGWB 1997).

Alternatively, groundwater recharge can be estimated by monitoring the vertical movement of injected tritium. This is known as the tritium tagging or tritium injection method. This method is based on the assumption that the soil water in the unsaturated zone moves vertically downward as discrete layers. Water added on the surface, either as precipitation or irrigation, will move downwards by pushing the older water beneath and this, in turn, will push the still older water further below; thereby, the water from the unsaturated zone is added to the groundwater reservoir. This flow mechanism is known as piston flow (Zimmerman et al. 1967a, 1967b). Therefore, by monitoring the vertical movement of the injected tritium through the soil column, recharge can be estimated. The position of the tracer is indicated by a peak or a maximum in the tritium activity versus depth plot. However, molecular diffusion, dispersion and aquifer heterogeneities may cause broadening of the peak. The methodology provides spot measurements of natural recharge and has been extensively used by various workers (Datta et al. 1973; Sukhija and Rama 1973; Datta 1975, Sukhija and Shah 1976; Verhagen et al. 1979; Gupta and Sharma 1984; Athavale and Rangarajan 1988; Sukhija et al. 1996). Other methods, such as the chloride method and soil moisture method, have also been used to a limited extent (Allison and Hughes 1978; Edmunds and Walton 1980; Sukhija et al. 1988, 2003).

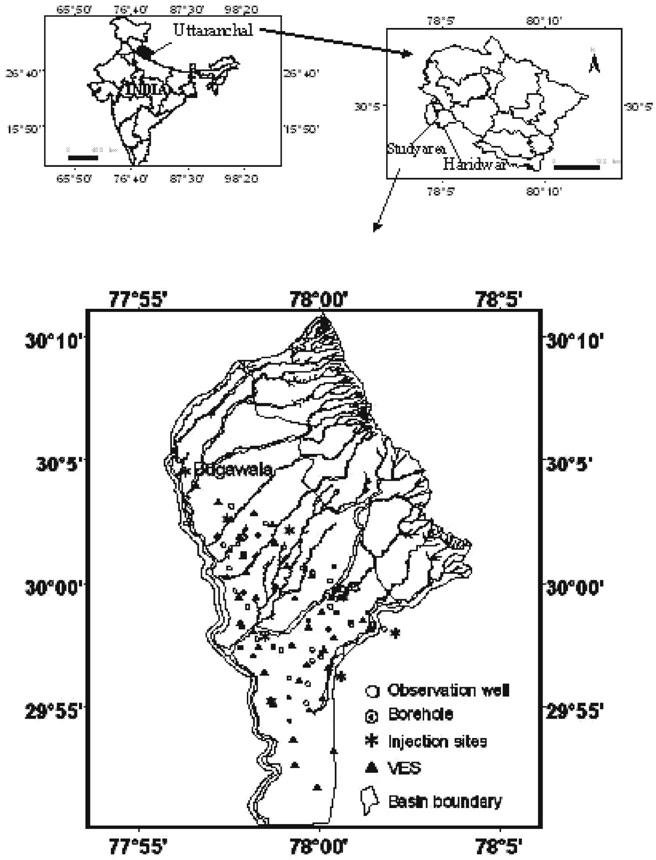

Fig. 1 Location map of the study area showing borehole, tritium injection sites and vertical electrical sounding (VES) points along with the basin boundary

The estimation of recharge using the above methods is time consuming, expensive and cumbersome. In the present paper, an empirical relationship has been developed by combining the results of surface electrical resistivity and a tritium injection method for the piedmont zone. The relationship is referred to as a recharge model. The model suggests that groundwater recharge can be estimated using surface electrical resistivity measurements. The model has been developed for the piedmont zone of the Himalayan foothills region (India). The study area is located between latitude 29°50′00″ to 30°11′21″ north and longitude 77°54′19″ to 78°6′21″ east and falls in Ratmau-Pathri Rao watershed (Fig. 1), which covers an area of about 437 km^2. Surface electrical resistivity measurements were carried out at station intervals of about 2 km. On the basis of the results of the surface electrical resistivity data, geomorphology and soil type, six sites were selected for the estimation of groundwater recharge for the period June 2002 (pre-monsoon) to Oc-

DOI 10.1007/s10040-004-0391-8

tober 2002 (post-monsoon) using the tritium tagging technique (TTT). These sites represent all the geomorphic units and soil types in the study area. The recharge model has been developed by correlating the results of tritium tagging technique with the resistivity of the unsaturated topsoil layer. The model can be used for the quantitative estimation of vertical recharge using surface resistivity methods for an area with a similar geology.

Geology and Hydrogeomorphology of the Study Area

Geologically, the study area is comprised of Siwalik rocks and alluvial deposits. The formations occurring south of the Siwalik are alluvial fan deposits of recent age. The alluvial fan deposits (referred to as the Piedmont zone) are made up of assorted sands and gravels with occasional clays. The belt extends in an elongated manner along the foothill region, roughly in a NW-SE direction (Fig. 2a). After necessary ground checking and correlation with the existing literature (Pandey et al. 1963; Sharma and Jugran 1992; Rao et al. 2001), the geologic units were mapped using GIS to prepare a thematic map for the geology of the area (Fig. 2a).

Hydrogeomorphologically, the area is classified into four geomorphic units. These are Siwalik hill, upper piedmont (Bhabhar belt), lower piedmont (Tarai) and flood plain. The geomorphic boundaries were digitized on the enhanced image through GIS and a hydrogeomorphological map was prepared (Fig. 2b)

The Siwalik hills are divided into the Upper, Middle and Lower Siwalik, (Pandey et al. 1963). The sand and gravel horizons associated with the Lower, Middle and Upper Siwalik formations constitute the main aquifer beds in these formations. The Lower Siwalik is generally hard and consists of indurated sandstones, with some clay stones, and bears less water-transmitting and storage capacity than the Middle or Upper Siwalik sandstones (Pandey et al. 1963). The Middle Siwalik sandstones, being normally medium grained and with relatively less compact rocks, form moderate to good aquifers separated by clay. The Upper Siwalik is the more permeable and porous formation in the entire Siwalik sequence. The boulder and pebble beds of the Upper Siwalik mostly act as good groundwater reservoirs when encountered at depth beneath the Bhabhar zone. The Lower Siwalik normally dips towards the north and does not contribute much to the groundwater in the area whereas the Middle and Upper Siwaliks, which are exposed in the study area, have southerly dips and act as feeders to the aquifers in the Bhabhar zone.

The Upper Piedmont zone (covering 193 km^2) of the area, also known as Bhabhar, bordering the Siwalik Hills with a gentle slope comprised of unconsolidated coarse material, was distinctly interpretable. This belt provides a very good hydrogeological setup for recharge and infiltration. The water table in this unit varies from 11–32 m below ground level (b.g.l.).

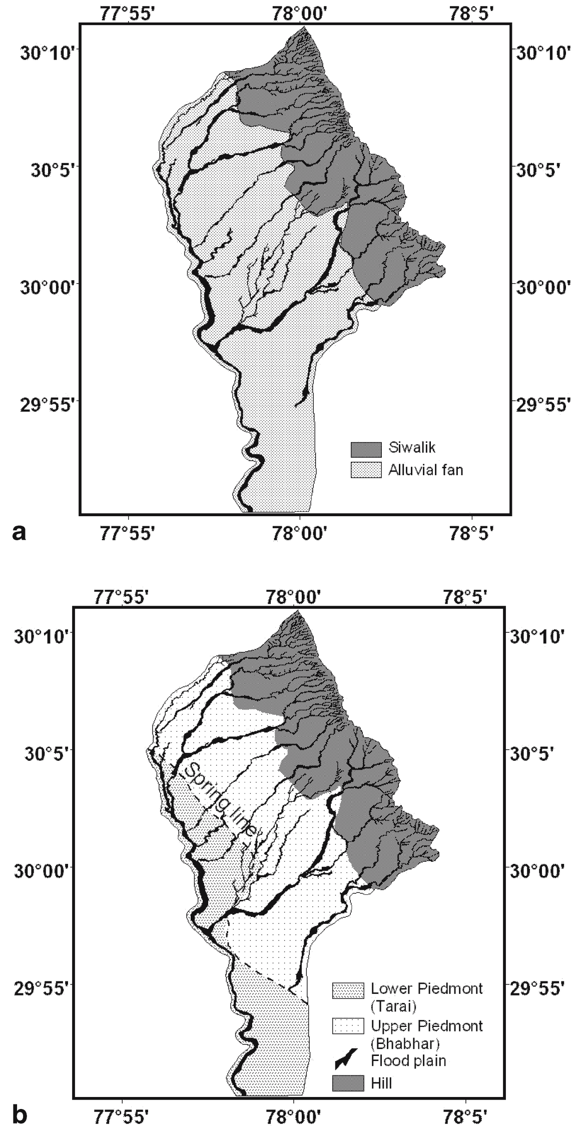

Fig. 2 **a** Geology of the study area. **b** Hydrogeomorphology of the study area

The Lower Piedmont, also known as Tarai, is separated from the Upper Piedmont by the spring line along their common junction line and covers about 109.82 km^2 of the area. Lithology derived from boreholes available in the study area shows coarse-grained sand and clays with gravel (boulders and pebbles). The depth of the water table monitored in observation wells in this unit ranged from 2 to 7 m b.g.l. Due to the occurrence of interbeded clays the groundwater occurs in confined to semiconfined conditions in the Tarai belt. The groundwater prospects in this landform are good.

Flood plains form the youngest geomorphic unit and include various landforms formed by fluvial action, i.e. sandbars, channel bars, palaeochannels and meander scars. These are characterized by very gentle slopes and the grains consist of subrounded to rounded fragments of

 DOI 10.1007/s10040-004-0391-8

sand, silt and clays. It is a highly permeable zone, which helps in partial bank recharge and subsurface flow.

Surface Resistivity Data Collection and Interpretation

The physics of the electrical current flow suggests that a good contrast in electrical resistivity exists between the different lithological units (e.g. clay, sand and gravels) and between the water-saturated and unsaturated formations (Zhdanov and Keller 1994). Thus, the electrical resistivity method can be used successfully to differentiate lithological units in the study area. The depth of investigation and resolution of surface resistivity measurements are controlled by electrode configuration and maximum electrode spacing used in the field measurements. A detailed discussion on the depth of investigation and the resolution for the various electrode configurations is given by Apparao and Gangadhara (1974) and Schulz (1985). Considering the depth used, and the resolution and ease in field operation, the Schlumberger configuration has been used for the field resistivity measurements in the present work.

Thirty-two vertical electrical soundings were recorded in the study area using the Schlumberger configuration with a maximum electrode spacing of about 900 m; the minimum electrode spacing was 1 m and recordings were made at station intervals of about 2 km. The electrode spacing is sufficient to provide information about the resistivity variation at near surface and deeper than 100 m, which provides information about the shallow and deeper aquifer system. The Zohdy (1989) method was used to invert measured apparent resistivity data to true resistivity as a function of depth at each site. The method works in apparent resistivity domain and can be used for the automatic iterative interpretation of Schlumberger and Wenner sounding data. The method is primarily designed on a certain rule of thumb based on the study of a large number of theoretical curves for layered media. The field curve is digitized at a logarithmic interval equal to (or a multiple of) sample interval of the filter to be used in calculating the theoretical sounding curve. A digitized field curve is interpreted by the iterative method, as also explained by Israil and Pachauri (2003). For the geological interpretation of resistivity values, the interpreted resistivity values were correlated with the known available borehole data in the study area. The correlations identify subsurface formations from resistivity values at the site where borehole data are not available.

The interpretation of the resistivity data shows that the resistivity of the top layer generally varies from 89–506 Ohm-m. However, at places where boulders are exposed near or on the surface the resistivity of the top layer reaches up to 1,000 Ohm-m. The thickness of the top layer varies from 2–7 m. The large variation in resistivity of the top soil layer indicates the varying nature of top soil (Boulders in the northern Bhabhar zone fining to silty sand in the southern Tarai formation). Due to the occurrence of finer materials in the Tarai belt, groundwater occurs in semi-confined aquifer conditions. The clay/clay with courser sand is characterized by low resistivity ranging from 14–37 Ohm-m in the Bhabhar zone 10–28 Ohm m in Tarai. Resistivity ranged from 26–144 Ohm-m and indicates medium sand with gravel, which is water bearing and forms the aquifer in the Bhabhar and Tarai zones. The thickness of this aquifer varies between 2–8 m in Bhabhar, and 5–15 m in Tarai. Depth to the upper aquifer zone varies from 17–32 m in the foothills (Bhabhar zone) to 0.8–6.9 m in the southern parts (Tarai) of the study area. On the basis of resistivity values of the top unsaturated soil type and the geomorphic units, six sites were selected for the estimation of quantitative values of recharge using the tritium tagging technique.

Tritium Tagging Studies

Tritium tagging studies were carried out at six sites (Fig. 1), selected on the basis of resistivity values and the unsaturated soil layer of the study area. These sites represent different geomorphic units and soil types present in the study area. Groundwater recharge was estimated by monitoring the vertical movement of injected tritium. The position of the tracer is indicated by a peak (maximum) in tritium activity versus depth plot. The radioactive tritium obtained from Bhabha Atomic Research Center (BARC), India, with specific activity of 40 μCurie/cm^3 was injected into five holes placed in a circular geometry at each site at a depth of 70 cm from the surface. The soil samples were collected at the time of injecting the tritium (pre-monsoon) and after 3 months in October 2002 (post-monsoon). The soil samples at 10 cm from the surface downwards to a depth of 2.5 m were collected using a hand auger at each site. Volumetric moisture content of each soil sample was estimated using standard gravimetric methods in the laboratory at the National Institute of Hydrology (NIH). The volumetric moisture contents at the six sites was 0.04 to 0.124. A liquid scintillation counter (LSC) was used to measure the tritium activity of soil moisture extracted from each soil sample. The liquid scintillation counter measures beta counts per minute with an efficiency of 60%. An aliquot of 1 ml of triturated water extracted from each soil sample was mixed with 10 ml of cocktail (whose background count was already measured with the LSC) in the scintillation vials. These vials were used in the liquid scintillation counter system for each sample and the count rate (counts per minute) for each sample was estimated. These count rates were corrected for background counts to obtain the net tritium counts per minute. The error associated in tritium activity measurement is the square root (sqrt) of the ratio (N/t), where N is the number of counts in time t (minutes). The error in tritium counting rate does not effect the determination of centre of gravity (CG) of the tritium activity peak. The centre of gravity of the tritium activity peak was determined to calculate the shift in injected tritium. The tritium activity peak broadens due to diffusion and

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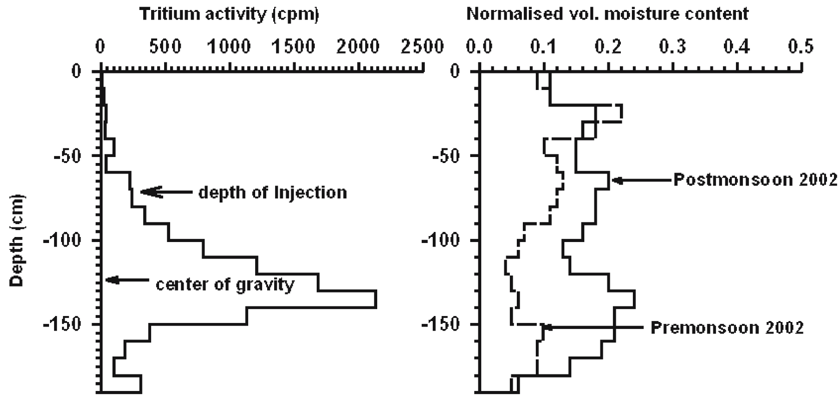

Fig. 3 Tritium peak shift and normalized volumetric moisture content measured at a site in the upper piedmont zone

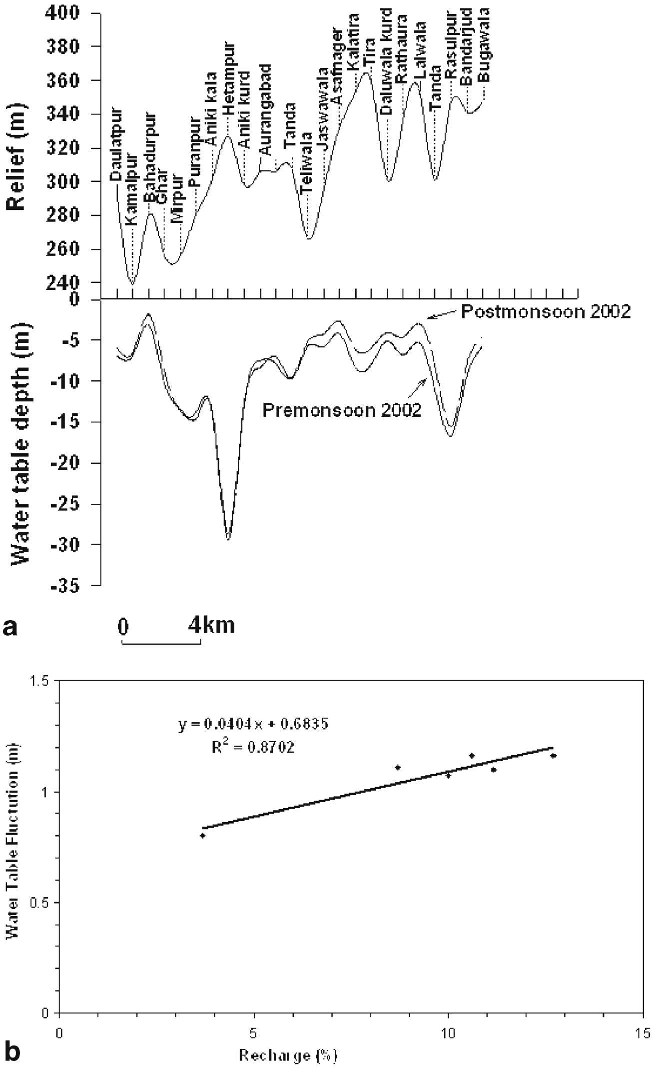

Fig. 4 a Surface elevation and water-table fluctuation measured in the villages shown in top plot in the study area. **b** Relationship between water-table fluctuations as monitored and recharge per cent estimated from the tritium tagging technique

dispersion processes. The count rates so obtained are plotted against depth for each site. An example of the plot of the count rate, centre of gravity of tritium peak and volumetric moisture content are shown in Fig. 3 for a representative site located in the upper piedmont zone at Bugawala. The shift in tritium peak was estimated by using the depth of tritium injection and the centre of gravity of the peak. The shift in tritium peak position varied from 23.95 to 129.7 cm in all six sites.

The amount of recharge during the time interval of tritium injection (pre-monsoon) and sampling (post-monsoon) was estimated by multiplying the tritium peak shift and effective average volumetric moisture content in the tritium peak shift region (Zimmerman et al. 1967a, 1967b). Mathematically, the equation for the estimation of percentage of recharge to groundwater can be written as

$$R = \theta_v * d(100/p) \quad (1)$$

where R is the percentage of recharge to groundwater, θ_v is the effective average volumetric moisture content in the tritium peak shift region, d is the shift of tritium peak in cm and p is precipitation and/or irrigation in cm.

The data for precipitation and/or irrigation were obtained from the Groundwater Department, Roorkee Division, Roorkee.

The depth of the water table was also monitored from these sites and nearby locations at the time of tritium injection (pre-monsoon), and at after 3 months (post-monsoon). They are plotted along with the surface elevation (relief) in Fig. 4a. The linear relationship between the water-table fluctuation and recharge per cent shows that the vertical infiltration constitutes the net recharge in the study area (Fig. 4b).

Recharge Model

The groundwater recharge estimated using the tritium tagging technique shows that the recharge in the study area varies between 3 and 13%. Conceptually, the vertical recharge depends on the infiltration characteristic of the unsaturated topsoil layer. The physics of the electrical current flow in an unsaturated soil depends upon soil type and its infiltration characteristics. Resistivity of low permeability soil is very low compared with the resistivity of high-permeability soil. The average resistivities of the

 DOI 10.1007/s10040-004-0391-8

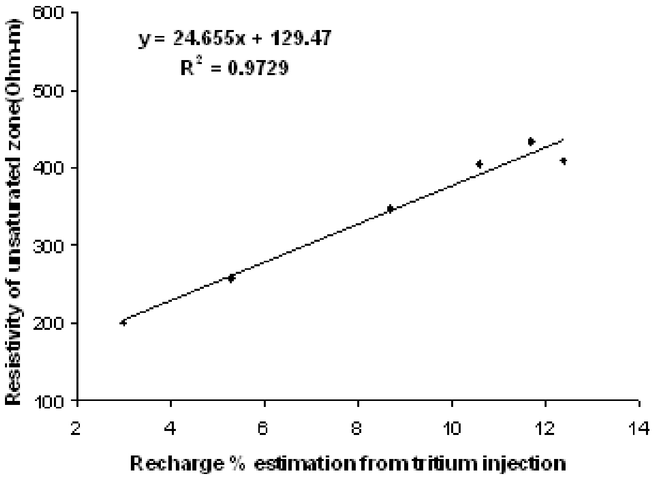

Fig. 5 Correlation of recharge per cent obtained from the tritium tagging technique and resistivity of unsaturated top soil layer

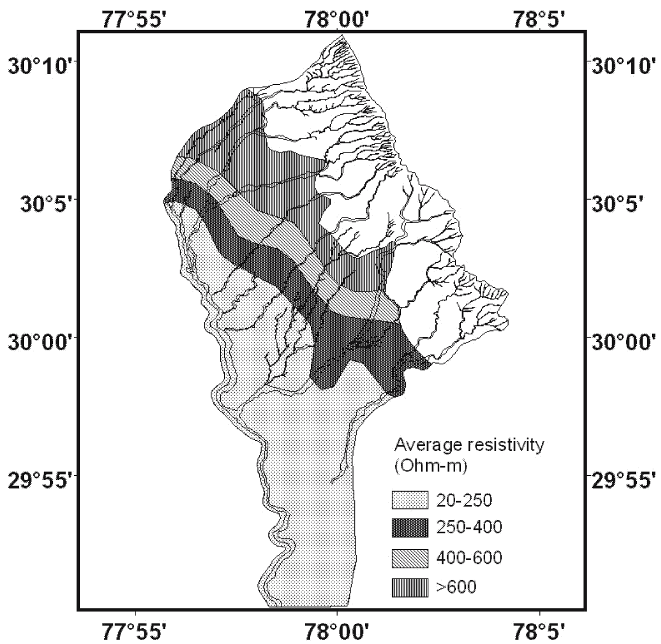

Fig. 6 Average resistivity of unsaturated top soil layer

unsaturated topsoil layer were calculated for each site from interpretation of the resistivity data collected in and around the site of interest. A linear relationship (Fig. 5) was obtained between the resistivity of the unsaturated topsoil layer and the estimated recharge per cent. This is an empirical relationship and is referred to as the recharge model for the study area. In the hydrogeology literature, other empirical relations between the resistivity and hydraulic properties of aquifers have also been investigated and are referred to as a model (Mazac et al. 1985). Validation of these models are possible by their extensive use in future applications in similar geological environments. The model is used to estimate the recharge per cent from the surface resistivity measurements using the linear relationship for the study area. For the estimation of recharge from resistivity values, the average resistivity of the top unsaturated soil layer has been computed from the resistivity data-interpretation in the study area. Figure 6 shows the average resistivity of the unsaturated soil in the study area. The recharge per cent, estimated from the resistivity value using the recharge model developed here, is shown in Fig. 7.

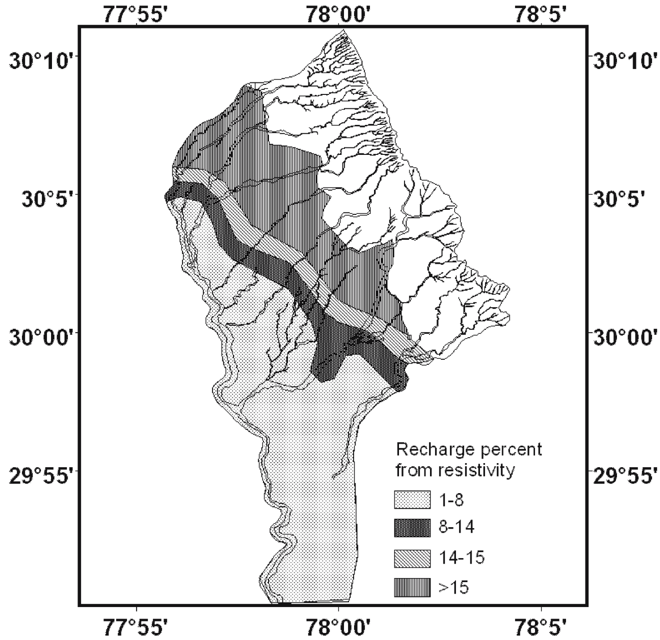

Fig. 7 Recharge per cent estimated using the present technique

Conclusions

This paper presents a new approach for the estimation of groundwater recharge in the area of a known geological formation. The relationship presented here is based on extensive studies using the surface resistivity method, an isotope tagging technique and groundwater level monitoring, which are mapped using GIS techniques. The relationship is extremely useful for groundwater-resources evaluation and recharges estimation in a particular area of interest and is valid for areas of similar geology. Once such a relation is developed for a given area, the estimation of groundwater recharge will be easier, economic and less time-consuming when using surface resistivity measurements.

Acknowledgement The authors are thankful to Dr S.K. Verma, scientist, National Institute of Hydrology Roorkee, for helping in the field programme related to the tritium injection studies.

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