# Electrical Resistivity and Other Geophysical Methods for Improved Modelling of Groundwater Flow

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# ABSTRACT

Groundwater models enable us to predict the dynamic responses of aquifers under different stress conditions such as groundwater pumping, recharge events, and climate and land use changes, thus helping in the implementation of water management plans. Groundwater models also help us to understand contaminant transport in the subsurface, and to model different remedial measures. However, all models are data 'thirsty' and can suffer from inadequate hydrogeological data across the spatial scales, making it challenging to reliably simulate the subsurface flow process. The conventional methods of data acquisition including borehole/well drilling for logging aquifer geometry, and pumping and slug tests for aquifer parameter estimation, are generally limited to giving data for small localised areas that are not able to provide information across larger spatial scales to reliably simulate the subsurface flow process for predictive modelling. In recent years hydrogeophysics has evolved to provide techniques for improved understating of subsurface properties and hydrogeological processes.

This book aims to synthesise knowledge on the advantages and utilities of electrical resistivity methods to reliably conceptualise the subsurface and hydrogeological processes, to improve groundwater flow and transport models. This edited book contains a total of nine chapters that cover geophysical investigations for groundwater flow studies and contaminant transport modelling from different sites across South India. All chapters emphasise the use of geophysical technical techniques for a better conceptualisation of sites where there is only limited borehole lithology data. The first chapter describes the development of hydrogeophysical inversions and describes a case study of the use of electrical resistivity tomography in groundwater modelling. The second chapter provides a case study of surface electrical resistivity to obtain aquifer parameters and conceptualisation for reliable simulation of groundwater flow. Chapter 3 explains how modelling techniques can help to deploy the geophysical investigations and also how electrical resistivity tomography can help to conceptualise the groundwater flow model of a coastal aquifer. Chapter 4 explains the utilities of time series electrical resistivity tomography for deriving hydrological parameters to support groundwater model

conceptualisation. Chapters 5 and 6 explain electrical resistivity tomography applications for aquifer characterisation and help identify suitable recharge locations for two case studies. In chapter 7, the authors show how groundwater flow modelling can be applied to mining applications by combining geophysical and extensive borehole lithology data. Chapter 8 briefly explains the use of 1D resistivity investigations to understand the structure of an aquifer and its quality for better conceptualisation. In chapter 9, the authors utilised 2D electrical resistivity tomography to build a groundwater flow and contaminant transport model for selecting the best location for a new groundwater production well.

# CHAPTER 1

# ADVANTAGES OF HYDROGEOPHYSICS FOR IMPROVED CONCEPTUALISATION AND PREDICTIVE MODELLING OF GROUNDWATER FLOW PROCESS: A CASE STUDY IN BELLARY DISTRICT, KARNATAKA STATE, SOUTH INDIA

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## Abstract

The use of distributed and process-based numerical models to model groundwater flow processes and estimate water balances to help policymakers with sustainable groundwater management has grown in recent years. However, aquifer characterisation and parametrization are still prime requisites for groundwater flow and solute transport modelling. Borewell lithology and aquifer pump tests are routinely used to obtain this information. Both methods are time-consuming, costly, and only provide limited information with low resolution and limited spatial coverage. Geophysical techniques can offer advantages and can complement routine hydrogeological data collection to overcome these limitations, providing high spatial and vertical resolution that can improve the predictive performance of groundwater models. This chapter provides a synoptic review of the advantages of hydrogeophysics for groundwater modelling and demonstrates the use of Electrical Resistivity Tomography (ERT) for deriving aquifer parameters with limited bore well drilling logs, helping to simulate groundwater flow more reliably.

**Keywords:** Geophysical techniques, aquifer Characterisation, groundwater modelling, and groundwater budget

## 1.1 Introduction

Groundwater is the only freshwater resource in most of the arid and semi-arid areas of the world. It is replenished by rainfall recharge. Due to land use patterns, climate change, and rising demands, many aquifers are under tremendous pressure and have shown rapid depletion of groundwater resources. Sustainable groundwater management requires reliable estimations of available water resources, an understanding of the different hydrogeologic processes, the parameterisation of the aquifer properties, and aquifer geometries. In recent years, fully processed and physically-based numerical groundwater flow models have emerged for effective groundwater resource management. Detailed knowledge of subsurface hydrogeology is a prerequisite for both groundwater flow modelling and to plan effective site contaminant remediation if needed (Ciampi et al., 1998). The conventional means of obtaining hydrogeological information is by borehole drilling and logging, and pump testing. These methods require capital spending and time, yet only provide information limited in the vicinity of the borehole, which is insufficient to accurately describe essential controls on subsurface flow and transport. In recent years hydrogeophysics has evolved to help explore the quantification of subsurface properties and processes. These non-invasive and economically cheaper methods provide broad spatial coverage of subsurface hydrogeological information in less time than conventional methods (e.g. Baroncini-Turricchia et al., 2014). There are many geophysical techniques available for subsurface Characterisation for various applications. The advantages and disadvantages of different geophysical methods are described in Table 1. Electrical resistivity tomography (ERT) techniques can be used to characterise the subsurface hydrogeology and to assist with contaminant zone mapping (e.g. Surinaidu et al., 2020); different hydrogeophysical methods can be used to monitor aquifer storage and recovery (ASR) systems (e.g. Minsley et al., 2010); cross-borehole radar and resistivity imaging can be used for vadose zone flow model parameterisation (e.g. Binley et al., 2002); cross-hole ground-penetrating radar (GPR) and borehole porosity log data can be used to characterise the porosity distribution in the saturated zone for groundwater flow and contaminant transport modelling (e.g. Dafflon et al., 2009). Sinha et al., (2009); Khalil (2016); Mondal et al., (2016) and Amaya et al., (2018) have demonstrated that geoelectrical soundings can be used to derive the aquifer parameters, replacing the need for aquifer pump tests. Baroncini-Turricchia et al., (2014); Walsh et al., (2014) and Mazzilli et al., (2016) have used magnetic resonance sounding (MRS) to obtain hydrogeological parameters of both saturated and unsaturated zones. Herckenrath et al., (2013) and Boucher et al., (2009) have tested Joint Hydrological inversion and sequential hydrological inversion with various hydrogeophysical data for groundwater modelling that has improved parameter estimation and reduced parameter uncertainty.

In this chapter, we have described the use of Electrical Resistivity Tomography (ERT) to characterise subsurface hydrogeological conditions with limited borehole lithology data, to improve the reliability of numerical groundwater flow modelling.

## 1.2 Study area and hydrogeology

The study area is focused on the Donimalai Township situated in Bellary district, Karnataka state, South India (Fig.1). The total population of the township is 6672 (2011 census data). The township's drinking water needs are met by surface water drawn from the Narihalla River after treatment. Groundwater from bore wells and hand pumps in the township is used for horticulture. Finding potential groundwater zones that are plentiful, reliable, safe, and sustainable, is a pressing problem for the township. The annual rainfall in the area is 671 mm, with only 35 rainy days per year.

In the Bellary district, sandy loam soil is present along the stream beds, while red soil is present in elevated places, and black soil is found on irrigated land. The district is underlain by hard rock comprising granitic gneisses, younger granites, and schist formation of Archean age. These formations form a major aquifer in the weathered and semi weathered zone up to 25 meters below ground level (m bgl), while deeper aquifers occur between the depths of 30 to 197 m bgl. Schists have a weathered upper profile with less granularity and more fracture openings than granites and gneisses (CGWB, 2012). Groundwater occurs in the area under phreatic and semi-confined conditions. The transmissivity (T) of granites/gneiss ranges from 0.24 to 292.38 $m^2$ /day and ranges from 1 to 70 $m^2$ /day for schists. The transmissivity of schists is low compared to granite due to the compacted and clay-filled pores of the rock. The fractured block's gross storativity is of the magnitude of $10^{-3}$ in granites and $10^{-4}$ in schist. The study

**Table 1.** Different geophysical methods, advantages and disadvantages

| Method | Measured Data | Estimated Property | Advantages | Disadvantages |
|---|---|---|---|---|
| Electrical Resistivity methods | Earth materials resistance | Electrical resistivity | A direct indicator of electrical conductivity, which, in turn, is an indirect indicator of soil moisture or percent saturation. Suitable for determining the depth of the water table. | Vertical resolution in the best of cases is somewhat coarse. The method needs special care when lateral features are encountered, adding significantly to acquisition cost, time and interpretation. |
| Electromagnetic | Response to electromagnetic pulses | Electrical resistivity | It is very effective for the rapid reconnaissance of an area for mapping depth to bedrock, depth to the water table, and detecting clay lenses. | Topography can be a problem in interpreting FDEM data. TDEM is not widely used for shallow studies (less than 20 m) in resistive terrains, except for shallow (1 or 2 m) metallic infrastructure investigations. |

| | | | | |
|---|---|---|---|---|
| Self-potential (SP) | Electric potential | Electrical resistivity | Very cheap and easy to carry out in the field. Little or no data processing. It is only the geophysical method that can determine the direction of groundwater flow. | Sensitive to noise from electrical installations. Several electrochemical mechanisms contribute to the SP phenomena, which could make the result difficult to interpret. |
| Induced polarisation | Voltage decay | Electrical chargeability | Excellent in characterizing disseminated mineralization. Less sensitive to noise than TEM. Robust instrumentation and a well-established technique | Sensitive to noise from train traffic and thunderstorms. Long cables require demanding cable logistics. |
| Nuclear magnetic resonance | Relaxation electromagnetic field | Fluid content and relaxation constants | It can be used effectively in small-diameter boreholes, and can measure fluid properties (porosity, permeability) without any additional information required. | Work in contact mechanism with the ground, signal-to-noise ratio that is often poor, long survey times, and bulky equipment. |
| Seismic survey profiles | Travel time refracted/reflected seismic wave | Density and elastic moduli | High resolution, deep penetration from a few tens to several hundred meters. | Slow method data and expensive to acquire, data processing is time-consuming. |

| | | | | |
|---|---|---|---|---|
| Gravity survey profiles | The gravitational field of the Earth in space and time | Density | Fast, inexpensive tool for evaluating large areas, can distinguish sources at exploration depths. | Needs geological and geophysical constraints to interpret, data quality may deteriorate in rougher terrain, finer structures are more challenging to map. |
| Magnetic survey profiles | Geo-magnetic field in space and time | Magnetic susceptibility | Often useful to delineate geologic features related to hydrogeology. | Local traffic and other magnetic disturbances often require gradient techniques. Depth resolution is poor except for small, shallow targets. |
| Radar | Travel time of the reflected radar | Dielectric constant | Can penetrate media such as clouds, fog, mist, and snow, insulators. It can give the exact position of an object. Based on velocity, it measures the distance of an object. It can tell the difference between stationary and moving objects. | It takes time to lock onto an object. It has a wider beam range (Over 50ft diameter). It has a shorter range (200ft). It cannot track if an object is decelerating at more than 1mph/s. Large objects that are close to the transmitter can saturate the receiver. |

*Source: Telford et al. ,1990; Dobrin and Savti, 1988; Keller, 1970* area is dominated by schists, and hence the maximum transmissivity is considered in the groundwater flow model to determine hydraulic conductivity (K) = T/b. The average thickness (b) of the aquifer is considered as 35 m, and hence K is 2 m/day.

## 1.3 Methodology

### 1.3.1 Hydrogeophysical investigations

A total of nine ERT were taken using the Wenner-Schlumberger electrode configuration with 5 m inter-electrode spacing and 120 m total length of the profile to identify the potential groundwater areas in the Donimalai Township based on space availability during May 2015 (Fig.1). The ERT investigations were carried out using a SYSCALL PRO-96, IRIS instrument. This is a ten-channel multi-electrode automatic resistivity meter with high accuracy, and multi-core cable equipment that supports 10 m maximum inter-electrode spacing. The measured apparent resistivity is converted into true resistivity using the inversion program RES2D.INV to produce the 2D resistivity cross-section image (Loke, 1997). RES2DINV will automatically determine a 2D resistivity model for the subsurface for the data obtained from electrical imaging surveys. The detailed methodology of ERT data processing can be found in Loke (1994). Some new bore wells at a few locations in Bacheli Township have provided some information on the lithology, collected during the borewell drilling. This lithology has been compared with ERT results to generalise the resistivity ranges of the formation.

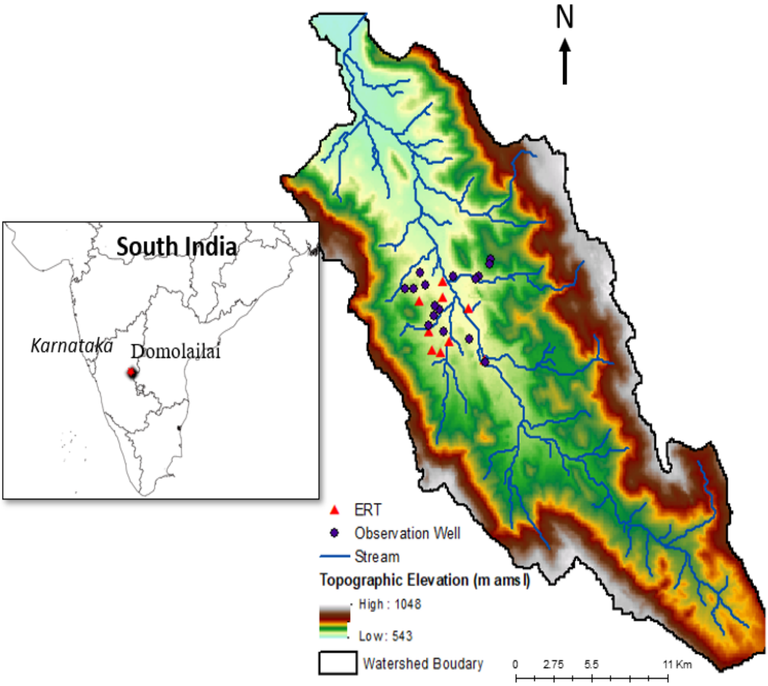


Figure 1. Location of ERT profiles and observation wells in the watershed covering Donimalai Township, Bellary District, Karnataka

## 1.3.2 Groundwater flow modelling

In this study, a steady-state variably saturated groundwater flow model (assuming an equivalent porous media approach) using MODFLOW was constructed (McDonald, 1988). The equivalent porous medium approach has been successfully used by many researchers in groundwater flow modelling (e.g. Wu, 2004; Varalakshmi et al., 2012; Surinaidu et al., 2013, 2014, 2016a, 2016b). The land surface of the groundwater model was generated using an ALOSPALSAR 30 m resolution digital elevation model (https://www.eorc.jaxa.jp/ALOS/en/about/palsar.htm). The aquifer's subsurface was conceptualised as a two-layer aquifer system with variable aquifer thickness based on hydrogeophysical and borehole data as described in the results and discussion section below (Fig.2).

Hydraulic conductivity and storativity were considered based on secondary data (CGWB, 2002). The entire model domain was divided into 50 rows and 50 columns with a cell size of 100 m by 100m (Fig.2). Groundwater recharge was estimated using the water table fluctuation method (GOI, 1997). The observed average groundwater level rise for the whole area was 0.92 m during the post-monsoon compared to pre-monsoon in the year 2014 based on observational data during the study. The specific yield values for weathered phyllite, shale, schist, limestone, and associated rocks are 1% to 3% (GOI, 1997). In the study area, the average specific yield of 2 % was considered for annual groundwater recharge estimation (1).

$$\text{Recharge (mm/yr)} = \text{Specific Yield } (S_y) * \text{Water table change (mm)} \quad - (1)$$
$$= 0.02 * 920 \text{ (mm)}$$
$$= 18.4 \text{ mm}$$

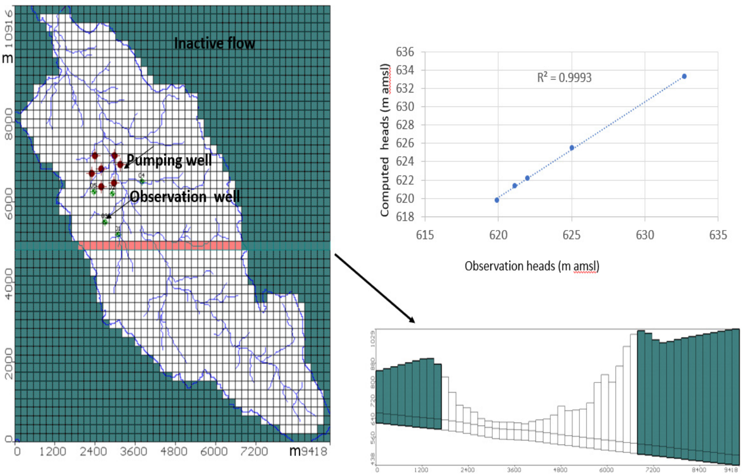


Figure 2. Spatial (left) and vertical (bottom right) discretisation of the study area (cell size: 100 x100 m). The green coloured cells show the inactive cells (no flow boundary); Top right corner: calibration results at the end of model calibration.

The estimated recharge was applied to the topmost active layer. The total estimated groundwater demand data was given by Donimalai township authority and is about 140 $m^3$/day, which we simulated with six pumping wells. Groundwater levels at five borewells were used to calibrate the flow model (Fig.2). The river boundary condition was specified in place of the major stream passing through the study area with a river width of 50 m, depth of 1 m, river bed thickness of 2 m, and vertical hydraulic conductivity of 0.1 m/day. The model calibration was achieved by matching observed groundwater heads with model-simulated heads by adjusting hydraulic conductivity and recharge manually. At the end of model calibration, the computed hydraulic conductivity is 1.5 m/day and the recharge is 24 mm/yr.

## 1.4 Results and discussion

### 1.4.1 Groundwater prospects and hydrogeology

The ERT profile No.2 was carried out with 24 electrodes and 5 m inter-electrode spacing that covers 120 m length of the profile. The obtained depth of investigation is about 24 m bgl. The low resistivity (< 80 Ohm-m) up to 12 m depth below the ground surface represents the weathered rock zone. The weathered zone is underlain by a fracture zone extending up to 16 m depth with resistivity < 135 Ohm-m. Basement rock is not reported at this location below 24 m bgl (Fig.3). The borewell lithology at this location has a good agreement with resistivity inferences of the ERT results. For ERT profile No.3, the occurrence of a low resistivity formation representing the weathered zone was inferred up to 14 m bgl, which is indicated by resistivity < 75 Ohm.m.

**Table 2. Generalised lithology in the study area based on nine ERTs carried out in the area**

| *Layer* | *Geology* | *Resistivity (Ohm.m)* | *Average thickness (m)* |
|---|---|---|---|
| *Top layer* | Red soil (topsoil) clay dominated | 10-50 | 2.5 |
| *1st layer* | Highly weathered chlorite schist | 50-120 | 14 |
| *2nd layer* | Fractured chlorite schist | 120-150 | 8 |
| *3rd layer* | The basement of the aquifer | >500 | |

The weathered zone is underlain by a fracture zone, which extends up to 18 m bgl with resistivity < 180 Ohm-m. Bedrock that occurs below the fracture zone (>24 m bgl) was reported with high resistivity (>500 Ohm-m) (Fig.3). ERT profile No.6 shows a weathered zone extending up to 18 m depth with resistivity < 80 Ohm-m and the ERT cross-section infers high saturation (< 10 Ohm-m) encountered at 10 m bgl. Hard bedrock is encountered at a depth below 20 m bgl (Fig.3). The ERT profiles displaying low resistivity formations and having good saturated conditions are recommended locations for the drilling of new bore wells. Three new bore wells were drilled from 16$^{th}$ May to 20$^{th}$ May 2015 at different locations out of the five best locations suggested. The bore well drilling revealed the presence of lateritic soils on the top cap in the Donimalai area, underlain by phyllitic clay (with various colours based on metamorphism), underlain by chlorite schist, followed by hard rock at greater depths.

The observations recorded during borehole drilling indicated that groundwater was struck at 16.5 m bgl at location 1. Drilling continued up to a total of 46 m depth. The casing was installed up to 20 m bgl. The observed well yield was reported as 142 $m^3$/day. After one day, the static groundwater level stood at 5.35 m bgl. At location 2, groundwater was struck at 33.3 m bgl and the borehole was drilled to 56 m depth. In this location, the static groundwater level was at 1.6 m bgl with an estimated well yield of 356 $m^3$/day. At location 3, the groundwater level was encountered at 20 m depth and drilled up to 51 m depth. In this location, a static groundwater level was observed at 10.12 m bgl. These additional bore wells could therefore be used to supply water to the township and local village after ensuring its quality for drinking water purposes.

In summary, the resistivity data combined with the bore well lithologs (Fig.3) revealed that the area has an average soil thickness of about 2.5 m, weathered chlorite schist of 18 m followed by fractured schist, and it is underlain by basement rock. In most of the cases, basement rock was encountered at a depth of 24 m bgl. Hence shallow bore wells are recommended for the area. This information was then used to feed into the construction of the two-layer groundwater flow model: soil and weathered rock together as a top layer with an average thickness of 16.5 m and fractured rock as the second layer with an average thickness of 8 m.

### 1.4.2 Groundwater flow modelling and budget

The entire area is dominated by lateritic soil with clay with steep slopes. Hence, the groundwater recharge is impeded, and there are poor specific yields. In the study area, only shallow wells are recommended since the aquifer has very low storage capacity and specific yields with relatively shallow depths to the basement rock. Wells drilled in the area may yield a moderate quantity of water, but without data to inform the drilling locations yields may be unreliable. However, wells at a few locations may yield a good amount of water for a long time if the well intersects fractures. Geophysical techniques may be used for mapping such locations (as in the current study).

The integration of bore well lithologs and resistivity data into the numerical groundwater model led to reliable 3D conceptualisation (Fig.4) of the aquifer system that can help reasonable calibration of groundwater flow processes. The model will help managers in the planning of sustainable groundwater management, by considering water balances. Groundwater budget from groundwater flow model zone budget indicates 14672 $m^3$ of groundwater recharge occurs per year while pumping is around 140 $m^3$. The river leakage to the aquifer is about 329 $m^3$ and outflows from the aquifer to the river is 14294 $m^3$ (Table 3). The simulated groundwater flow direction indicated a predominant flow direction toward the streams with an average groundwater elevation range between 650 m above mean sea level (amsl) to 595 m amsl from upstream to downstream in the catchment (Fig.4). The model budget shows significant groundwater leakage to streams.

The major limitation of the model is that the subsurface system is Generalised because of the very limited data available. Aquifer parameters were Generalised based on secondary data. Hence, the model results can be considered only preliminary, and one could follow the methodology used in the study to construct updated or more refined groundwater models. The calibration and groundwater budget estimation was done under steady-state conditions, which is another limitation.

**Table 3. Computed groundwater budget ($m^3$) in the study area**

| Component | Inflows | Outflows |
|---|---|---|
| Evapotranspiration | | 3240 |
| Pumping Wells | | 140 |
| Lateral flows from North-East | 2672 | |
| River Leakage | 329 | 14294 |
| Recharge | 14672 | |
| Total | 17673 | 17674 |

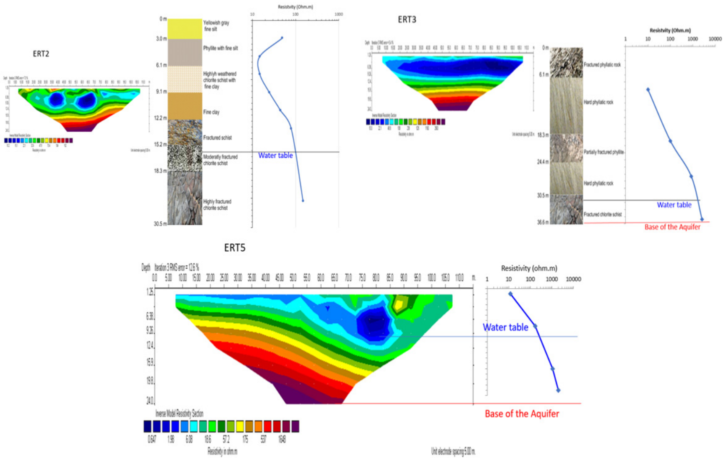


Figure 3. 2D Electrical resistivity cross sections, bore well lithologs and derived resistivity curves from three positions in the study area.

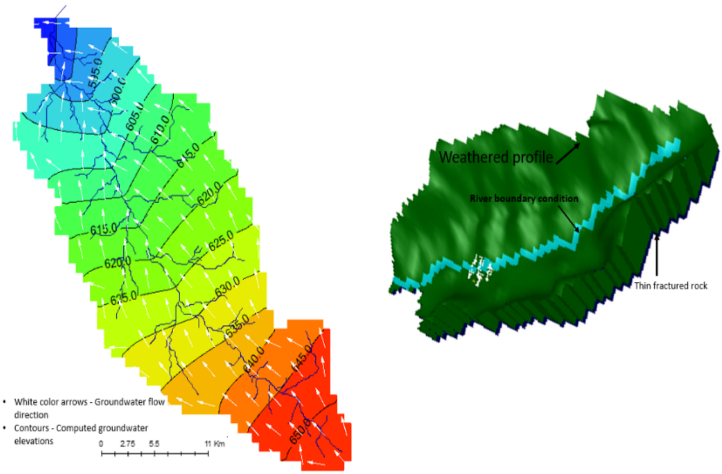


Figure 4. Computed groundwater elevations (left) with groundwater flow directions and 3D aquifer conceptualization in the groundwater flow model (right) for the study area

## 1.5 Conclusions

ERT data has been successfully utilised in many projects to suggest reliable target locations and subsurface strata for drilling new bore well locations. In the Bellary District, Karnataka, electrical resistivity inferences derived from ERT profiles have helped to determine the layer thickness of the subsurface lithology and, in turn, to conceptualise the aquifer layers for a numerical groundwater flow model. The study described here demonstrates that the use of easily deployed hydrogeophysical methods can increase the predictive performance of a groundwater model and increase the model's accuracy and reliability. These models can help to estimate groundwater budgets and simulate groundwater flow processes that can help to inform groundwater management and help to keep groundwater abstractions at sustainable rates.

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# CHAPTER 2

# A SURFICIAL ELECTRICAL RESISTIVITY SURVEY FOR ESTIMATING AQUIFER PARAMETERS FOR THE REGIONAL CHARACTERISATION OF GROUNDWATER FLOW IN A WEATHERED GRANITIC AQUIFER IN THE KODAGANAR RIVER BASIN, TAMIL NADU, SOUTHERN INDIA


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## Abstract

Aquifer parameters are needed to simulate groundwater flow processes using various modelling tools. Typically, these parameters are obtained from in-situ aquifer tests, which are time-consuming and expensive. The study presented here demonstrates the use of electrical resistivity methods for deriving aquifer hydraulic properties and geometry. A total of 19 surficial Vertical Electrical Soundings (VES) were carried out in a weathered granitic terrain covering 1752 km$^2$ in the Kodaganar river basin, Tamil Nadu, Southern India, and analysed with IX1-D v.3 Interprex software. In addition, pumping test data from 28 wells were gathered to assess aquifer parameters. An empirical relationship was established between the geoelectrical properties of the weathered granitic aquifer and data from in-situ methods for estimating hydraulic properties. A cross-correlation test was carried out between hydraulic conductivity (K) and

aquifer resistivity (ρ) obtained at 8 VES sites. It was found that the K values are best defined by an exponential function of aquifer resistivities. This result can be used to calculate predicted K values where no pumping test is likely to be carried out. A single layer phreatic aquifer model was constructed using Visual Modflow to understand the hydrodynamics of groundwater flows in this area. The model was calibrated against the observed water level data and it has reasonably reproduced the groundwater flow regime at the regional level.

**Keywords:** Geoelectrical properties; phreatic aquifer, hydraulic conductivity; groundwater flow model, weathered granite, Southern India.

## 2.1 Introduction

Groundwater is essential for irrigation, industry, and domestic purposes, and it is the only primary source of potable water supply in many countries (Akankpo and Igboekwe, 2012; Das, 2020). The scarcity of groundwater increases daily because of rising populations, urbanization, industrial and intensive agricultural related activities, and the impacts can have devastating effects on humans and ecosystems (Mondal and Singh, 2010a, 2011; Rahman et al., 2020, 2021). There is an increasing dependency on deeper aquifers to meet the increased demand for water, however, there are uncertainties over water quality, yields, and sustainability (Ahilan and Senthil Kumar, 2011). Therefore, the evaluation of any aquifer's potential is critical for its sustainable management. To achieve this, it is necessary to measure the hydrological and hydrogeological properties of the groundwater system through various modelling techniques to quantify the available water.

Unfortunately, pumping test methods to estimate hydraulic conductivity (K), and grain size analyses for parameter estimation, are relatively expensive and time-consuming. They are either integrating over a large volume or only provide information at the open well and borehole vicinity (Sarwade et al., 2007; Nicaise et al., 2013). Many researchers have studied the relationships between aquifer characteristics and geoelectrical parameters (Sri Niwas and Singhal, 1981; Singh, 2005; Mondal et al., 2016). Analytical relationships have been established between aquifer parameters and geophysical data in a particular geological environment under invariable groundwater quality (Sri Niwas and Singhal, 1981). For the unsaturated and saturated zones of aquifers, well-defined correlations have each been established. Sri Niwas and Singhal (1981) have found an analytical relationship between hydraulic conductivity and electrical resistivity through the well-established laws of physics, i.e., Darcy's law of groundwater flow, and Ohm's law of current flow in clean porous media. The obtained results provide a physical and mathematical basis for the statistically established relationships.

Resistivity data collected on the surface can provide useful information about the subsurface including aquifers. Estimation of aquifer properties using geoelectrical methods is mainly influenced by porosity and fluid resistivity (Chandra, 2015), and it depends on porosity, moisture content, and water quality such as electrical conductivity (EC). A good estimation of hydraulic conductivity and transmissivity from surficial geoelectrical measurements can provide crucial complementary information since hydraulic flow is influenced by porosity. Geophysical methods can reduce the costs of hydrogeological investigations, by replacing or reducing the number of pumping tests (Mondal et al., 2016).

Characterisation of an aquifer's thickness and geometry by interpreting surface resistivity data is very common, but transforming the aquifer resistivity in terms of the aquifer parameters is challenging. Thus, the objectives of this present study were to (1) estimate geoelectrical parameters through vertical electrical soundings, (2) establish a relationship between geoelectrical properties and hydraulic parameters, and (3) develop a groundwater flow model for understanding the flow hydrodynamics of an area of granitic terrain in Southern India.

## 2.2 Brief description of the study area

The study area has a size of 1752 km$^2$ between longitudes: $77^{0}53'08''$-$78^{0}01'24''$E and latitudes: $10^{0}13'44''$-$10^{0}26'47''$N in the state of Tamil Nadu, Southern India (Fig.1). Topography varies from 360 m above mean sea level (amsl) in the southern part to 120 m amsl in the northern part, with the plain areas sloping towards the north and northeast (Mondal and Singh, 2012). There is no perennial river, but the main Kodaganar river originates from the Pantrimalai hill along with some short distance streams encompassing second and third-order drainages, and these flow towards the confluence with the Amaravathi River in the north (Mondal et al., 2002). There are two surface water reservoirs, one at Attur in the southern corner, upstream, and another at Alagapuri, downstream. The annual average rainfall is about 875.8 mm in the upper basin and about 607.6 mm in the lower basin, which has been recorded at Dindigul and Vedasandur rain gauge stations, respectively. The mean of maximum temperature ranges from 36.5 to

41.8$^o$C, whereas the mean of minimum temperature varies from 17.4 to 24 $^o$C.

Geologically, granite and gneiss form most of the parts except in hilly areas where charnockite exists (Krishnan, 1982). The larger part of the area is occupied by highly folded, fractured, and jointed metamorphic crystalline rocks. Quartzite and pyroxenite also occur in patches. Lineaments are found to a limited extent in the entire area, but they are mainly orientated in the NNE–SSW, NEE–SWW, and NW–SE directions. The denudational terrain surrounded by structural hills occurs in the form of pediments. Both shallow and buried pediments are major geomorphic units in the study area (PWD, 2000, Mondal et al., 2002). In the shallow pediment, the occurrence of groundwater is moderate. The areas of low relief constituting buried pediments are the most favorable zone for groundwater potential (Mondal et al., 2018). Groundwater occurs in weathered portions under unconfined conditions, whereas at deeper depths it occurs in joints and fractures under unconfined, semi-confined, and confined conditions (Mondal and Singh, 2004). Local people are generally exploiting groundwater through dug, bore, and dug-cum-bore wells. The shallow weathered upper part facilitates the movement and storage of groundwater through a network of joints, faults, and lineaments in the study area. The depth to groundwater level varies from 3.90 to 24.0 m below ground level (bgl). Aquifer transmissivity (T) ranges from 4 to 1166 $m^2$/day, and storage coefficient (S), ranges from 0.00001 to 0.099 (Singh and Thangarajan, 2004).

## 2.3 Materials and methods

### 2.3.1 Vertical Electrical Soundings

Vertical Electrical Sounding (VES) is used for estimating the depth-wise layer resistivities (ρ) and thicknesses (m). The electrical resistivity measurement requires a four-electrode arrangement, two of them for injecting current into the ground and the other two for measuring the resulting potential. The Schlumberger configuration is most commonly used for VES data collection. In this configuration, all four electrodes are kept in a line at a distance symmetrical to the central point (Roy, 1999; Mondal et al., 2013; Chandra, 2015; Mondal, 2021). The direct current (I) is injected into the ground through the outer pair of electrodes (called current electrodes) and potential (δV) developed due to the current within the ground is measured across the inner pair of electrodes (called potential electrodes) with a small separation, typically less than one-fifth of the current electrode spacing.