Study of Influence of Terrain and Climatic Factors on Groundwater-Level Fluctuation in a Minor River Basin Using GIS

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Abstract  Terrain environment parameters play a vital role in controlling groundwater movement: its recharge and discharge mechanisms. Many earlier studies have been conducted relating terrain parameters and groundwater condition using conventional methods and remote sensing techniques. This study, however, endeavors to spatially visualize the degree of fluctuation in the groundwater level of Ongur, a minor river basin in different terrain units under different seasons (monsoon and summer) for three historical periods of time using Geographic Information System (GIS) raster analysis.

Keywords  groundwater; river basin; terrain environment parameters; seasonal fluctuations; GIS

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Introduction

Groundwater and its movement depend upon three principal factors: geological setting, physiographic features, and the climate.¹ Several previous studies have been carried out relating terrain parameters and groundwater condition using conventional methods and remote sensing techniques. Archaen crystalline rocks and alluvial deposits are the major geological formation along the coastal tract of Tamilnadu state in southern India.² It is always a major issue to study and understand groundwater table fluctuation in such a complex rock terrain.³ Some of the studies such as demarcating groundwater probable zone use remote sensing and Geographic Information System (GIS),⁴ mapping of groundwater fluctuation over a period of time,⁵ and integrating land and water resources for watershed management⁶ and stress the significance of understanding the relationship between terrain parameters and groundwater fluctuation of an area. In the present study, an objective is to understand the influence of terrain parameters such as geology, geomorphology, soil, and slope and climatic parameters such as rainfall on groundwater fluctuation using GIS. This study was carried out on a minor river basin Ongur in Tamilnadu, India.

1  Study area

The Ongur minor river basin is one among the 33 minor basins as classified by the Public Works Department, Government of Tamil Nadu. The geographical area of the Ongur minor basin is 1480.08 km². Two main rivers, Ongur and Periar, drain the system (Fig. 1).

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Both of them are ephemeral in nature and dry during summer. The drainage pattern is mostly east flowing from the western catchment. The eastern part is bound by the Bay of Bengal.

1.1 Climate

The Ongur minor basin experiences a hot climate with an average annual temperature of 32°C. Temperature soars to its maximum during the months of April and May (42°C) and humidity is usually between 65% and 80%. The northeast monsoon contributes a larger share of the total rainfall of the region (October to December) compared to the southwest monsoon (July to September). The average rainfall observed from the records is around 720 mm, nearly 60% of which is recorded during the northeast monsoon.

1.2 Relief

The study area is almost flat, except in the northwestern part where undulating terrain and small hilllocks were observed. The area comprises rocks from Archaean age to recent. Granites, gneisses, and charnockite represent the Archaean. Sandstone, shale, and conglomerates represent the Gondwanas. The unconsolidated sediments, boulders, and alluvium represent Quaternary period. Recent alluvium with sand dunes encouraging freshwater pockets comprise the coastal plain of the study area.

1.3 Drainage

Ongur and Periar rivers, which are ephemeral in nature, form the major rivers of the drainage system. Among them, River Ongur originates from the northwestern part and Periar from the western part draining the basin before reaching their confluence at Bay of Bengal. Ongur River encounters hard rock terrain during its overland flow, whereas the Periar River flows through a large fluvial plain. There are numerous minor first-order streams, flowing either for a short distance or joining the higher-order streams. They contribute to the surface storages such as tanks and ponds in the region and influence the groundwater condition of the area. [7] Despite such recharge mechanism, groundwater level in this area is moderate, apart from being contaminated with saltwater due to the poor soil condition in certain pockets along the coastal tract of the study area. Parallel to the coast, two large water bodies—Yedayanthittu Lagoon and Kalveli Tank—were observed showing tidal influence through Buckingham Canal. Study area was observed with sedimentary formation along the coast and hard rock terrain in the western part, which is discussed below.

2 Terrain units

Terrain parameters of the study area include lithology, landform, soil, and slope, which control the recharge and discharge mechanism of groundwater. Geology of the area exert a significant control in the terrain parameter as it gives rise to different landforms due to their susceptibility to erosion and weathering, [8] which in turn help in the development of soil groups and gradient.

2.1 Geology

The geology map was derived from IRS-1B satellite data (Fig. 2) collated with existing maps, literature, and field surveys and provided information on the lithological units of the study area. A clear demarcation of crystalline hard rock terrain in the west and coastal sedimentary rock units in the eastern part was observed based on the lithological units. The oldest crystalline rocks of Archaean age, covering an area of 74.54% (1103.28 km²), comprise granites, gneisses, char-
nockites and associated basic and ultrabasic intrusive. The granitic rocks are medium to coarse grained and less massive than the charnockites. Charnockites are well foliated and generally strike in NNE-SSW direction covered by thick weathered mantle supporting good vegetation and land use practice of the study area.

Small patches of shale, thin-bedded clays, and yellowish, fine grained feldspathic sandstone of Gondwanas dip with a low angle towards east. Due to their susceptibility to weathering, they formed gently rolling topography, and many places weathered into clays. The Tertiary formations comprising sand, clay, and reddish brown mottled quartz grit covering an area of 78.32 km² (5.29% of the total area), exposed in limited areas, were reported to occur below the laterites. Patches of laterite capping were also seen along the coast and in the western part of the basin near Kalveli Tank with varying thickness from 1 to 5 m.

The coastal part of the study area being a recent formation is composed of shale (7.73 km², i.e., 0.52%) and clayey sandstone (47.14 km², i.e., 3.18%), delineated near the lagoon and along the southern fringes of Kalveli Tank. Dune sands and beach sediments (123.65 km² or 8.35%) were also observed in the form of wind blown deposits stretching for a few kilometers with a width of few meters to 1.5 km.

The alluvial plains observed along the western and central portions of the study area consist of gravel, pebbles, fine to coarse sand, and clay. Stratigraphically, Archaean hornblende gneissic complex, mica schist, and charnockite form the basement overlain by Gondwana (feldspathic sandstone and clay) superimposed with cuddalore sandstone, clay, and shale and finally overlain by Quaternary to Recent alluvium, sand, and laterites.

2.2 Geomorphology

The geomorphology map as derived from IRS-1B satellite data (Fig. 3) provided information on the landform units of the study area. These geomorphic units have a significant role in the groundwater environment and its recharge mechanism. Buried Pediment was the major landform type and Buried Pediment-Deep (BPD), Buried Pediment-Medium (BPM), and Buried Pediment-Shallow (BPS), depending on the varying thickness of overburden and vegetation cover, were distinguished separately. They cover an area of BPD -10.26%, BPM -17.78%, and BPS -35.30%. The geomorphic units were classified based on the technical guideline provided by National Remote Sensing Agency (NRSA), Department of Space, Government of India.

Lateritic upland was seen in the eastern part cover an area of 127.06 km² (8.59%) and areal extent of coastal dune was 123.65 km² (8.35%). A lagoon was another interesting landform unit observed near the confluence of River Ongur, covering an area of 80.6 km² and influence Kalveli Tank, during high tide periods of both diurnal and seasonal.

2.3 Soil

The soil map (Fig. 4) showing the soil type details was prepared to understand the soil characteristics (salinity, graveliness, texture, irrigability, permeability, land use capability, and calcareousness) and was
subsequently used to study groundwater level fluctuations. [12] Soil properties were considered carefully and each unit was given weightage according to its significant role [13] in controlling groundwater flow and water level fluctuations during raster analysis. Generic names were avoided and substituted with type names (from Types A to H) and soil types of similar character were grouped together.

Fig. 4 Soil types of the study area

The study area was predominantly poorly sorted and poorly drained clay loamy soil in the east (Type B) and moderately sorted to well sorted sandy soil in the western catchment part (Type A) with kankars (Type G) in few places. The soil in the northwestern part of the catchment was moderately sorted and well drained in nature (Type C). The soil condition showed moderate land capability suitable for seasonal cultivation and grazing. The central part showed well-drained and well-sorted sand and sandy loamy soils supporting excellent agricultural activities (Type D). The northeastern and southeastern parts showed well-sorted loamy sand with intermittent presence of clay loamy soil. This soil condition supports good agricultural activities with some limitations. Mostly, plantations of *Casuarina* spp. were observed in this part of the study area. In the eastern part near Kalveli, the soil condition was very poor with poorly drained clay soils (Type E) and marshy lands (Type F). The influence of tidal water was evident with the presence of salt tolerant plant species, halophytes.

2.4 Slope

The slope map of the study area was derived from contours and spot heights were taken from the topographical map and ground surveys. The contour values from the map were digitized with a Triangulated Irregular Network (TIN) model. The TIN model was used to produce surface modelling output like contours, and this facilitated derivation of contours accurately by calculating points on the triangle slopes. Along with the existing contours, spot heights, and surveyed ‘z’ points, the interpolated ‘z’ values were also added manually to generate a more meaningful and smoother triangulation. [14]

The contours were generated using triangulation points. The slope map thus derived range from 0 to 15.5 and were grouped into five classes as gentle slope (0-1%), rolling topography (1-3%), slightly steeper (3-4%), steep slope (4-10%), and very steep slope (10-15.5%).

3 Spatial database for groundwater fluctuation studies

The spatial database containing terrain parameters derived from thematic maps were digitized and converted into a raster data set. Apart from these, point data such as rainfall and water level data were converted into spatial information by adopting suitable statistical operations (focal gravitation). The details of point data (rainfall and water level) and their significance in the analysis of water level fluctuations are discussed below.

Rainfall data collected from 1985 to 1999 were observed to study its pattern and the average rainfall was estimated to be around 750 mm per annum. Interestingly, 1991 and 1999 showed a value of 760 and 748 mm, while 1995 showed 788 mm. Based on the rainfall data, these three periods were selected for the analysis since they represent both normal and anomalous rainfall years. The cumulative values of rainfall for both summer and monsoon seasons were rasterised using their numerical value in the data attribute. These are then used to generate spatial information using focal operation (neighborhood algebra generating a new theme on which every cell is set to the value computed as a specified function of the values in the input file with a specified neighborhood distances). Later, focal gravitation operator was performed on the raster theme specifying an optimal distance to generate resultant spatial interpolated
theme, which was used for further analysis. Similarly, groundwater level data corresponding to their rainfall years were selected and water levels during January and June (representing northeast monsoon and summer) for the three periods, namely, 1991, 1995, and 1999, were extracted and rasterised.

4 Terrain units and groundwater level fluctuation

The analysis of groundwater level fluctuations was carried out in two phases: (1) spatial fluctuation in different terrain conditions by means of GIS raster analysis and (2) temporal fluctuation of different groundwater level zones during summer and monsoon for three selected periods.

4.1 General approach

Raster layers of summer and northeast monsoon seasons were added to lithological, climatological, and terrain parameters. Various other layers such as rainfall, lithology, geomorphology, drainage, soil, and slope were integrated using a local sum operator. The above layers were integrated separately with a layer containing information about water level with the water level of a particular season (for example, summer) of a period (for example, 1995). The resultant layers derived were reclassified into five groups ranging from “excellent” to “poor”. For example, to analyze the influence of northeast monsoon (from October to December), the water table data of January were selected. In the case of groundwater level fluctuation observations during the northeast monsoon of 1995, the groundwater level observation of January 1996 was selected, as the subsurface recharge by that time would have reached its maximum limit, replenishing the groundwater table. Similarly, for summer (April to May), June data were taken for the analysis. Then, the process of integrating layers as explained in the previous section was carried out and the resultant values were reclassified and stored separately. The derived resultant layers were integrated using the local combination to get the final composite coverage of the season for a given period.

The composite coverage depicts different zones of water level fluctuation—very low, low, moderate, high, and very high. The categorization of degree of fluctuation was determined from observations of monthly water level data over a period. The groundwater water level along the coast varies from 0.1 to 2.3 m, while in the crystalline formations in the western part it varies from 7 to 13.4 m. It may be noted that reduction of groundwater level by 13.4 m indicate drying up of a well. Based on these observations, the fluctuation range may be estimated as 0.1 to 6.4 m. Based on the intensity of fluctuation, five classes were recognized. They were very low (range 0.1-1 m), low (1-2.3 m), moderate (2.3-4 m), high (4-5 m), and very high (5-6.4 m) degrees of fluctuation. This zonation of classes was repeated for all the periods: 1991, 1995, and 1997. The results are discussed in the following section using both graphical output and raster maps.

The raster overlay analysis using local sum and local combination operators were used to understand seasonal water level fluctuations between 1991 and 1999. The operators are in-built in the Regis raster GIS software dividing the study area into grids of user-defined cell size. The local sum operator was used to add different themes with the gridded water-level theme. In this context, local sum does mean adding the values of same grid cell $x_n, y_n$ of theme 1 to the same grid cell $x_n, y_n$ of theme 2. The resultant layer was reclassed and stored as a separate raster file. In this fashion, all the layers were added to get a final raster layer that reflected the behavior or characteristic of thematic analysis. In similar fashion, geology, geomorphology, soil, slope, and rainfall were added individually and stored as separate resultant themes. These layers were later integrated by local combination operator (similar to union operator in vector GIS) and reclassed to show range of values indicating the various degrees of fluctuations. Thus, the final composite coverage reflects the influence of terrain parameters in seasonally fluctuating (climate) water level.

4.2 Spatial variations in groundwater level fluctuation and lithological units

Raster overlay analyses of all the terrain parameters indicated different intensities or degrees of fluctuation in different lithological units (Fig. 5). The degree of fluctuation is observed to be generally very high in the crystalline formations in the western part of the study area. It gradually varies from high to very low progressively towards the coastal part. However,
the areal extents of these zones vary spatially and temporally depending upon either the precipitation conditions or geological setting of the terrain.

Based on the above, the study area was divided into three major units: Archaean crystalline formations, Tertiary sandstone, and Quaternary coastal deposits. The spatial variations of groundwater level fluctuations that were observed in these three lithological units are discussed below.

4.2.1 Archaean crystalline terrain unit

The Archaean basement of the study area is composed of weathered charnockite and schistose formations as described earlier. Areas coming under this unit showed a marked fluctuation in the water table. During the analysis, western and northwestern parts of the study area near Tindivanam showed a high fluctuation behavior. The areas in the western, northwestern, and southwestern parts of the river basin showed very high to high fluctuation. These regions experience dry conditions during winter and summer and enjoy excellent recharge during the monsoon periods, with average water level rising to the extent of 6.2 m. The thickness of weathered overburden in the western part is low and buried pediments of shallow and medium (BPS and BPM) were also observed. The area showed an erosional surface in the western part characterized by soil problem, causing slower percolation of surface water. The hydraulic gradient was from west to east and most of the groundwater flows towards east and southeast. This was inferred from the varying nature of groundwater level fluctuation. During the monsoon periods, very high degree of fluctuation is confined to the western parts only. Many of the places showing very high degree of fluctuation during summer were observed with high degree of fluctuation during the monsoon periods. These pointers indicated a moderately developed groundwater system where the recharge had not been in full vigor and could be augmented further.

The crystalline terrain in the eastern part of this unit showed high to moderate fluctuation confined mainly to the central and eastern parts. BPD and BPM were the dominant landform observed in this part of the terrain unit. The spatial trends of water level in the crystalline unit showed variation from very high in the west to moderate in the central part of the study area. The area south of the crystalline unit was observed to be a lateritic terrain. The spatial trends of groundwater level fluctuation in lateritic terrain are discussed below.

4.2.2 Lateritic terrain unit

The lateritic terrain of this region is highly eroded and gullied. The spatial patterns of groundwater level fluctuations in this region were mainly high to low. The high degree of fluctuation was observed in the western part of this unit. The area adjacent to the coastal tract and south of Kalveli Tank were observed to have moderate to low fluctuation. The topography and landform controlled the degree of fluctuation in this particular terrain unit. The terrain condition of the area showed a very gentle slope of 0 to 1%. The lateritic upland (LU) of this region lying in the southern part of Kalveli Tank showed a low degree of fluctuation.

The spatial trends of the groundwater level fluctuation did not vary appreciably from season to season. The western part of the upland showed little variations: oscillating from moderate to high during summer. The spatial trend of the groundwater level fluctuation in this unit indicated that only discharge mechanism, rather than recharge, was operational in this part of the study area. This was evident from low to moderate spatial fluctuation witnessed around Vidur and Vanur in the southern part of the study area. The regions in the east have coastal alluvial deposits of Quaternary and Recent age. The spatial variations observed along this zone are discussed in the following section.

4.2.3 Coastal deposit

The coastal tract of the observed study area has stabilized dune deposits (CD), mudflats (MF), marshy area (MA), and a lagoon (L). The lagoon opening into the sea in the north is connected to Kalveli Tank in the south through the Buckingham Canal. This region was observed to have low or very low degree of fluctuation since the water level has almost reached the static lower limit, sea level.

The marshy and water logged conditions helped to identify the terrain as a groundwater discharging unit. The above conditions also led to the inference
that the groundwater is discharged to the adjoining areas (coastal dunes). This was understood by observing the water level conditions in the coastal dune deposits. The groundwater (shallow aquifer) in the area was observed to show moderate to low degree of fluctuation during summer and monsoon seasons. Coastal hamlets located on the dunes, such as Kunimedu and Panichamedu, showed seasonal fluctuation from moderate to low during summer and monsoon periods, respectively.

The spatial variations of water-level fluctuation observed in all these three major litho-units suggested a seasonal variation in the spatial extents of various categories (of fluctuation) and also showed a significant geomorphic control. Hence, a discussion on influence of the season on water level is imperative for better understanding of groundwater fluctuations. Moreover, seasonal analysis also aids understanding the extent of saline water intrusion along the coastal tract of the basin.

Based on the above analysis, a table showing relation between zones showing various degrees of fluctuation and terrain parameters was prepared (Table 1). The Table 1 helps to visualize the relation between groundwater fluctuation and terrain parameters. The following conclusions were arrived at from the spatial analysis of terrain parameters and their influence on groundwater level fluctuations.

| S. No. | Fluctuation zones | Lithology | Landform | Soil | Slope | Areal extent | Season |
|--------|-------------------|-----------|----------|------|-------|-------------|--------|
| 1      | Very high         | Crystallines (weathered) | BPD & BPM | Types F, G, A | High | Low | High | Summer, Monsoon |
| 2      | High              | Crystalline rocks | BPD, BPM, & RA | Types A, H, G | High | Low | High | Summer, Monsoon |
| 3      | Moderate           | Crystallines & shaly s.st | BPM, LU, CD | Types A, G, C | Medium | Low | High | Summer, Monsoon |
| 4      | Low               | Shale and clayey s.st | Lagoon, MF, CD | Type J | Low | Low | High | Summer, Monsoon |
| 5      | Very low          | Marshy     | Lagoon & MF | Type J | Very Low | Low | High | Summer, Monsoon |

Fig. 5 Terrain units controlling groundwater condition

5 Conclusion

This study described two major aspects of the study: the influence of terrain parameters on groundwater movement and its fluctuation and the seasonal variations in such terrain environment using GIS. The GIS based methodology was useful in understanding the relationship between terrain units and groundwater condition. In the hard rock terrain (Archaen crystalline units), groundwater showed a very high degree of fluctuations leading to the inference in recharge during monsoon and rapid depletion during summer partly owing to surface and subsurface groundwater...
movement controlled by hydraulic gradient and agricultural activities. Coastal deposits showed a low to very low degree of fluctuation due to saturated groundwater conditions even reaching the sea level. Lateritic terrain in the central part showed high to low degree of fluctuation controlled mainly by slope gradient and poor soil condition allowing for little recharge during monsoon periods.

Thus, this study emphasizes the significance of terrain parameters such as lithology, landforms, soil, slope, and rainfall (climate) in controlling the groundwater condition of Ongur minor river basin. It also demonstrates the utility of integrating remote sensing and GIS in groundwater level fluctuation studies.

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