Using GIS Techniques and Quantitative Morphometric Analysis to Evaluate the Groundwater Resources in the Central Flinders Ranges, South Australia

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SUMMARY

The quantitative analysis of a drainage system is essential in understanding the hydrological behavior of the catchment. The present study was carried out in a drainage basin (Oratunga basin) in the Central Flinders Ranges, South Australia. GIS techniques were used to assess critical morphometric characteristics of the dendritic to sub-dendritic drainage pattern. The analysis has shown that the total number and length of stream segments decreases from first order to fifth order streams. The bifurcation ratio (Rb) between different successive orders varies and the shape parameters indicate the elongated shape of the basin. The compilation of the different parameters reveals that the groundwater is mainly controlled by geomorphology, slope, geology, and drainage density. Based on these factors groundwater potential of the basin was classified into good, moderate and low zones. The study reveals that quantitative analysis based on GIS techniques and available data is a useful tool for geo-hydrological studies. Future research will focus broaden the study area in the Flinders Ranges and similar semi-arid areas.

Keywords: GIS, Quantitative Morphometric Analysis, Groundwater.

INTRODUCTION

Groundwater in Australia amounts to around 33% of the estimated total water use. This increased by 60% during the period from 1983-1997 as a result of the population increase and the uptake of groundwater use in place of surface water which had become limited and more strongly regulated across the country [1]. Groundwater is essential for sustaining life, performing basic functions in ecosystems and represents an important input into the Australian economy, particularly agriculture and tourism. It is often the only water source for many areas like the Flinders Ranges, it is necessary for sustaining stream flows as an alternative source during droughts [1, 2]. The demand for water made the assessment and utilization of water resources most critical. There is an urgent necessity for the evaluation of water resources. In the Flinders Ranges of South Australia groundwater is the main source of water and plays a significant role in occupation and human settlement (Figure 1). Wells are located mainly in fractured bedrock in an area where evaporation is high and recharge erratic [3]. Although the geology and stratigraphy of the host bedrock have been studied in some detail [4, 5] there is little about the water resources documented in the scientific literature.

To effectively evaluate the water resources, the factors which control the water evolution and occurrences need to be better linked and understood. In the present study it is supposed that the geomorphic setting influences the groundwater regime. Studying the geomorphic setting is essential in understanding the hydrogeology of the watershed. The characterization of geomorphic features enables understanding of the relationship among different aspects of the basin's drainage pattern and also enables a comparative evaluation of different drainage basins developed in various geologic and climatic regimes [3]. A study of the geomorphic setting, particularly in areas of limited data like the Oratunga Area in the Central Flinders Ranges provides important understanding for the sustainable management of groundwater resources.

The remote sensing and GIS based drainage basin analysis has been used as an effective tools for a multi-criteria decision analysis and the hydrogeological evaluation [6, 7]. The increased resolution of satellite imagery creates a large impact on water resource management. Thus, the digital elevation models (DEMs), such as ASTER GDEM (Global Digital Elevation Model) were used to extract the geomorphological parameters of drainage basins [8]. Also, Shuttle Radar Topographic Mission (SRTM) data has been used to provide a precise, fast, and an inexpensive study of the hydrological systems [9].

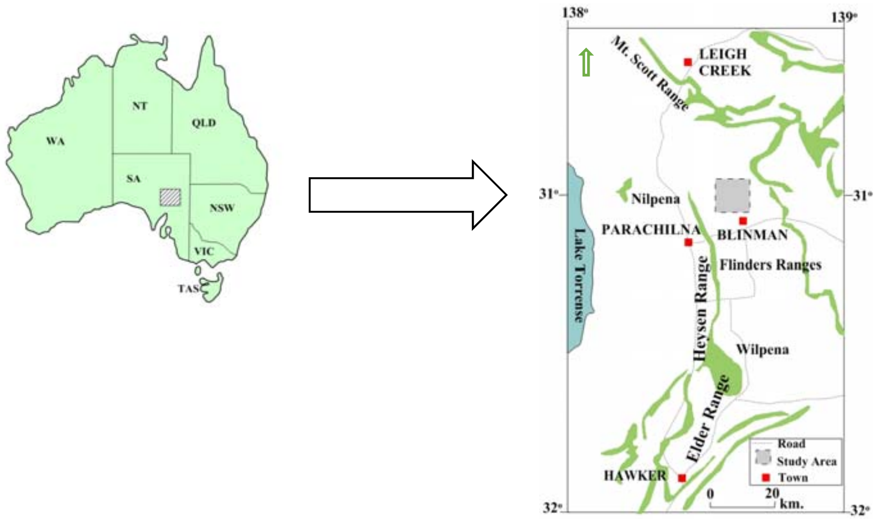

Figure 1. Location map of the study area.

The morphometric parameters of a watershed could be useful in selecting the recharge sites of the groundwater, watershed modeling, runoff modeling, watershed delineation and groundwater prospect mapping [10, 11]. A quantitative morphometric characterization is considered to be the most acceptable method for good watershed management. The hydrological analysis and morphometric evaluation of the Oratunga watershed were done using GIS software and DEM analysis. The study aimed to explore the different morphometric parameters to develop a better understanding of the recharge potential of the study area.

STUDY AREA

The study area includes about 341 km^2 in the Central Flinders Ranges, South Australia (Fig. 1). Geographically it lies between 30° 54' 30" and 31° 8' 30" S latitude and 138° 29' 30" and 138° 43' 30" E longitude. The climate of the Flinders Ranges is semi-arid [12]. The area covers the northern sector of the Central Flinders Ranges. It is located about 79 km southwest of Leigh Creek and 210 km north east of Port Augusta. The boundaries of the study area coincide with the topographic boundaries of the watershed (Figure 1).

MATERIALS AND METHODS

The Shuttle Radar Topographic Mission (SRTM) data was downloaded as GeoTiff tiles (Geospatial Tagged Image File Format) in geographic coordinates WGS84 datum from the CGIAR-CSI (Consultative Group of International Agricultural Research–Consortium for Spatial Information). Only tiles falling within South Australia were selected. All the GeoTiff files were imported into ERDAS imagine and converted into a single file. Then, reprojecting the SRTM from its original geographic coordinate system to a new projected one, thus the horizontal and vertical units should be in meters. Clipping the study area was done using subset tool in ERDAS and hence can be used in ArcGIS for the morphometric analysis. The ArcGIS hydrology toolset of Spatial Analyst was used to generate the stream networks from SRTM. The Hydrology Tools require filling of any elevation holes in DEM; this could be done from the elevation of the surrounding pixels. To facilitate the use and analysis of these networks, these rasters were converted into shapefiles. The morphometric parameters for the present study are done from the SRTM of 90 m resolution data and ArcGIS 10.1.

RESULTS

Assessment of watershed using quantitative morphometric analysis can give information about the hydrological nature of the exposed rocks. The quantitative description of drainage networks and basin characteristics has been carried out for the Oratunga Area. The quantitative analysis of morphometric parameters is found to be important in basin evaluation, water conservation and natural resources management. Factors like drainage characteristics could plays a role in the distribution of runoff, indicate sites for water infiltration and control the water flow, while rock type could direct the flow and storage management.

The drainage pattern reflects the structural and lithologic controls of the underlying rocks. For the study area, the drainage patterns are dendritic to sub-dendritic which is most common in the Flinders Ranges (Figure 2). It is generally characterized by a treelike branching system indicating homogenous and uniform underlying rock types. The details of various morphometric parameters used in the present study are discussed below.

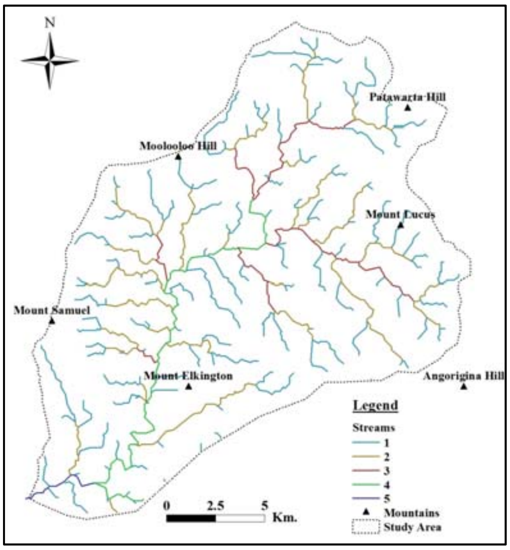

Figure 2. Drainage Map of the study area

The stream order has been determined using the method proposed by Strahler (1964). The study area is a five order drainage basin with a total number of 449 streams (Figure 2), of which 228 (50.8%) are first order streams, 121 (26.9%) are second order, 39 (8.7%) are third order, 53 (11.8%) are of fourth order and 8 (1.8%) are fifth order. The high number of streams in the study area reflects the role of erosional and weathering processes. A negative correlation between the stream orders and stream numbers indicates low permeability and infiltration (Figure 2).

Stream length is a significant hydrological parameter as it reveals surface runoff characteristics and hence recharge potential. The total length of stream segments is generally high for the first order streams and decreases as the stream order increases (Figure 3). The total length of streams is 553 km and ranges from 284.7 for the first order to 17 km for the fifth order (Table 1). Longer streams are common in steep slopes and shorter streams are dominant in areas of low slopes.

The bifurcation ratio introduced to define the ratio of the number of stream order (u) to that of the next highest order (u+1); Rb=Nu/Nu+1. It is a measure of elongation, relief and dissection [13]. The Bifurcation Ratio is a main parameter to evaluate and describe the hydrological regime of a watershed [14]. The bifurcation ratio will not be exactly same from one order to the next order because of the changes in the geometry and lithology along the drainage basin. The bifurcation ratio of the study area ranges from 0.9 to 3.4 for the different orders (Table 1). The low Rb value suggests structural disturbance for second and fourth order areas and therefore low potentials for discharge compare to those with high bifurcation ratio [15]. In addition, the high mean bifurcation ratio for the whole area indicates an elongated shape. The elongation of the study area could provide prolonged surface runoff, allowing higher infiltration and recharge of the shallow aquifer.

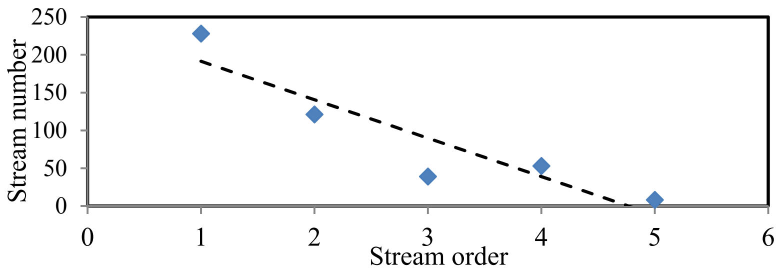

Figure 3. Geometric relationship between stream order and stream number.

Form factor is defined as the ratio of the basin area (A) to the squared value of the basin length (L). The value of the form factor for circular shape would always be less than 0.7, higher values indicate less elongation of the drainage basin while lower values reflect elongation of the studied basin. The computed Form Factor for the present case is 0.38 which indicates a moderately elongated basin. The shape of the basin can also control peak flows and their duration. A basin with a low Form Factor will have fewer but longer duration peak flows (Table 1). In the present study, the low Form Factor value suggests that more flatter peak flow of longer duration.

Elongation ratio (Re) is the ratio of diameter of a circle of the same area as the basin to the maximum basin length [16]. Elongation ratio can be classified as circular (0.9 - 1), oval (0.8 - 0.9), less elongated (0.7 - 0.8), elongated (0.5 - 0.7), more elongated (<0.5). Areas of high elongation ratio values are more prone to high infiltration capacity and low runoff. It generally varies from 0.6 to 1.0 over a wide variety of geologic types. The Re of this area is 0.6 which indicates elongation and more subject to erosion with relatively less infiltration capacity (Table 1).

Table 1. Morphometric parameters of the drainage basin.

Parameter	1st	2nd	3rd	4th	5th	Total
Number of streams	228	121	39	53	8	449
Number%	50.8	26.9	8.7	11.8	1.8	-
Stream length	284.7	152.9	45.6	52.8	17	553
Bifurcation ratio	-	1.9	3.4	0.9	3.1	-
Mean Bifurcation ratio	2.33					
Form factor	0.38					
Elongation ratio	0.61					

The drainage density (D) is defined as the length of the streams per unit area. It provides a quantitative measure of the average length of streams in the whole basin. The drainage density of the whole study area is 1.6 m/km^2. In general, low drainage density is more likely to occur in high permeable areas of dense vegetation and low relief while high drainage density occurs in less permeable areas with less vegetation and high relief [8]. Accordingly, the high drainage areas indicate a low infiltration rate whereas the low density areas are favorable with a high infiltration rate [17]. The spatial drainage density map was prepared for the Oratunga Area (Figure 4), areas of low drainage density are good to facilitate recharge, and areas with high density facilitate less infiltration and recharge.

Basin slope (Sb) is an important parameter in geomorphic studies. The slope is controlled by the climate processes in the area having the rock of varying resistance. It enables the assessment of runoff generation and direction. The general slope of the basin decreases towards south-southwest. For a slope analysis, topographic slope within the Oratunga Area was classified as low to steep slope. The slope values varies from low (<5^o), moderate (<15^o) and high (<45^o). The slope varies from one geomorphic unit to another with steep slopes in the mountainous areas, moderate to steep slopes in the hilly areas and gentle to moderate slope in the valley bottoms (Figure 5).

DISCUSSION

Geomorphological features have a direct effect on the hydrogeological setting of the area, whereas physiographic elements like relief and slope show the amount of runoff and infiltration, slope and drainage density of the basin plays a significant role in increasing the water flow velocity with a reduction in recharge [18]. For the Oratunga basin, the drainage pattern is dendritic with a high number of streams; varied lengths and relatively high bifurcation ratio indicates an extended runoff and high chance for recharge. The shape of the basin is another factor that affects the peak and duration of flow. Parameters such as Form factor and Elongation ratio are essential factors to describe and understand the shape of the basin. In the present study, the Form factor is relatively low reflecting elongated shape with a low peak flow and longer duration. As well, the values of the Elongation ratio are relatively high. Consequently, the high values describe a moderately high relief and the structural control of the basin. The drainage density is another key controller of the groundwater regime. It has inverse relation to permeability. The lower the permeability the lower the infiltration of rainfall, which conversely tends to be more concentrated in surface runoff. This gives rise to a fine drainage system. Since the drainage density can indirectly indicate the groundwater recharge of an area because of its relation with surface runoff and permeability, it was considered as one of the indicators of groundwater potential. Density is influenced by many factors such as weathering, permeability of rocks, climate, and vegetation. The Low drainage density value is dominant in areas that are underlain by less eroded, permeable and low topography while high value is associated with areas of weathered, impermeable subsurface material and less vegetation and high relief [8]. In the study area, the results indicate that the effective groundwater recharge potential zone is located on marginal areas of the study area. In this region, the low drainage density over higher relief and fractured areas has more infiltration ability.

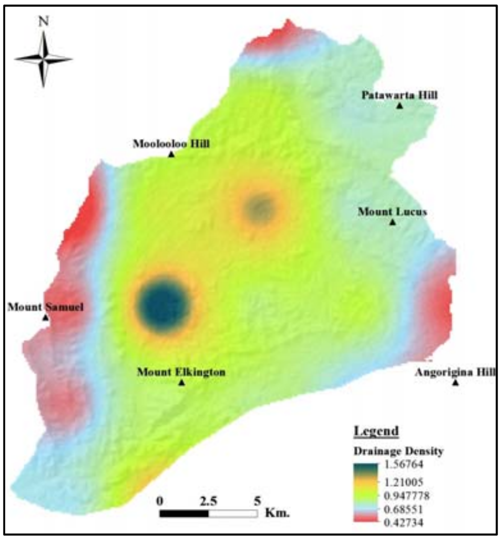

Figure 4. Drainage density map

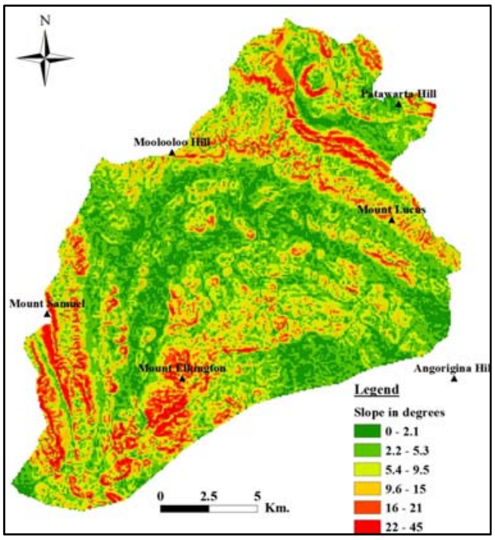

Figure 5. Slope Map of the study area

CONCLUSION

A quantitative analysis supported by GIS mapping techniques is a useful tool in the assessment of hydrogeological system with distinctive morphological and geologic features. In this study, different indices were applied in order to carry out a multi-criterion analysis intended to produce an evaluation of water resources. The drainage network is dendritic indicating homogeneity in texture and structural controls. The dendritic structure of the basin would also help to explain various hydrogeological parameters like the infiltration capacity, groundwater recharge, and runoff and soil erosion. The morphometric analysis results show that the basin has an elongated shape with significant influence of geological structures, low peak flow and long duration of runoff. Also, a moderate drainage density indicates a moderate permeability rate. This study shows that a watershed analysis using Shuttle Radar Topographic Mission (SRTM) and GIS is an efficient and convenient tool for determining the different geomorphic parameters such as the infiltration capacity and runoff. The results can be used in understanding the groundwater potential for watershed management. It can also be used for building a suitability model for water conservation structures. Consequently, integrating these parameters with other hydrological attributes such as geology, standing water level and structural features in the GIS domain facilitates decisions about suitable sites for water conservation structures (recharge shaft or dams) for groundwater development and management.

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