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ORIGINAL ARTICLE

Delineation of groundwater potential zones in the Comoro watershed, Timor Leste using GIS, remote sensing and analytic hierarchy process (AHP) technique

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Abstract Groundwater plays an important role for socio-economic development of Comoro watershed in Timor Leste. Despite the significance of groundwater for sustainable development, it has not always been properly managed in the watershed. Therefore, this study seeks to identify groundwater potential zones in the Comoro watershed, using geographical information systems and remote sensing and analytic hierarchy process technique. The groundwater potential zones thus obtained were divided into five classes and validated with the recorded bore well yield data. It was found that the alluvial plain in the northwest along the Comoro River has very high groundwater potential zone which covers about 5.4 % (13.5 km^2) area of the watershed. The high groundwater potential zone was found in the eastern part and along the foothills and covers about 4.8 % (12 km^2) of the area; moderate zone covers about 2.0 % (5 km^2) of the area and found in the higher elevation of the alluvial plain. The poor and very poor groundwater potential zone covers about 87.8 % (219.5 km^2) of the watershed. The hilly terrain located in the southern and central parts of the study area has a poor groundwater potential zone due to higher degree of slope and low permeability of conglomerate soil type. The demarcation of groundwater potential zones in the Comoro watershed will be helpful for future planning, development and management of the groundwater resources.

Keywords Groundwater · Potential zone · Comoro watershed · GIS and remote sensing · Analytic hierarchy process

Introduction

The majority of the coastal areas of Timor Leste depend on groundwater as a vital natural resource and trustworthy water supply in urban and rural areas. Currently, groundwater accounts for more than 60 % of the total annual water supply for agriculture, domestic, and industrial purposes in the Dili city which is the capital of the country (Aurecon Australia 2012). Rapid population growth combined with increasing demand of water from multiple sectors such as municipal, agricultural, industries, and tourism becomes a major issue in the country, particularly in Dili city (Aurecon Ausralia 2012). The Government of Timore Leste as developing country is seeking various ways to increase the freshwater availability and ensure the continuous supply of water to the individual and the community (Aggarwal et al. 2009; Rodell et al. 2009; Chawla et al. 2010). Although country receives higher rainfall in the wet season, people often face water scarcity in dry season. There are uncertainties and high degree of variation in aquifer types to explore the availability of groundwater resources in the watershed (Wallace et al. 2012). Various factors are responsible for water scarcity in Comoro watersheds such as unfavorable topographical condition, rapid population growth and urbanization, poor knowledge, and lack of better water management practices.

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In addition, only one-fourth of the Comoro watershed consists of sedimentary rock formation, known as Dili alluvial plain which is favorable for groundwater occurrence. The groundwater in the Dili alluvial plain is being exploited by constructing shallow and deep wells. The groundwater extraction is usually high in dry season. It is important to note that since 1999 as the nation born, multisectorial activity increased the water demand. As a result, drilling and construction of new bore wells without proper knowledge have led to unsustainable water resource development. Therefore, it is imperative to investigate the suitable areas for groundwater extraction to increase the freshwater availability and curb the water scarcity in the watershed.

Several conventional methods such as geological, hydrogeological, geophysical, and photogeological techniques were employed to delineate groundwater potential zones. However, recently, with the advent of powerful and high-speed computers, digital technique is used to integrate various conventional methods with satellite image/remote sensing (RS) techniques and geographical information system (GIS) technology. The GIS and RS tools are widely used for the assessment of various natural resources (Israil et al. 2004; Solomon and Quiel 2006; Junge et al. 2010; Abel and Tijani 2011; Kartic and Jatisankar 2012; Kuria et al. 2012; Deepika et al. 2013; Pandian and Kumanan 2013; Ayele et al. 2014; Gitas et al. 2014; Redowan et al. 2014; Salari et al. 2014). They are also effective tools for delineating the groundwater potential zones. Application of these tools helps to increase the accuracy of results in delineation of groundwater potential zone and also to reduce the bias on any single theme (Rao and Jugran 2003). Nowadays, the widespread availability and use of satellite data with conventional maps and terrain correction processes have made it easier to create the baseline information for assessing groundwater potential zones (Tiwari and Rai 1996; Das et al. 1997; Thomas et al. 1999; Harinarayana et al. 2000; Muralidhar et al. 2000; Magesh et al. 2012a, b; Machiwal et al. 2014; Nampak et al. 2014). Remote sensing not only provides a wide-ranging scale of the space–time distribution of observations, but also saves time and money (Murthy 2000; Leblanc et al. 2003; Magesh et al. 2012a, b). In addition, it is widely used to characterize the earth's surface (lineaments, drainage patterns, and lithology) as well as to observe the groundwater recharge zones (Sener et al. 2005; Chowdhury et al. 2010; Kaliraj et al. 2014). Groundwater exploration combines several different thematic layer maps such as drainage density, slope, topography, geomorphology, soil, rainfall, land use, and lithology—as different parameters to determine a groundwater potential area, (Imran et al. 2010; Magesh et al. 2012a, b; Olutoyin et al. 2014) not only relying on the lineament factor (Teeuw 1995).

There are no such studies related to demarcating potential groundwater resources in Comoro watershed of Timor Leste. Therefore, the present study attempted to assess the groundwater potential zones using more variables with the inclusion of the multi-criteria decision analysis (MCDA) technique. This gives a broader view of the potential groundwater distribution in the study area. The Saaty's Analytic Hierarchy Process (AHP) is a widely used MCDM technique in the field of water resource engineering (Aggarwal et al. 2009; Bhatnagar and Goyal 2012; Kaliraj et al. 2014). The method was first developed by Professor Thomas L. Saaty in the 1977s (Saaty 1977). Furthermore, the Analytic Hierarchy Process (AHP) (Saaty 1980, 1986, 1992), an international acceptable quantitative tool, adopted in this study appears to be a flexible decision-making tool for multiple-criterion problems such as the assessment of the potential zones of groundwater resources in rapidly urbanized area of Comoro watershed. It enables decomposition of a problem into hierarchy and assures that both qualitative and quantitative aspects of a problem are incorporated in evaluation process. In recent years, numerous studies reported that multi-criteria decision making (MCDM) offers an effective tool for water resource management by adding structure, auditability, transparency, and accuracy to decisions (e.g., Dunning et al. 2000; Flug et al. 2000; Joubert et al. 2003; Machiwal et al. 2011; Adiat et al. 2012; Mallick et al. 2014). Hajkowicz and Higgins (2008) proposed that while the selection of a MCDM technique is essential for water resource management, more importance is required on the initial structuring of a decision problem which includes choosing criteria and decision options. The AHP has been successfully applied in several studies of water resource management by integrating MCDA (Saaty 1980, 1986, 1992) with RS and GIS techniques.

Therefore, the present study employed AHP-coupled MCDA, GIS and RS techniques to integrate hydrogeological, geomorphologic as well as climatic data to evaluate groundwater resources of the Comoro watershed in Timore Leste. The major purpose is to delineate the groundwater potential zones of the study area and to develop a prospective guide map for groundwater exploration/exploitation so as to ensure optimum and sustainable development and management of this vital resource.

Study area

This study is conducted in the Comoro watershed, which consists of the Dili City as the capital of Timor Leste. The Dili City has experienced rapid population growth and increased demand for groundwater in recent years. The Comoro watershed lies between 8°43′12″ and 8°33′40″ to the North, 125°19′24″ and 125°40′48″ to the East (Fig. 1). The watershed covers an area of 250 km^2 with the highest peak at 1,410 m above sea level (masl). The elevation in the northern coastal line ranges from 0 to 1,410 masl toward the southern edge of the Comoro watershed. The watershed is formed by two valleys surrounded by the steep mountains at elevations between 1,000–1,300 masl in the south and 700–800 masl in the north. The Railaco valley formed by the rivers Anggou and Buamara which has elevation of 450–650 masl, while the Dili alluvial is the flat part of the watershed with the elevation of 0–60 masl in the north (MAP and JICA 2010).

The Comoro watershed is characterized by a tropical hot climate. The watershed is influenced by the Northern Monomodal Rainfall Pattern which has 4–6 months of wet season from December to May (Wallace et al. 2012). Daytime temperatures in the month of November generally reach around 33 °C. At night, the average minimum temperature drops down to around 28 °C. In recent years (2003–2013), the highest temperature recorded was 36 °C in November 2011, and the lowest temperature of 14 °C was recorded in August 2013 at Comoro climate station. The average monthly rainfall varies from 0 to 230 mm in the central western part of the Comoro watershed. The coastal area in the north of the watershed has a monthly rainfall of 4–170 mm. The lowland forest (36 %) and agriculture (34 %) land use are the dominant land-use type in the watershed (MAP and JICA 2010).

Materials and methods

For the study, existing hydrogeological and relevant data on soils, geological/lithological units, structural features, geomorphologic, and climatic conditions of the study area were collected. The overall study concept involved integration of eight thematic layers of conventional geology, soil, drainage and lineament maps, rainfall data as well as remotely sensed data of land use, slope and topography using ArcGIS 10.1 software.

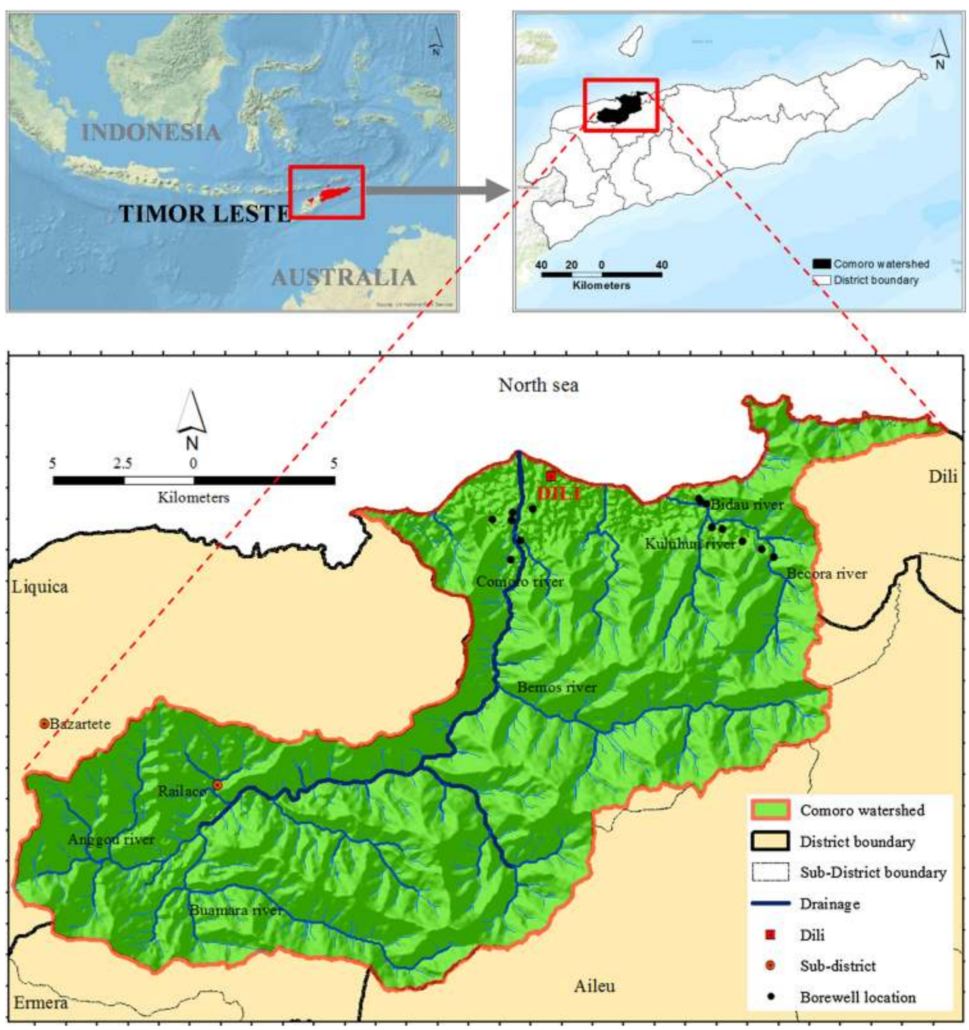

Fig. 1 Location map of the study area

Development of thematic layers

A toposheet map at the scale of 1:250,000 was used to develop required maps for further analysis. The drainage density map, topography map, and slope map of the study area were generated from ASTER DEM data (30 m resolution) using ArcMap 10.1 software. The ASTER DEM is GDEM version 2 which was distributed by the Ministry of Economy, Trade and Industry (METI), Japan and the National Aeronautic and Space Administration (NASA), USA.

To extract the lineament of the study area, the PCI Geomatica 2013 version was used. According to Kocal (2004) the Geomatica has the ability to extract lineaments from images automatically with the LINE option. Lineament density of an area can indirectly expose the groundwater potential, since the presence of lineaments usually denotes a permeable zone. Areas with high lineament density are considered excellent for groundwater potential zones (Haridas et al. 1998). Lineaments are structurally controlled linear or curvilinear features, which are extracted from the satellite imagery by their relative linear alignments. These articulate the surface topography of the underlying structural features. Lineaments characterize the fault and fracture zones—resulting in increased secondary porosity and permeability. These factors are very important hydrogeologically as they provide the pathways for groundwater flow into the subsurface. For testing the reliability of the software output, the lineament is extracted manually by directional filtering. Furthermore, the lineaments detected are compared with those appearing on the slope face and faults of a geological cross-section map of the study area. To obtain a rock fracture alignment, Landsat-5 images were downloaded and analyzed using Geomatica 2013, and then the fracture line was analyzed within ArcMap 10.1 to produce a lineament density map. The image obtained from Landsat-5 satellite images composed of seven bands of images with UTM projection, spheroid, and datum WGS 84, zone 51 south.

The land use, geology, and soil maps were extracted from the Ministry of Agriculture and Fisheries, Department Agriculture Land-use GIS (ALGIS) in polygon shape file data, and then thematic layer maps were generated using ArcMap 10.1.

The drainage density is a measure of the length of stream channel per unit area of the drainage watershed (Magesh et al. 2012a, b). Normally, drainage density is computed by dividing the distance of the stream into area coverage which will generate drainage density value. The drainage density is an opposite function of permeability. High drainage density value is favorable for runoff and therefore indicates a low groundwater potential zone. The stream networks were used to generate the drainage density of the study area.

The slope is an important factor for the classification of groundwater potential zones. A higher degree of slope results in rapid runoff and increased erosion rate with insufficient recharge potential (Magesh et al. 2012a, b), where alluvial plain, flood plain, or plateau areas are more favorable for groundwater occurrence due to a longer duration of travel time to downstream and provide adequate time for infiltration to increase groundwater recharge. Slope grid is identified as “the maximum rate of change in value from each cell to its neighbors” (Burrough 1986). The slope map of the study area was generated in unit (degree) from ASTER DEM data with cell size of 30 m resolution and pixel depth of 16 bit using spatial analysis tool in ArcMap 10.1.

The rainfall map was prepared using monthly rainfall data from 15 rain gages of 2003–2013 obtained from the Timor-Leste Meteorological Department (TLMD) and Ministry of Agriculture. These are Comoro and Dare raingage stations which are inside the Comoro watershed and remaining 13 stations are nearby the watershed, such as Atauro, Liquisa, Soibada, Gleno, Hatulia, Maliana Ainaro, Same, Betano, Suai, Oecusi, Fohorem, and Bobonaro. These data were then spatially interpolated using the Inverse Distance Weighted (IDW) method to obtain the rainfall distribution map. This interpolation method combines the concepts of proximity to follow Thiessen polygons with gradual changes of the trend surface (Magesh et al. 2012a, b).

The eight thematic layer maps such as lineament, drainage, slope, land use, lithology, soil, rainfall, and topography map generated were converted into the raster format using Arcmap 10.1, and used them for the overlay analysis. Groundwater potential zones were obtained by the weighted overlay analysis method using spatial analysis tools in ArcMap10.1. During weighted overlay analysis, a rank was given for each individual parameter of each thematic layer map, and weights were assigned according to the output of the MCDM (AHP) technique to that particular feature on the hydrogeological environment of the study area. The data used and their description are provided in Table 1. The data such as bore well yield, well depth, well diameter, and groundwater level were obtained from the report of national groundwater survey in the Dili area (Aurecon Ausralia 2012).

Analytic hierarchy process (AHP)

The nine points of the Saaty’s scale values to each map were assigned according to their importance of influence in groundwater potential (Saaty 1980). The Saaty nine points

Table 1 Hydrogeological factors in relation to groundwater productivity

Category	Hydrogeological factors (unit)	Description	Data type	Source
1. Topology	Drainage density (km/km^2)	Drainage density is an inverse function of permeability, and therefore an important parameter in evaluating the groundwater zone. High drainage density values are favorable for runoff, and hence indicate a low groundwater potential zone	Grid	ALGIS
	Slope (degree)	The slope of the study area varies between a rise of 0 and 45 % obtained from ASTER DEM with 30 m resolution		ALGIS
	Topography (masl)	The topography of the study area is mostly mountainous with an elevation of between 0 and 1,410 m high, which is the lowest in the northern part and favorable for high groundwater potential and hence assigned higher priority		ALGIS
2. Climatology	Rainfall (mm)	Rainfall is the major source of recharge. The rainfall map was grouped into four classes which are <940–1,223; 1,223–1,454; 1,454–1,599 and >1,599–1,761 mm/year. High rainfall is favorable for high groundwater potential and hence assigned higher priority	Grid	Department Climatology and ALGIS
3. Satellite image	Lineament density (km/km^2)	Structures are the rock failure and deformation created by the changes in stress over time. Lineaments, faults, and fractures are important linear structures for increasing the permeability of the bedrock	Line	Landsat 5
4. Soil	Soil texture (unit less)	The soil texture property for groundwater infiltration	Polygon	ALGIS
5. Geology	Hydrogeological (unit less)	Geologically, the area has been divided into various lithology classes, i.e., Class 1: conglomerate, sandy, and sandy stone. Class 2: loose sediment, siltstone, and gravel. Class 3: phyllite, schist, amphibolite, and some volcanic rocks	Polygon	ALGIS
6. Land use/land cover	Land-use type (unit less)	Land uses are extracted from land-use maps provided by the Ministry of Infrastructure. Four categories of land-use patterns are identified in the study area 1: lowland forest-single, 2: estate crop, 3: lowland forest-mixed 4: settlement, 5: highland forest-single, 6: grassland, 7: water body, 8: smallholder estate crop, 9: dryland food crop and 10: coastal forest	Polygon	ALGIS

values were obtained from interview and group discussion of 22 international experts who are working for Government of Timor Leste, Panel of Water Resources Management of Timor Leste; Groundwater experts of National Institute of Technology Karnataka, India and Asian Institute of Technology in Bangkok, Thailand.

The relationship between the eight thematic layers has been derived using the MCDM to compute the relative importance of theme. Two main steps in computing the AHP method are as follows:

Step 1: *Construction of model* On the basis of a literature review, many models have been identified for mapping groundwater potential. For the construction of a model, the problem should be clearly defined and then decomposed into various thematic layers containing the different features/classes of the individual thematic map to form a network of the model.

Step 2: *Generation of pairwise comparison matrices* The relative importance values are determined using Saaty's 1–9 scale, where a score of 1 represents equal influence between the two thematic maps, and a score of 9 indicates the extreme influence of one thematic map compared to other one.

The AHP captures the idea of uncertainty in judgments through the principal eigenvalue and the consistency index (Saaty 2004). Saaty gives a measure of consistency called the Consistency Index (CI) as a deviation or degree of consistency using the following Eq. (1):

$$\mathrm{CI} = \frac{\lambda\mathrm{max} - \mathrm{n}}{n - 1} \quad (1)$$

where $\lambda_{\max}$ is the largest eigenvalue of the pairwise comparison matrix, and n is the number of classes or features. To control the consistency analysis and scale judgment, the Consistency Ratio (CR) which is a measure of consistency pairwise comparison matrix is calculated by Eq. (2):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad (2)$$

where RI is the Ratio Index. The value of RI for different n values is given, which in this research is equal to 1.41 ($n = 8$). If the value of the CR is less than or equal to 0.1, the inconsistency is acceptable, or if the consistency ratio CR is equal to 0.00, it means the judgment of the pairwise comparison matrix is perfectly consistent. If the CR is greater than 0.1, we need to go back to the step pairwise comparison matrix to rank the judgment value carefully with regard to the dominant factor that influences groundwater occurrences in the overall thematic layer map. To save time during AHP computation and to minimize errors during assignment of weights, the Super Decision Models software was used.

Overlay analysis

The relative weights obtained from AHP were assigned to each thematic map to generate a cumulative weight of the respective thematic maps and the weight value of each map with the highest or lowest weight was assigned in accordance with the real situation on the field. The summary of the assigned and normalized weights of the features of the different thematic layers and the consistency ratio of its thematic map were also computed and assigned for respective thematic map. Then, the eight different thematic maps were integrated using GIS Arcmap 10.1 as a summation of overall groundwater influencing factor to generate the groundwater potential map (GPM) for the study area. The following formula was used to estimate the groundwater potential map (Rao and Briz-Kishore 1991; Prasad et al. 2008; Muheeb and Rasheed 2009; Kumar et al. 2014):

$$\begin{aligned} GPM = {} & (\mathrm{MC1w} \times \mathrm{SC1r}) + (\mathrm{MC2w} \times \mathrm{SC2r}) \\ & + (M\mathrm{C3w} \times \mathrm{SC3r}) + (\mathrm{MC4w} \times \mathrm{SC4r}) \\ & + (\mathrm{MC5w} \times \mathrm{SC5r}) + (\mathrm{MC6w} \times \mathrm{SC6r}) \\ & + (\mathrm{MC7w} \times \mathrm{SC7r}) + (\mathrm{MC8w} \times \mathrm{SC8r}) \end{aligned} \quad (3)$$

where GPM is groundwater potential map, MC1–MC8 is the main criteria (1–8 thematic layer map), w is weight of the thematic map, SC1–SC8 is the sub-criteria of each thematic layer map and r is the sub-criteria class rating.

Results and discussion

Lineament density map

The lineament extracted from Landsat 5 image is shown in Fig. 2 and the lineament density map of the study area is shown in Fig. 3. The lineament density ranges from 0 to 1.94 km/km^2 and highest density (1.45–1.94 km/km^2) is

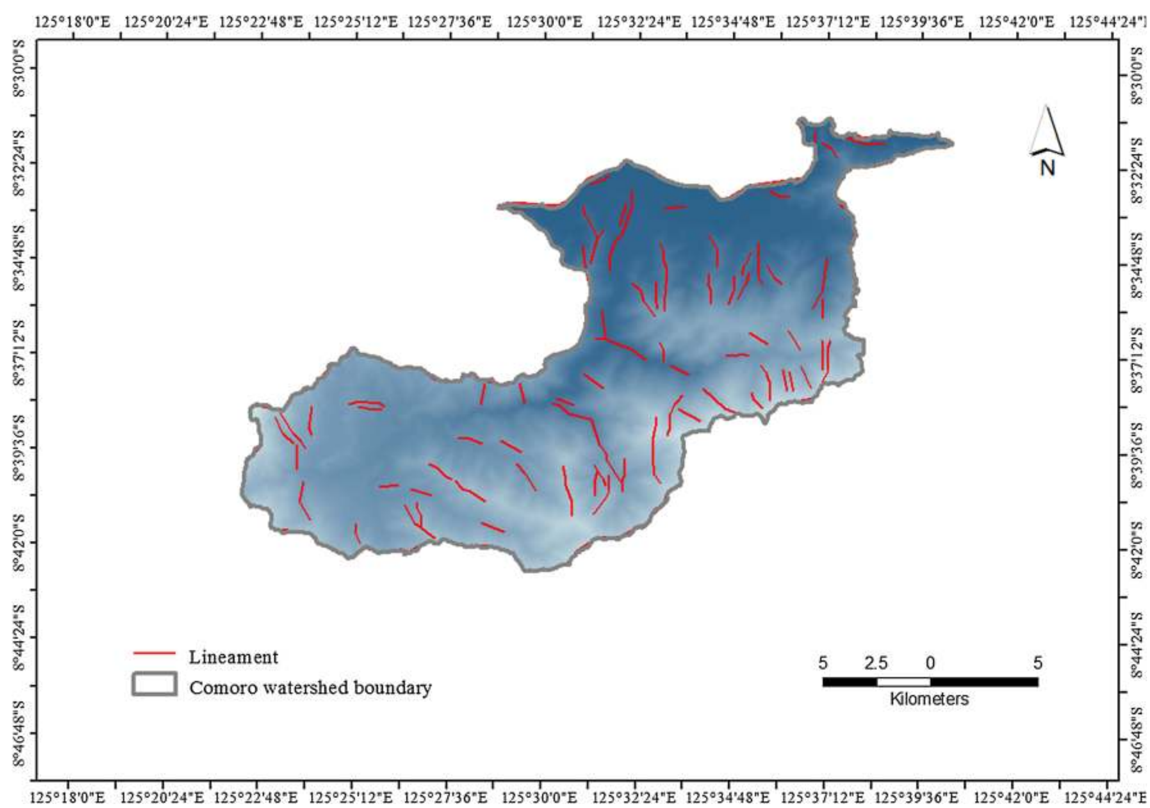

Fig. 2 Lineament extracted from Landsat 5 image

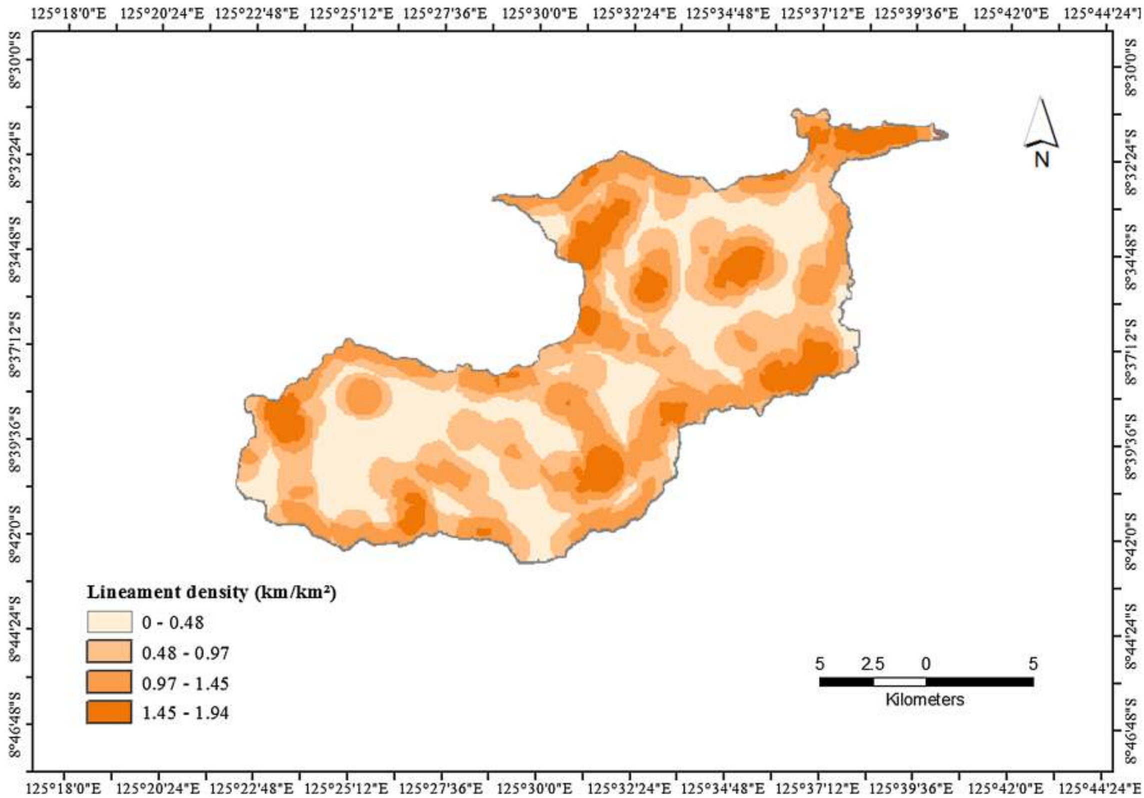

Fig. 3 Lineament density map of the study area

observed in the northern and southeastern parts of the watershed. The areas with higher lineament density are regarded as good for groundwater development.

Land use map

Land use/land cover plays an important role in the occurrence and development of groundwater. The land use of the study area is classified into ten classes: settlement, lowland forest, lowland forest-mixed, dryland food crop, estate crop, grassland, highland forest-single, lowland forest-single, smallholder estate crop, and water body (Fig. 4). Approximately 36 % of the total area is covered by lowland forest, and 34 % of the area is under cultivation as agriculture land. Settlements represent 12 and 10 % area is covered by the lowland forest-mixed. The remaining small part (0.08 %) represents grassland, smallholder estate crop, coastal forest, dryland food crop, water body, and highland forest (Table 2). Classification of land use for weighted analysis was decided based on the land-use type, area coverage and properties to infiltrate water, and their characteristics to hold water on the ground surface.

Slope map

The study area was divided into four classes based on the range of slope. The areas having 0–10° slope are categorized as 'very good' because of the flat terrain and relatively reduced runoff movement to downstream. Most of the study area are formed as mountainous and have steep slope greater than 45° which is not favorable for groundwater recharge. Those areas with 10°–45° slope are considered as 'good' for groundwater occurrence due to the slightly rising and falling topography with some runoff. The areas having slope of more than 45° are considered as 'very poor' due to the higher slope, which causes higher runoff. The slope map of the study area is illustrated in Fig. 5. Most of the area dominates by the high slope in the southern part whereas a small part in the north of the study area is indicated as low slope area.

Topography map

Approximately 90 % of the study area are mountainous, starting from east to west, the northeastern area is a coastal flat plain composed with sedimentary rock and tertiary

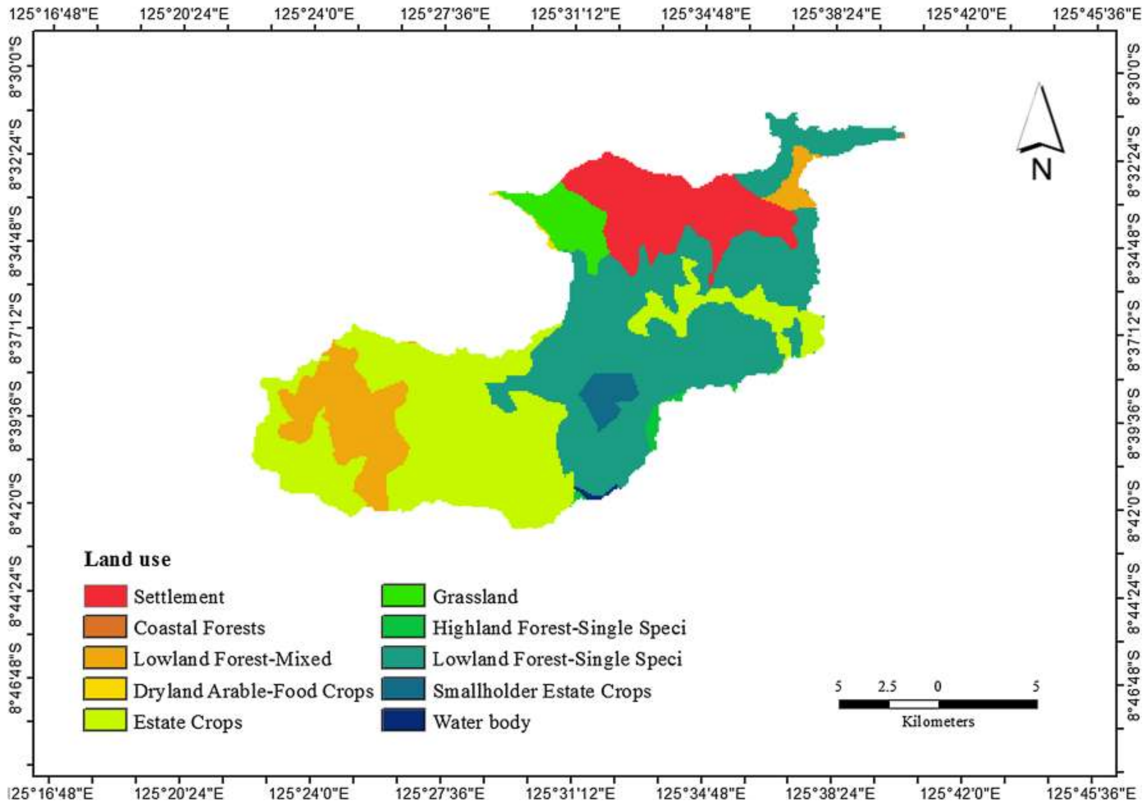

Fig. 4 Land use map of the study area

Table 2 Different land-use classes and categories of the study area

ID	LU code	LU class	LU category	Area (km^2)
1	Hld	Lowland forest-single	Forested	108.34
2	Hc	Coastal forests	Forested	0.05
3	Hlx	Dry lowland forest-mixed	Forested	30.96
4	Hhs	Highland forest-single	Forested land	1.95
5	Pd	Dry land-food crops	Agricultural	0.41
6	Pw	Water body	Agricultural	0.50
7	Ka	Estate crops	Agriculture	101.68
8	Kp	Smallholder estate crops	Agriculture	5.36
9	Ma	Settlement	Settlements	36.28
10	Sa	Grassland	Fallow land	11.07

Source: Ministry of Agriculture, Timor Leste

depositions. The topography map was generated from ASTER DEM data using the GIS ArcMap 10.1 and constructed as an elevation in raster format. The topography map of the area was classified based on the shape and features of the terrain into four different elevation classes as sub-criteria. To consider the flat shape of the terrain, semi-built-up area and soil type which is favorable for the infiltration, the topography map was divided into four different elevation group as follows: 0–70 masl considered as 'very good'; 70–550 masl considered as 'good'; 550–1,000 masl considered as 'poor'; and 1,000–1,410 masl considered as 'very poor'. As described above, an elevation of 70–1,410 masl was grouped into four different elevations above mean sea level as hilly and steep slope, and it has less influence to groundwater occurrence. The pairwise comparison shows that areas with a rolling hill shape and flat terrain are calculated as a higher weight, and a hilly and mountainous shape was calculated as a lower weight, and the reclassified topography map was produced based on these principles (Fig. 6).

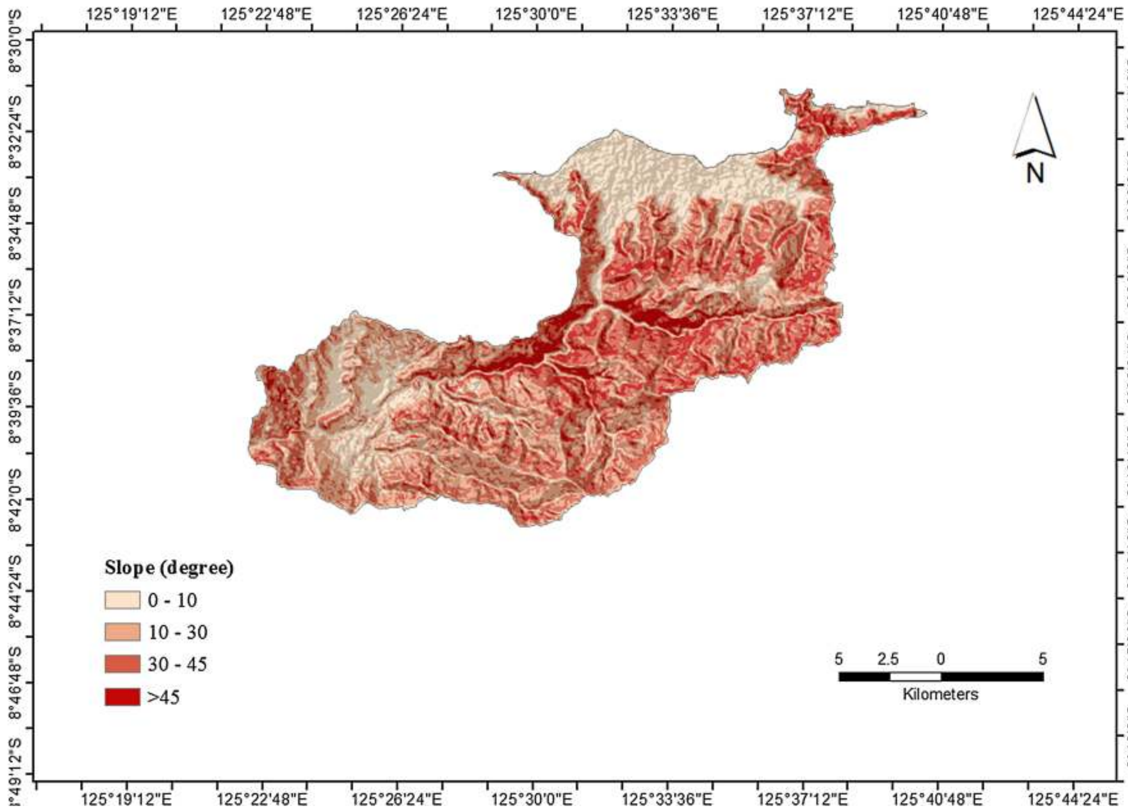

Fig. 5 Slope map of the study area

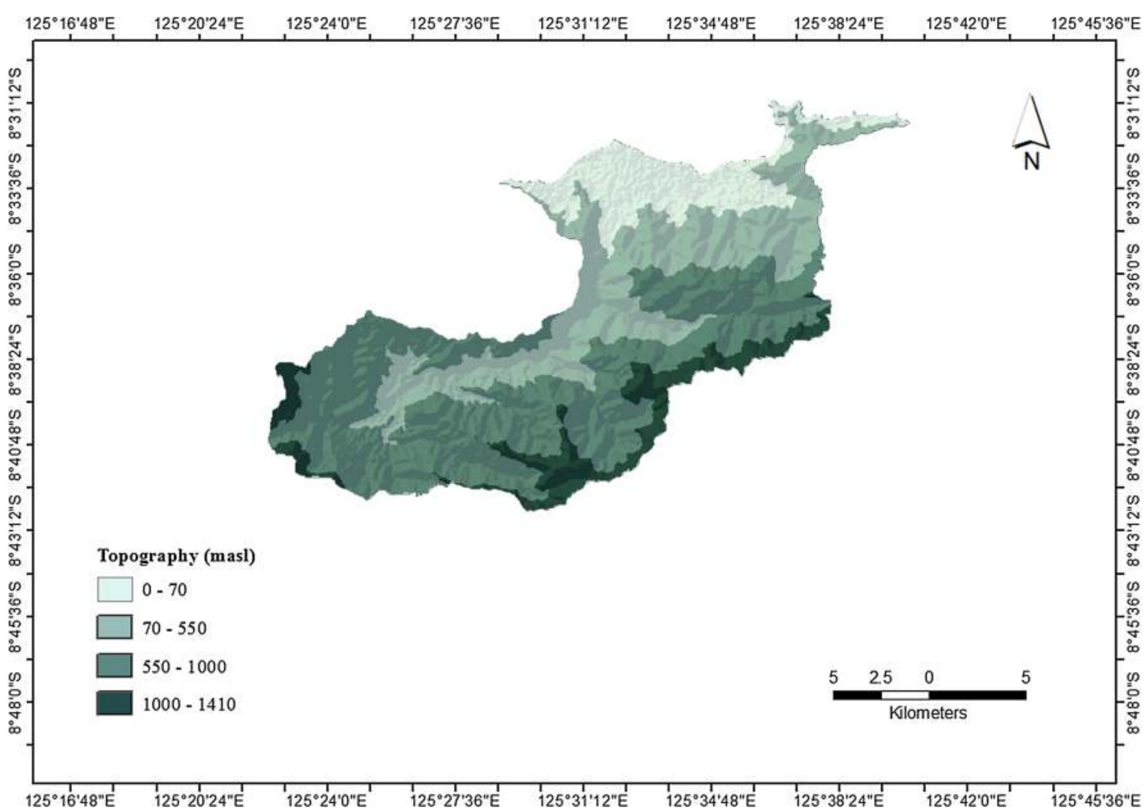

Fig. 6 Topography map of the study area

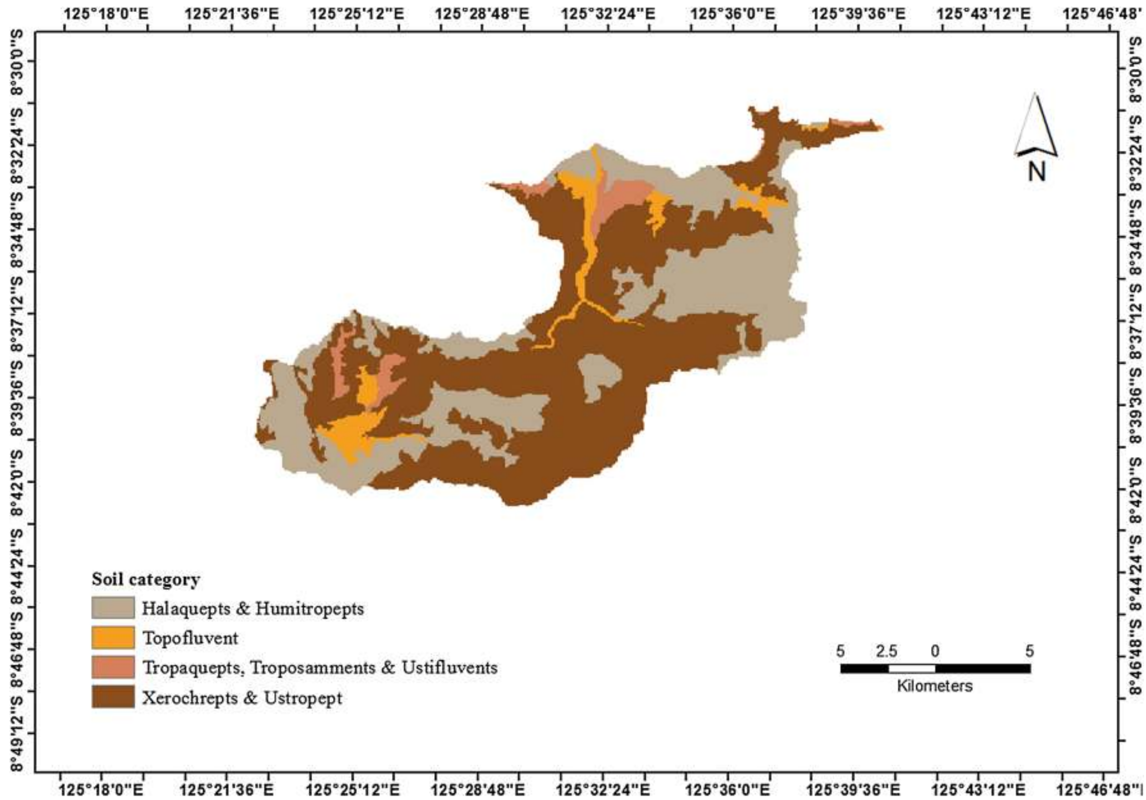

Fig. 7 Soil map of the study area

Soil map

Thematic layer map of soil type reveals that the study area is largely covered by the xerochrepts and ustochrepts group derived from the inceptisols soil order which is highly dominated by volcanic soil. The second largest soil group is halaquepts and humitropepts, also derived from the inceptisols soil order dominated by volcanic soil. The tropofluvent soil group is derived into the same soil type as the first soil group and second soil group (Thomson 2011). Almost the entire watershed is dominated by the volcanic soil because of geological formation named Aileu formation. The soil map was reclassified based on the coverage of the larger and smaller areas due to the entire watershed having the same soil type as described above (Fig. 7).

Lithology map

The geology of the study area is divided into three types of rocks formation named Alieu, Ainaro and sedimentary rock formations. The sedimentary formation consists of loose sediments, clay to thick boulders of 150 m, located in the northern region. The Aileu formation consists of phyllite, schist, amphibolite, slate, and some volcanic rocks with a thickness of 300 m spread over almost the entire area, and conglomerates, sand, and clay act as an Ainaro formation with 100 m thickness in a small area in the southwest part.

The pairwise comparison of lithology map was prepared based on the importance of aquifer type to store groundwater underground (Fig. 8). In the study area, aquifer type was classified into three different lithology, where greater amount of storage is in conglomerate–sand–clay in the upper part than loose sediment forming downstream. The Phyllite–Schist–Amphibolite soil group is considered as the least important. Furness (2011) reported that in the downstream area, sedimentary rock formation contains huge sand and gravel layer of about 150 m underground.

Drainage density map

The drainage density of the study area is classified into four classes: ‘very good’ (0–1.157 km/km^2) cover 30 km^2 of the area, ‘good’ (1.157–2.313 km/km^2) cover 85 km^2, ‘poor’ (2.313–3.470 km/km^2) cover 80 km^2, and ‘very poor’ (3.470–4.627 km/km^2) cover 55 km^2, respectively. High to very high drainage density covers almost the entire area—giving a recorded range of 2.313–4.627 km/km^2 representing 54 % of the study area. Only a small part of the study area has less drainage density which lies in the northern region. The reclassified drainage density map is

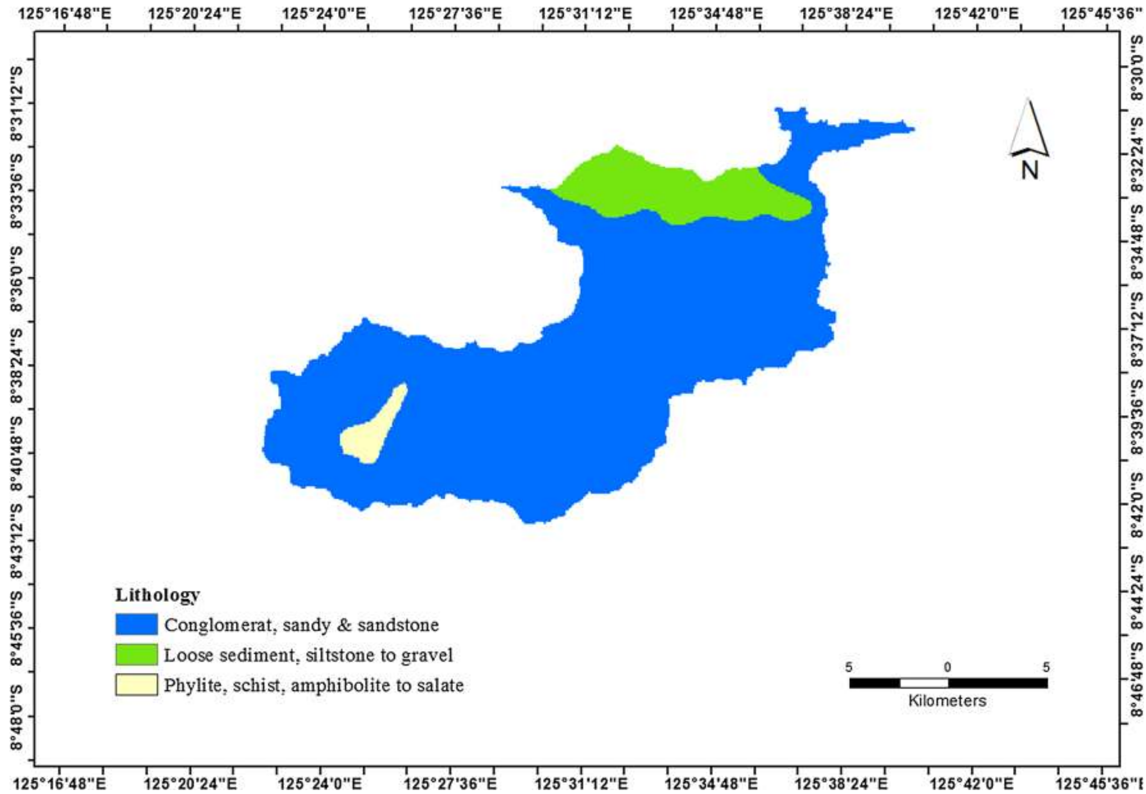

Fig. 8 Lithology map of the study area

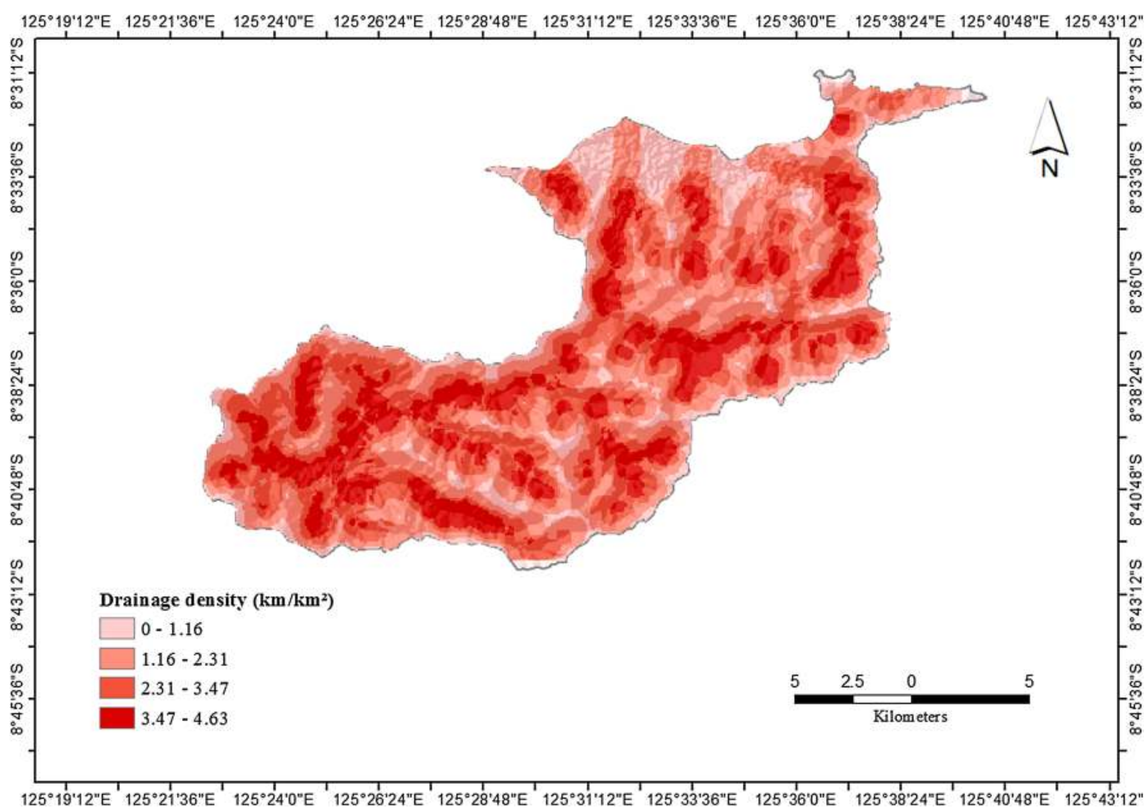

Fig. 9 Drainage density map of the study area

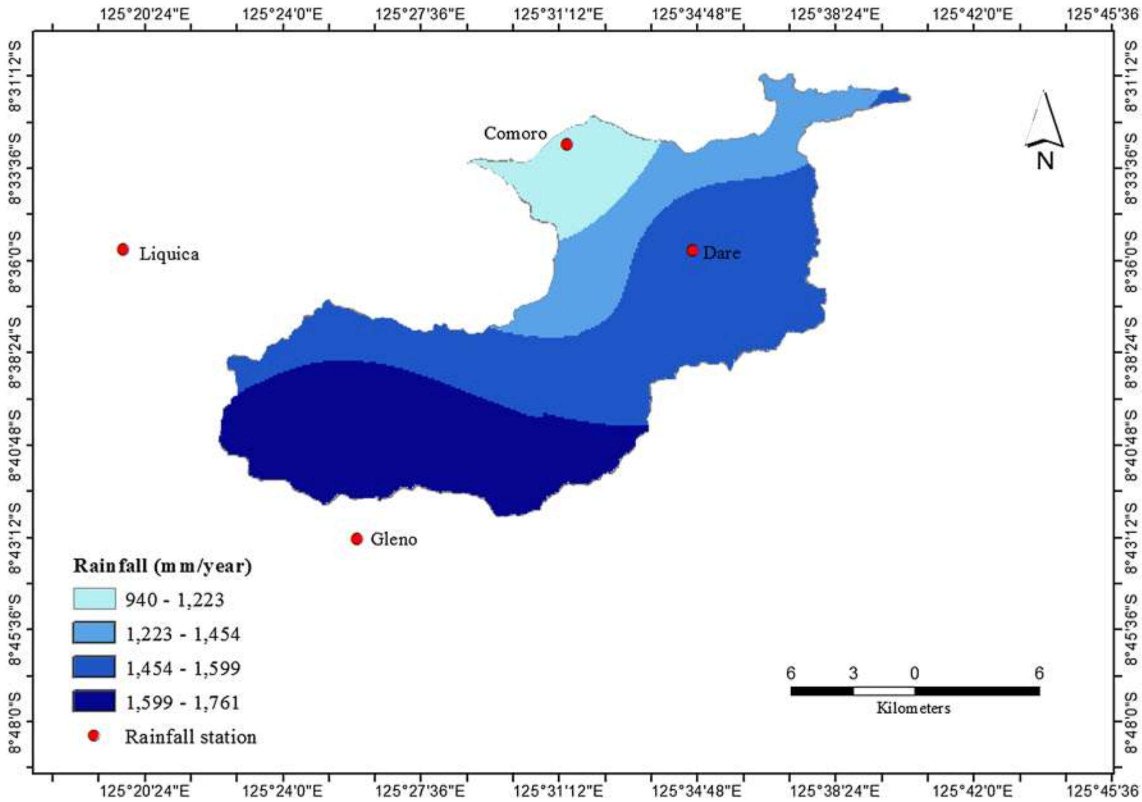

Fig. 10 Rainfall map of the study area

shown in Fig. 9. The suitability of groundwater potential zones is indirectly related to drainage density because of its relationship with surface runoff and permeability. The higher the drainage density the lesser the infiltration of water to the subsurface, which in turn leads to higher runoff and vice versa.

Rainfall map

The rainfall map of the study area is shown in Fig. 10. The northwest part of the study area receives rainfall of around 940–1,223 mm/year; the eastern part receives rainfall of around 1,223–1,454 mm/year. In the southern part, the recorded rainfall is around 1,454–1,599 mm/year, and in the northeast part, the recorded rainfall is around 1,599–1,761 mm/year. The rainfall influence on groundwater occurrence likely depends on the southwest and southeast rainfall, which has a high amount of rainfall from November to April, about 1,599–1,761 mm/year. The rainfall distribution along with the slope gradient in the upstream southwest part directly affects the infiltration rate and hence increases the possibility of groundwater potential zones in the downstream Northern part.

Table 3 Pairwise comparison matrix and normalized weight

Thematic map	Drainage density	Land use	Lineament density	Lithology	Rainfall	Slope	Soil	Topography	Normalized weight
Drainage density	1.00	0.25	5.00	0.14	0.33	0.50	0.50	2.00	0.07
Land use	4.00	1.00	3.00	0.33	0.33	0.25	0.33	3.00	0.09
Lineament density	0.20	0.33	1.00	0.14	0.14	0.17	0.33	2.00	0.03
Lithology	7.00	3.00	7.00	1.00	0.50	2.00	3.00	3.00	0.24
Rainfall	3.00	3.00	7.00	2.00	1.00	2.00	3.00	5.00	0.26
Slope	2.00	4.00	6.00	0.50	0.50	1.00	2.00	5.00	0.17
Soil	2.00	3.00	3.00	0.33	0.33	0.50	1.00	3.00	0.11
Topography	0.50	0.33	0.50	0.33	0.20	0.20	0.33	1.00	0.04
Total	19.70	14.92	32.50	4.79	3.34	6.62	10.50	24.00	1.00

Table 4 Relative weight of various thematic layers and their corresponding classes

No	Theme	Various classes				CR	Weight
1	Drainage (km/km^2)	0–1.57	1.57–2.313	2.313–3.470	3.470–4.627	0.04	0.07
	Weight	0.57	0.26	0.12	0.06		
	Ranking	1	2	3	4		
	Land Use (km^2)	Lowland forest-single	Estate crop	Lowland forest-mixed	Settlement		0.09
	Weight	0.36	0.34	0.1	0.12		
	Ranking	1	2	3	4		
2	Land Use (km^2)	Highland forest-single	Grass land	Water body	Smallholder estate crop	0.09	
	Weight	0.006	0.04	0.011	0.02		
	Ranking	5	6	7	8		
	Land Use (km^2)	Dryland food crop	Coastal forest				
	Weight	0.001	0.002				
	Ranking	9	10				
3	Lineament (km/km^2)	0–0.48	0.48–0.97	0.97–1.45	1.45–1.94	0.02	0.03
	Weight	0.62	0.22	0.11	0.05		
	Ranking	1	2	3	4		
4	Lithology	Loose sediment	Conglomerate, sand and clay	Phyllite and Schist		0.06	0.24
	Weight	0.73	0.22	0.05			
	Ranking	1	2	3			
5	Rainfall (mm)	3,470–4,627	2,313–3,470	2,313–1,157	0–1,157	0.01	0.26
	Weight	0.57	0.26	0.12	0.06		
	Ranking	1	2	3	4		
6	Slope (degree)	0–5	5–10	10–45	>45	0.04	0.17
	Weight	0.50	0.31	0.14	0.04		
	Ranking	1	2	3	4		
7	Soil	Halaquepts group	Xerochrepts group	Tropaquepts group	Tropofluvents group	0.03	0.10
	Weight	0.57	0.21	0.14	0.07		
	Ranking	1	2	3	4		
8	Topography	0–70	70–550	550–1,000	1,000–1,310	0.04	0.04
	Weight	0.51	0.37	0.07	0.05		
	Ranking	1	2	3	4		

CR consistency ratio of weight judgment

Weightage analysis and normalization

To compare the importance of two layer maps to show that one of them has more influence to the groundwater occurrence than the other, the pairwise comparison matrix was carried out using the MCDM (AHP) technique (Table 3). The Consistency ratio (CR) value was found to be 0.07 and hence considered to be acceptable.

Drainage, rainfall, geology, lineament, land use, slope, topography, and soil maps were generated and assigned a suitable weight as shown in Table 3. To calculate the cumulative weight of both the main criteria and sub-criteria, the relative weight of both criteria and their corresponding classes were considered (Table 4). Finally, the cumulative weight was used to prepare the raster map and groundwater potential zone map was produced using GIS environment.

Groundwater potential zone

On the basis of the normalized weighting of the individual features of the thematic layers, the groundwater potential zones were estimated (Table 4). The groundwater potential zone was reclassified into very poor, poor, moderate, high, and very high groundwater potential zones. As shown in the Fig. 11, the alluvial plains in the northwest along the Comoro River were explored as a very high groundwater potential zone. The total areal extent of the very high potential zone covers about 5.4 % of the total area. The high potential zone

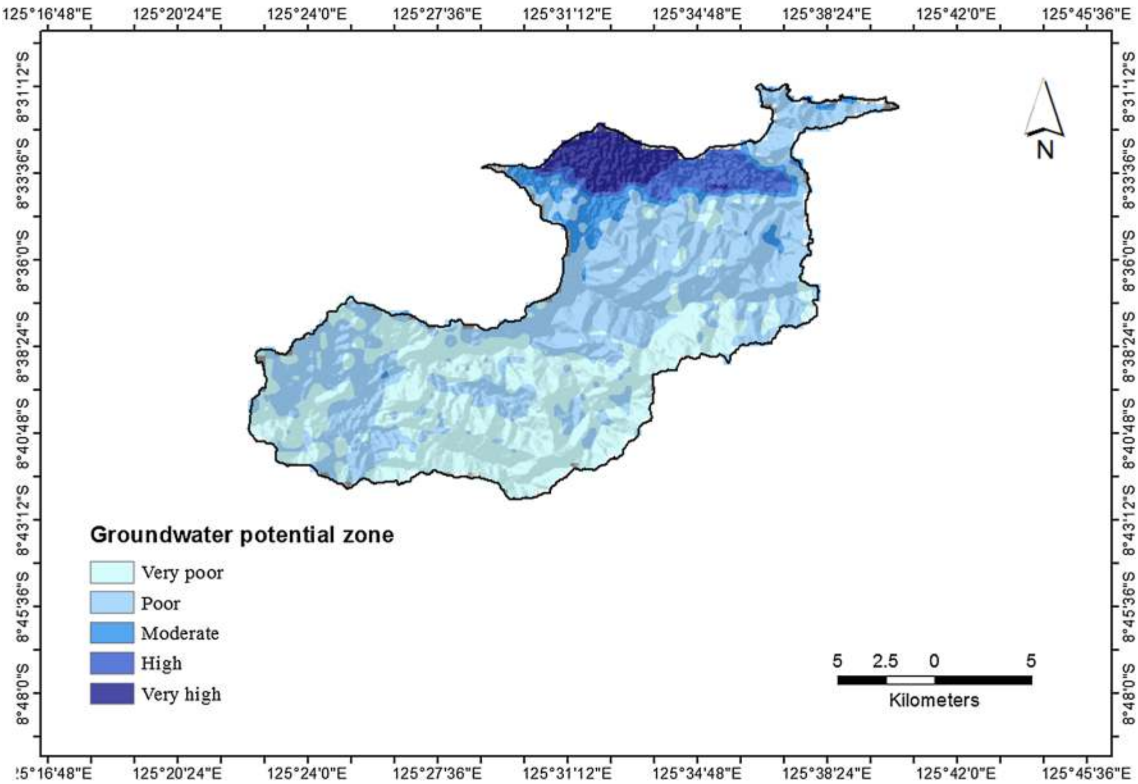

Fig. 11 Groundwater potential zone map in the Comoro Watershed, Timor Leste

was found in the eastern part and along the foothills which cover about 4.8 % of the area, and in the upstream of the watershed has a moderate zone covering 2.0 % of the study area. The remaining areas consist of a poor zone and very poor zone which covers about 45 and 42.8 % of the study area, respectively. The high potential zones comprised of loose sediment, clay to boulders with 150 m depth, the lineament density ranges from 0.48 to 0.97 km/km^2, and drainage density ranges from 0–1.157 to 1.157–2.313 km/km^2. The hilly terrain located in the southern and central parts of the study area has poor groundwater potential due to the high degree of slope and low permeability of conglomerate soil type (Table 5).

A careful observation of the groundwater potential zone map shows that the availability of groundwater is more or less a reflection of the rainfall and geological formation patterns together with slope. In addition, areas underlain by saprolite and impermeable bedrock, especially in the northern coastal area along the Comoro river sections although characterized by relatively low rainfall, have high groundwater potential. This can be attributed to the groundwater movement from higher slope in the upstream to the downstream in the lower part of coastal area. Similarly, lower drainage density and lower slope can enhance the infiltration of water into the groundwater system in those areas.

Table 5 Classification of groundwater potential zone and the degree of area coverage with the respective yield category

Potential zone	Area (%)	Area (km^2)	Yield classification (l/s)
Very high	5.40	13.50	32.06
High	4.80	12.00	19.57
Moderate	2.00	5.00	12.50
Poor to very poor	87.80	219.50	na

Result validation

The groundwater potential zone of the study area is shown in Fig. 11. The groundwater potential zones thus obtained were validated with well yield data of 14 bore holes with depth ranging from 20 to 85 m. It is observed that high potential zones are located in the northwestern part of the Comoro watershed and the western part of the Dili alluvial plain. A cross-validation study has been carried out in this area to ensure that the groundwater potential zone is as per the field data reported by Aurecon Ausralia (2012). The well yield of 32.06 l/s capacity is found in the very high potential zone, 19.57 l/s in the high potential zone, and 12.5 l/s in the moderate potential zone (Fig. 12). The correlation between groundwater potential map and well

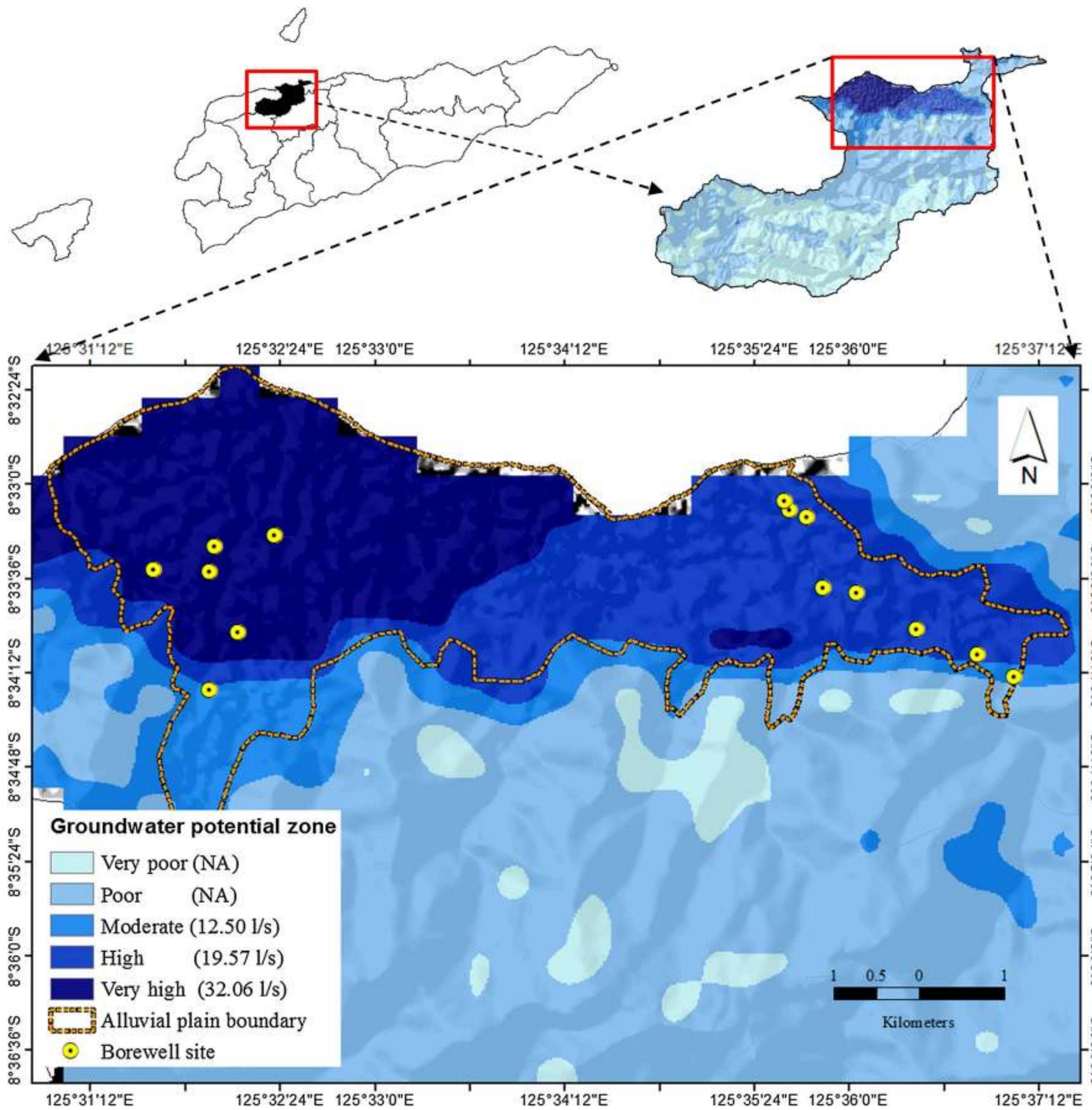

Fig. 12 Groundwater occurrence validation map using bore well yield in the study area

yields capacity is also in agreement with the aquifer potential reported by Australian Geoscience. Australian Geoscience reported the vertical thickness of the Dili aquifer as intergranular aquifer of 82–130 m thickness which is considered to be huge aquifer to store groundwater (Wallace et al. 2012).

Conclusions

The application of geospatial technology, remote sensing, and the AHP technique is demonstrated as the best tools for the identification of groundwater potential zones in the Comoro watershed. The present study demarcates the potential zones for groundwater occurrences by analyzing several thematic layer maps as influencing factors. The analysis reveals that out of 250 km^2 area, around 13.5 km^2 is identified as a very high potential zone for groundwater occurrences at the downstream of the Comoro River in the western part of the city and it covers only 5.4 % of the study area; around 12 km^2 of the eastern part of Dili City is identified as a high potential zone which covers 4.8 % of the area; around 5 km^2 of the area is identified as a moderate potential zone and covers 2.0 % of the area along the foothill in southern part of the city; and the remaining larger area of 219.5 km^2 in the southern part of the Comoro watershed cover 87.8 % is identified as poor and very poor groundwater potential zone due to the high slope and mountainous terrain.

The very high potential zone is characterized by the lithology type such sedimentary rock formation and the lower slope in the downstream of the Comoro watershed. The groundwater potential zone map was compared with the well yield data to ascertain its validity and found that the results are in agreement with the wells yield data. The occurrence of groundwater in the study area is controlled by rainfall, lithology, slope, and land use as revealed from GIS and direct observation in the field. This potential map will serve as the basis of information to local authorities and planners about the suitable area for prospective exploration of groundwater wells and protect the area from contamination of domestic and industrial activities.

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Conflict of interest The authors declare that there is no conflict of interest in this research work.

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