

system, while IBA and NAA produced shoots as well as roots. IBA/NAA initiated an average of two shoots per node in all concentrations used and simultaneously a root system containing five to eight roots at the base. The plantlets were ready for soil transfer within 41 days of culture and thus reduced the time period. Therefore, only IBA/NAA can be used for rooting of shoots of *L. reticulata*.

The timescale for initiation of organogenesis to the final hardening process from the callus took nearly 8 months, while the same process from the node took 3–4 months. Therefore, mass propagation from the multiple shoot production from the node was preferable instead of the organogenic pathway. Plantlets were successfully established in the soil by one month and ready for the field transfer in 3–4 months. Plantlets were transferred to the field during July to September. This period gives less mortality and high survival rate of plantlets during the hardening stage because of high moisture content of the air, which prevents quick desiccation of the plantlets.

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Direct determination of aquifer configuration using geoelectrical techniques in a piedmont zone, Himalayan foothills region, India

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Geoelectrical techniques have been used to define the geometry of aquifer systems in the Pathri-Rao watershed situated in the piedmont zone of the Himalayan foothill region, Uttarakhand, India. This has been done by integrating the results of dc resistivity and electromagnetic data recorded in the area. Two-dimensional resistivity imaging was carried out to define the horizontal and vertical geometry of the aquifer system and to infer the local groundwater flow condition. On the basis of resistivity values it was found that shallow and deep aquifers have different degrees of interaction in the area. The study demonstrates the versatility of geoelectrical techniques.

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Keywords: Aquifer system, electrical resistivity imaging, Himalayan foothills region, piedmont zone.

THE rate of withdrawal of groundwater in the piedmont area is increasing continuously due to increasing population and agricultural and industrial development. Over-exploitation of groundwater is manifested by the lowering of the water table and a regional imbalance associated with the problem of water scarcity for domestic, agricultural and industrial uses. Hence, detailed identification of the aquifer system is essential for sustainable development of groundwater in this region. The methodology for delineation of the aquifer system, by surface hydrogeological and remote-sensing techniques^{1,2}, is based mainly on surface hydrogeological and geomorphologic features. In the absence of proper depth control and reliable subsurface data, estimation of the aquifer system by these methods remains unreliable. For delineation of aquifers in a multi-aquifer system, like the piedmont zone, geophysical methods can be effectively used to estimate the depth, thickness and lateral extent of the aquifers. Recent developments in geoelectrical data acquisition and interpretation methodology provide electrical images of subsurface features. A properly calibrated electrical image can be used to infer the aquifer configuration: depth, thickness, horizontal and vertical extent of the aquifers. Thus by combining data on the surface hydrogeological features with subsurface information obtained from geoelectrical investigations, one may define the subsurface features and details of aquifer geometry. Venkateswara Rao and Briz-Kishore³ have used geophysical and hydrogeological methods to estimate groundwater potential in the arid and semi-arid areas of South India. Shahid and Nath⁴ have also used integrated remote sensing and electrical sounding data for spatial hydrogeological modelling of a soft rock terrain in Midnapur District, West Bengal, India. The objective of the present study is to apply integrated Vertical Electrical Sounding (VES), Electrical Image Profiling (EIP) and Time Domain Electromagnetic (TEM) techniques to delineate the aquifer system and its geometrical configuration in the Pathri Rao watershed of the Himalayan foothills region, Uttarakhand, India.

The study area is located between 29°55' to 30°03'N lat. and 77°59' to 78°06'E long. and covers an area of about 52 sq. km in the Pathri Rao watershed (Figure 1). The area falls in the Upper piedmont zone of the Himalayan foothills region, Uttarakhand, also referred to as Bhabhar in northern India. Thick deposits of poorly sorted sediments and deep water tables, are the main features of the area. Consequently, development of groundwater in such an area is cost-prohibitive. Therefore, delineation of the aquifer system and its detailed geometrical configuration are important for sustainable groundwater development.

Geologically, the Pathri Rao watershed is mainly characterized by Upper piedmont formation of the Quaternary age, formed by sediments of the Himalayan foothills re-

gion and Tertiary deposits of the Siwaliks. The Siwaliks are exposed in the northern part of the Pathri Rao watershed. Bhabhar Formation of the Pathri Rao watershed is bounded by the Siwaliks in the north and the Tarai Formation in the south. Piedmont deposits are composed of unconsolidated coarse sand with boulders, fine to medium sand with pebbles, and boulders and clay, derived from the Siwalik ranges. The formation exhibits high porosity and permeability, allowing easy infiltration of water. The depth to water level monitored in the observation wells located in the area lies between 7 and 31 m below ground level (bgl).

Geoelectrical techniques are powerful tools and play a vital role in delineation of the aquifer configuration in complex geological environments. A planned geoelectrical investigation is capable of mapping an aquifer system, clay layers, the depth and thickness of aquifers and qualitatively estimating local groundwater flow⁵.

The popular electrical resistivity method of data collection requires the use of four electrodes, which are moved for each measurement. When the spacing between electrodes is constant and the locations are moved across the ground surface, a profile of apparent resistivity values across an area can be developed. When the spacing between electrodes is varied around a central location, a sounding is developed by spreading the electrodes further apart for each measurement. One-dimensional inversion is used to model geological features by geophysical parameters such as depth, thickness and resistivity.

Electrical image profiling using a multi-electrodes resistivity imaging system, facilitates the simultaneous recording of profiling and sounding data efficiently. Loke and Barker⁶ have developed a rapid least squares inversion method for the data collected using the multi-electrode resistivity system. The resistivity method is not successful in areas where galvanic contact of electrodes with the

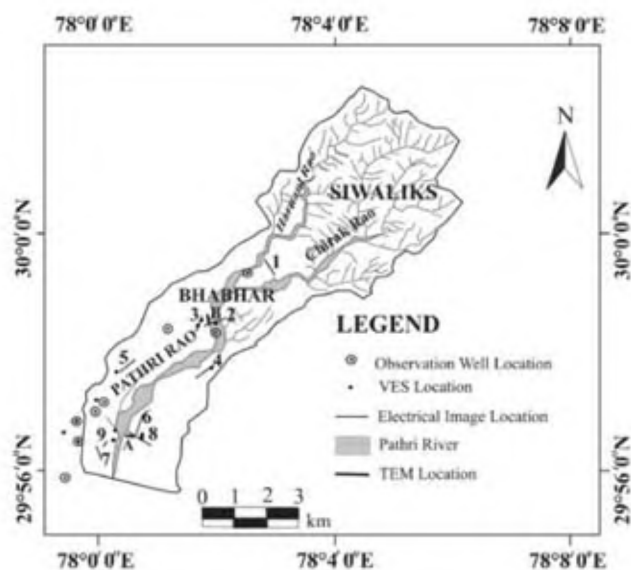


Figure 1. Study area showing locations of investigated sites.

ground is not possible or the surface is highly resistive. In such areas, the inductive method (electromagnetic) is more effective. The TEM method does not require any galvanic contact with the ground for current injection. Therefore, it can also be used in highly resistive ground.

Thus integration of VES, EIP and TEM data can be effectively used to determine aquifer configuration in a complex geological environment.

The location of 11 VES, nine EIP and two TEM profiles is shown in Figure 1. VES data were collected using the Schlumberger configuration with maximum electrode spacing of 900 m. As the northern zone of the area is restricted and inaccessible, the survey was carried out only in the southern part. Electrode spacing is sufficient to provide information about resistivity variation near the surface and deeper than 100 m, which is capable of delineating shallow and deeper aquifers. The least squares method is used to invert apparent resistivity data in terms of resistivity and thickness of the subsurface layer. The interpreted 1D model consists of 3 to 5 layers with varying resistivity and thicknesses. The root mean square (rms) error obtained between the observed and modelled apparent resistivity lies below 6% in all datasets. Resistivity of the top layer in the northern part of the study area is high (900 ohm-m). Resistivity decreases in deeper layers, indicating a saturated condition in the deeper zone. In the southern area, resistivity is relatively lower at all depths in comparison to the northern zone. For geological interpretation, resistivity values are calibrated with known lithology from the available borehole data. An example of lithological correlation of resistivity values obtained from the interpretation of measured apparent resistivity in the area is shown in Figure 2.

With the objective of mapping the detailed lateral and vertical variation of resistivity in the area, nine EIPs were systematically recorded to cover the entire accessible region. These profiles were arranged serially from north to south. The exact location and orientation of these profiles are shown in Figure 1. EIP-1, 2 and 8 are oriented nearly perpendicular to the Pathri Rao river, whereas the others are oriented almost along and on either side of the river bed. In eight EIP lines, 72 electrodes are placed at 10 m intervals, making the total length of each profile as 710 m. The last profile (EIP-9) was recorded at 5 m electrode spacing with a total profile length of 355 m. Data were recorded using an IRIS resistivity meter in a sequence generated using the Schlumberger–Wenner configuration with 895 quadripoles (datapoints) in each sequence. Surface topographical elevations have been recorded using a hand-held GPS system along the profile line to define topographic elevation. The initial processing eliminated spiky and error-prone data. Subsequently, 2D inversion was performed for each EIP dataset using RES2DINV code⁷, with smooth constrained least square method to delineate resistivity depth image along the profile line. Figure 3 shows the 2D model representing resistivity–depth sec-

tion along nine EIP lines. The absolute rms error between the observed apparent resistivity data and the modelled data is less than 1.7 in all cases (Figure 3). These geoelectrical sections present a systematic variation of electrical resistivity with depth along each profile line. In the northern area unconsolidated coarse materials and boulders transported from the Siwalik Hills are characterized by high resistivity (900 ohm-m) for near surface unsaturated layers. At a depth of about 30 m, the resistivity is low (50 ohm-m), indicating saturated sand below the river channel (Harnaul Rao). Further southward, EIP-2 indicates comparatively low resistivity (600 ohm-m) of near surface formation. Underneath the top resistive layer, a consistent aquifer zone dipping towards the southwest is delineated and is characterized by low resistivity (50–100 ohm-m). EIP-3 is also located near EIP-2, being oriented approximately along the river bed. A low resistivity (18 ohm-m) zone is present underneath the ends of the profile; this zone is discontinuous in the middle of the profile (EIP-3). Further south in EIP-4 and EIP-5, the low resistivity zone extends almost along the entire profile line. EIP-5 represents a typical example of the existence of two aquifer systems (shallow at about 10 m depth and deeper at nearly 30 m depth) separated by a thick clay layer. Further towards the south, as indicated by EIP-6–EIP-9, the saturated zone is at shallower depths, and finally intersects the ground surface as manifested by the spring line⁵. Thus the profiles oriented in different directions show the configuration of the aquifer zone and its elevation along the profile line. The aquifer zones are

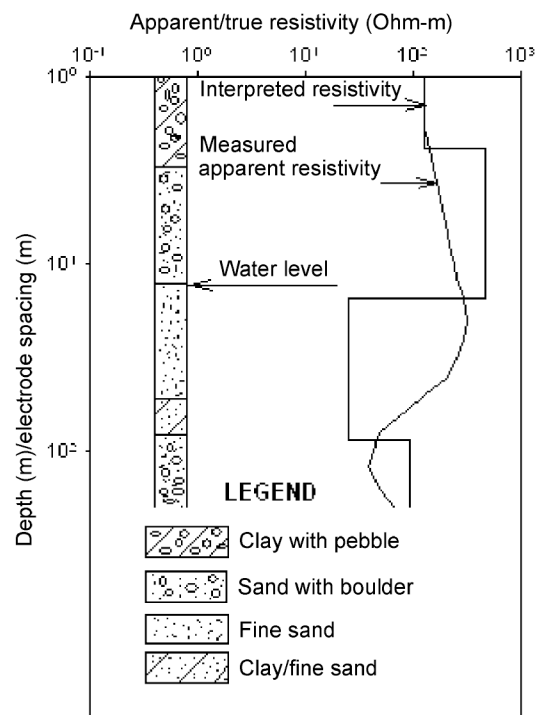


Figure 2. Lithological correlation of resistivity data in Bhabhar zone.

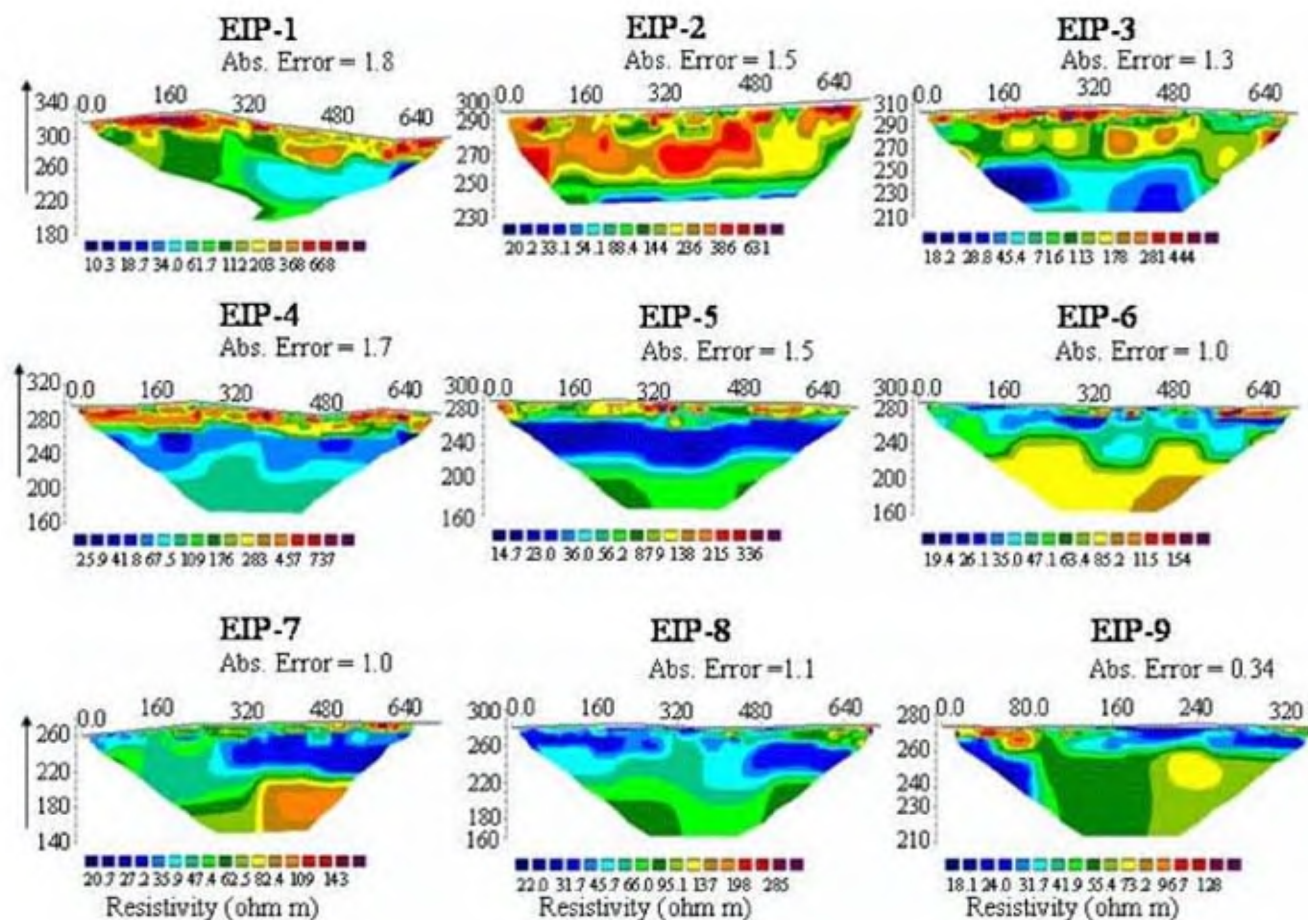


Figure 3. Interpreted resistivity–depth sections along EIPs. Vertical scale represents height above mean sea level (amsl) and the horizontal scale is the distance (in m) along the profile line.

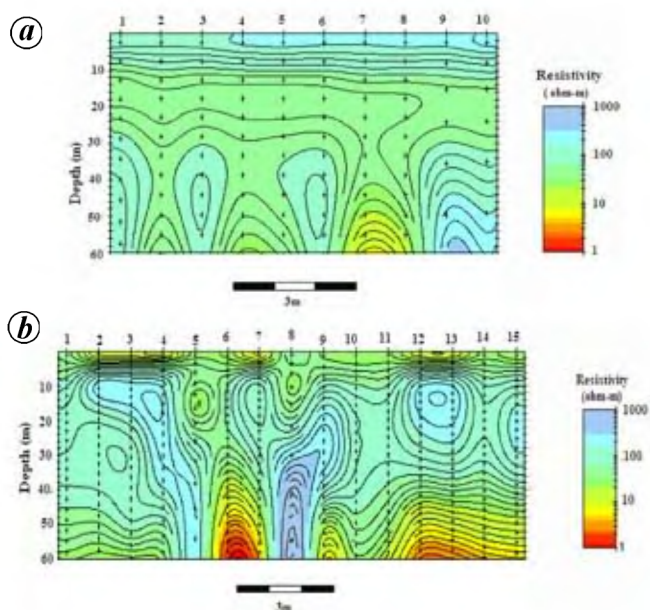


Figure 4. *a, b*, Smoothed resistivity–depth section obtained from TEM data along two profiles.

normally dipping southward, indicating local groundwater flow direction from north to south in the area. The direction of groundwater flow delineated from electrical images is consistent with the local hydrogeological setting. The middle part of the study area is a typical example of two aquifers separated by a thick, impermeable clay layer (EIP-5). Similar hydrogeological conditions are also revealed on the eastern side of the Pathri Rao rivers (Figure 3).

In the study area, unconsolidated and unsaturated coarse material transported from the Siwalik Hills, is represented by high resistivity (900 ohm-m), saturated sand with pebbles with a resistivity range of 30–100 ohm-m and saturated clay with a resistivity range of 10–25 ohm-m.

TEM data along two profiles (A and B) are shown in Figure 1. The Zonge GDP-32 NanoTEM system has been used to record data from 25 stations along two profiles (10 stations in profile A and 15 stations in profile B) with a station spacing of 20 m. The TEM technique does not require galvanic contact of the electrode with the ground, and hence it can be used in high resistivity ground also.

We compared these results with those obtained by the direct current resistivity method. The depth of investigation of TEM data is determined by the time at which the signal decays to noise level, source strength, loop size and resistivity of the earth⁸. In the present investigation, we have used 20×20 sq. m transmitter loop powered by a 12 V battery and a 5×5 sq. m receiver loop placed in the centre of the transmitter. Data collected from the field are processed and interpreted to generate resistivity–depth images from the decay curve. The smooth interpreted section along the two profiles is shown in Figure 4a and b. The resistivity section obtained from TEM data at shallow depth broadly agrees with the corresponding section obtained by imaging and VES data.

Aquifer geometry and groundwater flow direction in a complex geological environment of the Himalayan foothills region are defined on the basis of integrated VES, EIP and TEM geoelectrical techniques. The study indicates high resistivity of unsaturated, unconsolidated and porous coarse material of the Bhabhar Formation. Finer subsurface material in saturated condition towards the southern part is indicated by low resistivity. Two aquifers separated by a clay formation are inferred in the middle part of the area. The clay layer is discontinuous in some areas, indicating interconnection between the two aquifers.

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Development of GIS interface Con2grid for groundwater model

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Simulation of groundwater behaviour is required to predict water-table fluctuation in response to varying groundwater pumping and recharge conditions. Groundwater models are widely used for simulation of groundwater behaviour. Numerical simulations often involve handling of large-scale spatial and non-spatial input and output datasets. Geographic Information System (GIS) provides an integrated platform to manage, analyse and display these datasets and facilitates modelling efforts in data compilation, calibration, prediction and display of results. Groundwater models, such as MODFLOW, needs datasets of various parameters such as surface elevation, bottom elevation, percolation, seepage, etc. in ASCII format. Preparation of input files of these parameters is a difficult task and time-consuming, which can be made simple with the use of GIS. However, an interface program is necessary to couple the GIS with the groundwater model. An attempt was made to develop an interface for preparing the data file required for MODFLOW. ArcInfo interface Con2grid for groundwater flow model PMWIN was built as an extension for facilitating the simulation of groundwater behaviour. The extension includes pre-processing of spatially distributed (point, line and polygon) data for model input and post-processing of model output. With the help of ArcInfo interface, any coverage of spatially distributed data can be converted into ASCII files of user-defined grid dimensions. The pre- and post-processing capabilities of Con2grid were demonstrated for simulation of groundwater behaviour in western Indo-Gangetic Plains, Uttar Pradesh, India.

Keywords: Con2grid, groundwater models, interface, simulation.

SIMULATION models play an important role in the estimation of groundwater potential and prediction of aquifer response to groundwater pumping and recharge. Extensive reviews of groundwater models are available in the literature^{1–3}. According to Johnson *et al.*⁴, numerical models such as MODFLOW⁵ provide an efficient tool to assist in the water resource decision process. A simplified representation of the system may in some cases, be obtained by the development of response function from numerical models. It was also reported that MODFLOW could produce pre-

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