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INTEGRATED APPROACH FOR LINEAMENT EXTRACTION IN ASSESSING GROUNDWATER POTENTIAL: A CASE STUDY IN THE HIGHLANDS OF ERITREA

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Abstract
Groundwater exploration is crucial for sustaining ecosystems and human activities, particularly in semi-arid regions like the highlands of Eritrea. This study evaluates the effectiveness of manual and automated lineament extraction methods for identifying geological structures indicative of groundwater potential. Using a 30-meter resolution SRTM digital elevation model (DEM), we generated hillshade images and extracted lineaments manually by ESRI ArcGIS and automatically with MATLAB's edge detection algorithms, including Canny, Sobel, Prewitt, Roberts, Approximate Canny, and Laplacian of Gaussian (LoG). Our findings reveal significant differences between the manual and automated methods. Directional analysis showed that manually identified lineaments primarily followed NE-SW and NW-SE directions. Among the automated methods, Canny, Approxcanny, and Prewitt exhibited similar directional trends. Lineament density maps indicated high-density areas in the western and northern parts of the study area for both manual and automated methods. The LoG algorithm showed the highest correlation (0.8561) with the manual method, suggesting it as a reliable alternative for lineament mapping, contributing to more efficient groundwater exploration in semi-arid regions.

Keywords: Lineament extraction, Lineament density, MATLAB, Eritrea, Groundwater potential assessment

1. Introduction

The presence of groundwater is facilitated by various parameters, among which lineaments are significant indicators. The density of lineaments provides useful information on groundwater potential, as the fractures can influence the movement and storage of water. Areas with high lineament density often have enhanced permeability, which can affect water flow and aquifer recharge (Hung et al., 2005; Chuma et al. 2013; Gaber et al. 2020; Embaby et al. 2024). This study was conducted in the highlands of Eritrea, where the assessment of groundwater potential relied on lineaments as a key input parameter.

Remote sensing and Geographic Information System (GIS) techniques have emerged as valuable tools in identifying potential groundwater sources by analyzing geological features such as lineaments, fractures, and structural trend (Solomon & Quiel, 2006). The utilization of geostatistics and automatic lineament extraction from Digital Elevation Models (DEMs) has enabled researchers to map and analyze lineaments effectively (Oluwaseun et al., 2022; Mogaji et al., 2011). By integrating thematic layers in GIS, researchers have identified potential zones for groundwater exploration based on lithology, landforms, and lineament distributions (Coulibaly et al., 2021).

The identification of the geological structures, such as faults and fractures is relied on semi-automated or visual interpretation of remotely sensed data and digital elevation models. However, these methods are often subjective and time-consuming.

To address the challenges in automated lineament extraction, several studies have proposed and evaluated various methodologies. One such effort is the MATLAB-based toolbox, which aims to automate the process of tectonic lineament mapping using a combination of advanced image processing techniques (Rahnama et al., 2014a; Rahnama et al., 2014b). The effectiveness of this toolbox has been validated using synthetic DEMs and tested in regions with known fault structures. Comparative analyses have been conducted to evaluate its performance against other lineament extraction algorithms and manual extraction methods (Salui, 2018; Sharifi et al. 2018).

The development of tools like LINDA (LINeament Detection and Analysis) offers automated detection and analysis of linear features across multiple datasets (Masoud & Koike, 2017). This integrated tool simplifies parameter selection and facilitates interactive visual analysis, proving effective in various terrains, including desert regions of Egypt. Kusák and Krbcová (2017) analysed the relationship of manually and automatically extracted lineaments and tectonic faults in Ethiopia by applying the PCI Geomatica. DEM based shaded relief images with multi-azimuthal illumination can be also used for automatic mapping of lineaments with improved detection capabilities (Alhirmizy, 2015; Soliman & Han, 2019). Shaded relief images combined with Aster satellite images can be also applied for identification of structural lines (Papadaki et al., 2011). DEM derivative indices, like Topographic Position Index (TPI) can also be involved in lineament analysis (Villalta Echeverria et al., 2022).

Many research dealt with the comparison of different lineament mapping methods. The effect of elevation model properties on the extraction of these lines were analysed by comparing SRTM, Aster DEM, Cartosat (Das & Pardeshi, 2018; Nugraha et al., 2018), ALOS (Advanced Land Observing Satellite) PALSAR (Phased Array L-band Synthetic Aperture Radar), JAXA (Japan Aerospace Exploration Agency) (Gaikwad et al., 2023) and TanDEM-X (Shetty et al., 2022). Meixner et al. (2018) found that remote sensing techniques in combination with elevation models can be used to get results of spatial arrangement of critically stressed faults. Comparison of Landsat-8, Aster, Sentinel-1 (Adiri et al., 2017) and Sentinel-2A (Javhar et al., 2019) satellite data found that radar data are more efficient in restitution of lineaments than optical imagery. Comparative study (Salui, 2018) on automated lineament extraction found that the MATLAB based technique proved to be better than PCI Geomatica algorithm.

According to the review published by Ahmadi and Pekkan (2021) the lineaments extracted by a wide variety of manual, semi-automated, and automated GIS techniques are not consistent, therefore, a single method may not provide accurate lineament distribution and may include integration of multiple algorithms, e.g., manual and automated algorithms. The effects of differences in lineament extraction methods on accuracy of groundwater mapping have not been widely examined. The novelty of this research is that we performed a comparative analysis of the expert knowledge based manual method and the MATLAB provided automated lineament extraction methods to identify the usability and accuracy of these methods in semi-arid environment.

2. Materials and methods

Study area

The study area is the Dbarwa catchment within the Debarwa region, located in the Debub administrative sub-zone of Eritrea (Figure 1). Debarwa is situated 25 km south of Asmara, the capital city of Eritrea. The catchment covers an area of 534 square kilometres and lies at an elevation ranging between 1811-2569 m asl.

The geological settings of the basement in general are characterized by metavolcanic and metasedimentary rocks. Metavolcanics include metabasalts and metafelsites (rhyolites, tuffs and pyroclastic volcanics). Metasedimentary units are comprised of slates and turbiditic sediments of greywacke (Teklay, 1997). A variety of felsic rocks with granitic-dioritic composition (gneissose granite, porphyritic granite, granodiorite, syenite) intruded the sequence. The form of the intrusions preserved as roof pendants and rounded circular masses (Hamrla, 1978). Mesozoic sandstone and Cenozoic volcanic rocks lie over the metavolcanic, metasedimentary rock units and the granitoids. These plateau-forming volcanic rocks are a sequence of basaltic and rhyolitic volcanic rocks, interspersed with minor sedimentary layers (Solomon & Quiel, 2006; PorterGeo.com).

The area experiences arid to semi-arid climatic conditions, with July being the wettest month and December the driest. January is typically the coldest month. The region has a variable rainfall pattern, averaging an annual precipitation of 540 mm and a mean temperature of 23°C (weatherandcimate.com).

The natural vegetation cover is sparse and consists dominantly of acacia trees and bushes occupying rocky steep slopes and lowlands. Dense vegetation cover is common along rivers and forms a limited woodland type of forest (Solomon & Quiel, 2006). Beside the spots of remaining natural vegetation, the watershed is covered with open and sparse shrubs and mild slope agricultural lands (Ghebrehiwot & Kozlov, 2019).

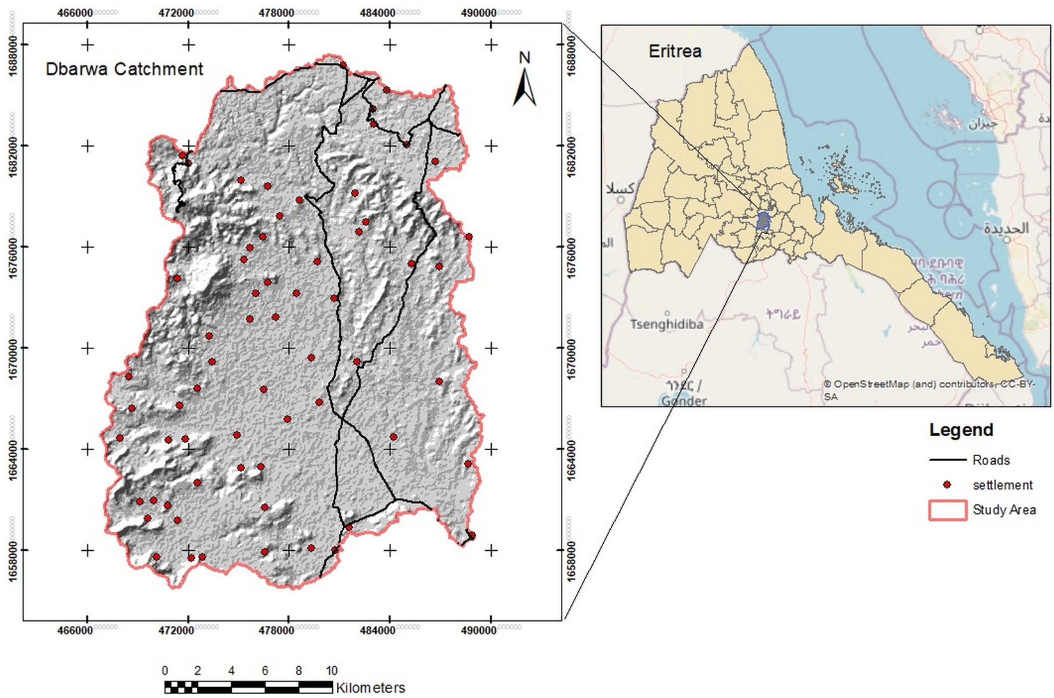

Fig. 1. Location of the study area

Debarwa is a historic market town in central Eritrea, home to approximately 84,150 residents. The local economy is predominantly agricultural, with the cultivation of diverse crops such as teff, finger millet, maize, and barley. However, the agricultural sector faces significant challenges due to the impacts of climate change and the overexploitation of groundwater resources, leading to water scarcity issues. These challenges highlight the critical importance of effective water resource management strategies to sustain agricultural production and livelihoods in the region. For the development of these strategies, the detailed knowledge of groundwater recharge potential zones must be established. The characteristics of these zones are highly influenced by the geological and geomorphological settings, including the location and density of the lineaments.

Description of used data (DEM, hillshade)

In our research, we used the SRTM digital elevation model with a spatial resolution of 30 meters, available at the USGS website (earthexplorer.usgs.gov). The extraction of the lineaments was done by using hillshade layer that was derived from the SRTM.

Methods for lineament extraction

The workflow of our research can be seen on Figure 2. The manual lineament extraction was made by using ESRI ArcGIS software. This method is time-consuming and tedious. It needs a series of visual looks to identify the lineament and experience of knowing the places will give more valid information in the analysis. From the DEM four hillshade at different angles were extracted those are at an angle of 315-45, 90-50, 100-60, 200-50. The lineaments were then digitized by creating polyline shapefile by following all the visible lines. In order to bring the best visualization, the four hillshades were switched one from the other.

Application of edge detection in MATLAB

Edge detection is a fundamental tool in image processing and computer vision, aimed at identifying points in a digital image where the image brightness changes sharply. MATLAB offers several built-in functions to perform edge detection, each with its own advantages and use cases. The Laplacian of Gaussian (LoG) method first smooths the image with a Gaussian filter to reduce noise, then applies the Laplacian operator to highlight regions of rapid intensity change, making it effective for noisy images (Nagasankar & Ankaryarkanna, 2016; İlkin et al., 2017). The Approximate Canny method simplifies the Canny edge detector to reduce computational complexity while maintaining performance, ideal for real-time applications. The Sobel operator uses convolution with 3x3 filters to estimate the gradient of image intensity, emphasizing edges in both horizontal and vertical directions (İlkin et al., 2017; Canny, 1986). The Roberts Cross operator, employing 2x2 convolution kernels, is one of the simplest and fastest methods, suitable for real-time applications with limited computational resources (Roberts, 1963). The Canny edge detector, a multi-stage algorithm known for its robustness to noise and accurate edge localization, involves noise reduction, gradient calculation, non-maximum suppression, and edge tracking by hysteresis (Nagasankar & Ankaryarkanna, 2016; İlkin et al., 2017). Finally, the Prewitt operator, similar to Sobel, approximates the gradient of image intensity with slightly less accuracy but greater computational efficiency. Each of these algorithms, accessible via MATLAB functions, allows users to implement edge detection in their image processing workflows effectively, catering to different application needs in terms of efficiency, noise robustness, and edge accuracy (Chaple et al., 2015).

These edge detection techniques can also be applied to DEM hillshade files. By highlighting the edges in these hillshade images, we can effectively identify and extract lineaments, which are significant linear features in the landscape. This application is particularly useful in geological and geomorphological studies where understanding the structural features of the terrain is crucial.

Steps of the edge detection workflow

At first, we need to prepare DEM which can be used for generating of the hillshades. The hillshades were extracted with 45 and 315 degrees. The generated hillshades were forced to RGB and stored on the same folder with the MATLAB algorithm.

Using the above method each six edge detection methods for the hillshades, 12 lineament layers were produced. The lineament stored in the folder and to be georeferenced we needed to copy the extension file from the RGB hillshade to each generated lineament, this will allow the normal image to have a reference value which can be uploaded to GIS software for further processing.

In GIS environment, the first step to take is to reclassify each of the layers with zero to NoData. After that, the lineament rasters were converted to polyline shapefiles. Then the length of each polyline segments was calculated in the attribute table, then proceed to generalization using a tolerance of 100 m. This tool helps to generalize the unnecessary lengths created during the process.

An optional tool was applied to select the polylines of lineaments with lengths greater than 500 m. The next step was merging the 12 polyline layers (which were generated from the 45 and 315 degrees hillshades), as a result of this step, we got 6 layers, one for each edge detection method.

Directional statistical analyses

We performed directional statistical analyses on both manually digitized and automatically extracted lineament polyline datasets. For the directional statistical analyses, we used the 'Creating Rose Diagrams from Endpoint Data' tool in RockWorks 16 software. We examined the direction of the lineament sections by their frequency (number of lines in given directions) and

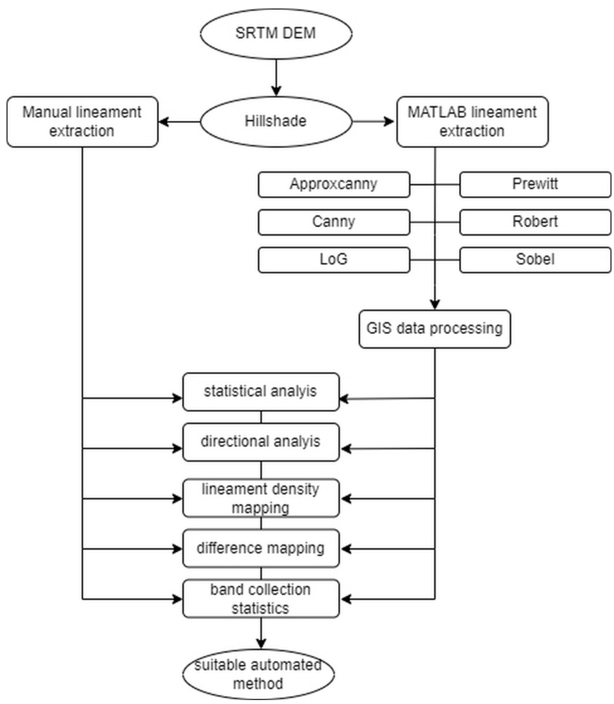

Fig. 2. Flowchart of the research

by their total length. Both the directional frequency and length frequency of the lineaments were illustrated in a rose diagram with 10-degree class intervals, expressed as a percentage (Pecsmány et al., 2021; 2022).

Spatial analysis of the lineaments

Beside the analysis of the direction of the lineaments we also examined the characteristics of their spatial distribution in the pilot area. It was done by creating a series of lineament density maps, separately for the manually digitized polyline data, and for each of the 6 automatically extracted lineament layers. The density maps were created by ArcGIS 10.4 applying the Kernel density tool with the default search radius.

In our research we focused on the differences between the spatial distribution of manually and automatically extracted lineaments, it was analysed with 2 methods in ArcGIS environment: We used the density maps (manual + 6 automatically extracted) to create the maps showing the differences in density by applying the Raster calculator tool. The spatial correlation of density maps was also examined by using the Band Collection Statistics tool which made it possible to rank the lineament mapping algorithms of MATLAB.

3. Results and discussion

In the research area, there have been no comprehensive or detailed previous analyses specifically focusing on the characteristics of lineaments, including their orientation, distribution, density, and potential correlations with geological structures and hydrological processes. However, in other regions, such as the Carpathian Basin (Pecsmány et al. 2021, 2022), there is considerable experience that has explored the significance of lineaments, offering valuable insights into their influence on geological structures, which can be used as a reference for this study.

The statistical results of lineaments can be seen in Table 1. Manually we identified 113 lineaments. Among the edge detection methods, the Canny algorithm produced the most line segments (1151), while the Robert method identified the least lineaments (61). Due to the applied methodology – filtering the lines shorter than 500 metres – there is no difference in the minimum lengths, it is ~503 m in all cases. However, there is a significant difference in maximum length: the longest manually digitized line has a 2671,12 m length, while all the automated algorithms produced much shorter lineaments: Sobel: 1551,43m – Canny: 1986,06 m. In case of mean length, and standard deviation similar can be stated. The mean length of manual method is bigger (802,61) than any of the MATLAB algorithms' (661,13 m – 708,08 m). The standard deviation is 410.85 in case of manual method, while it is much smaller in case of the algorithms derived method (162,96 – 196,10).

Comparing the results of manual digitization with the results of automated edge detection we found, that analysing the number and length of the lineaments there is no clearly identifiable best fitting automated method to the manual method. From the

Table 1. Statistics of the different lineament methods

	manual	Approxcanny	Canny	LoG	Prewitt	Robert	Sobel
Count	113.00	167.00	1151.00	639.00	132.00	61.00	124.00
Minimum	502.92	503.00	502.99	503.03	503.03	503.03	503.03
Maximum	2671.12	1693.00	1986.06	1915.50	1551.43	1253.76	1551.43
Sum	90695.29	115053.00	801201.50	433633.83	91137.22	40329.20	87802.12
Mean	802.61	688.94	696.09	678.61	690.43	661.13	708.08
Standard Dev.	410.85	180.13	196.10	181.49	186.50	162.96	188.22

Table 1. Statistics of the different lineament methods

	manual	Approxcanny	Canny	LoG	Prewitt	Robert	Sobel
Count	1.000	1.478	10.186	5.655	1.168	0.540	1.097
Minimum	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Maximum	1.000	0.634	0.744	0.717	0.581	0.469	0.581
Sum	1.000	1.269	8.834	4.781	1.005	0.445	0.968
Mean	1.000	0.858	0.867	0.846	0.860	0.824	0.882
Standard Dev.	1.000	0.438	0.477	0.442	0.454	0.397	0.458

count point of view the Sobel 's results (1,097) are the most similar to the manual method, the Canny is the best by the maximum length (0,717), the Prewitt's sum value (1,005) is almost the same as the manual sum, while by the mean values, the Sobel method is the best fitting algorithm.

Results of directional analysis

The directional frequency of manually digitized lineaments shows that most of the linear elements has a NE-SW direction and there is also a secondary, NW-SE direction (Figure 3). However, by length frequency, it can be seen, that summarizing the lineaments' length the NW-SE is the primary direction, while there is a secondary NE-SW direction as well. Among the 6 edge detection methods there is no algorithm with perfectly fitting results, however, there are some similarities.

In case of directional frequency, the Canny, Approxcanny and Prewitt algorithms produced clearly identifiable NE-SW primary and NW-SE secondary directions. The Sobel method has no primary direction, while the LoG and Robert algorithms produced NE-SW primary directions.

In case of length frequency, the LoG and Robert algorithms has the same primary and secondary directions as the manual method. The Approxcanny method has no primary direction, while the Canny, Prewitt, and Sobel methods produced the opposite, NE-SW primary direction compared to the manual method.

Results of lineament density mapping

We also analysed the spatial characteristics of manually and automatically generated lineaments by creating lineament density maps (Figure 4.). Despite the significant differences between these two approaches in the statistical data (Table 1-2.) and the directional analysis (Figure 3.), in case of lineament density maps it can be stated, that there is no difference in the spatial distribution of the lineaments. Both the manual and MATLAB based methods resulted similar maps: the areas with the highest density can be found on the western edge and on the northern part of the pilot area with a NW-SE direction. However, there are differences in the maximum density values. This value is 1.5 km/km^2 for the manual method, the Canny and LoG algorithms has much higher maximum densities, 4.3 km/km2 and 3.1 km/km^2, respectively. The Approxcanny, Prewitt, Sobe and Robert methods have much smaller values (0.98; 0.8; 0.75; 0.27 km/km^2, respectively).

To examine the differences in the spatial distribution of lineament densities, we compared each of the MATLAB based maps to the map created by the manual method by using the ArcGIS raster calculator tool (MATLAB algorithm density raster - manual lineament density raster). The results can be seen on Figure 5. The greenish color on these difference maps indicates areas with minimal differences, while the darker bluish and reddish colors indicate increasing (negative and positive, respectively) differences.

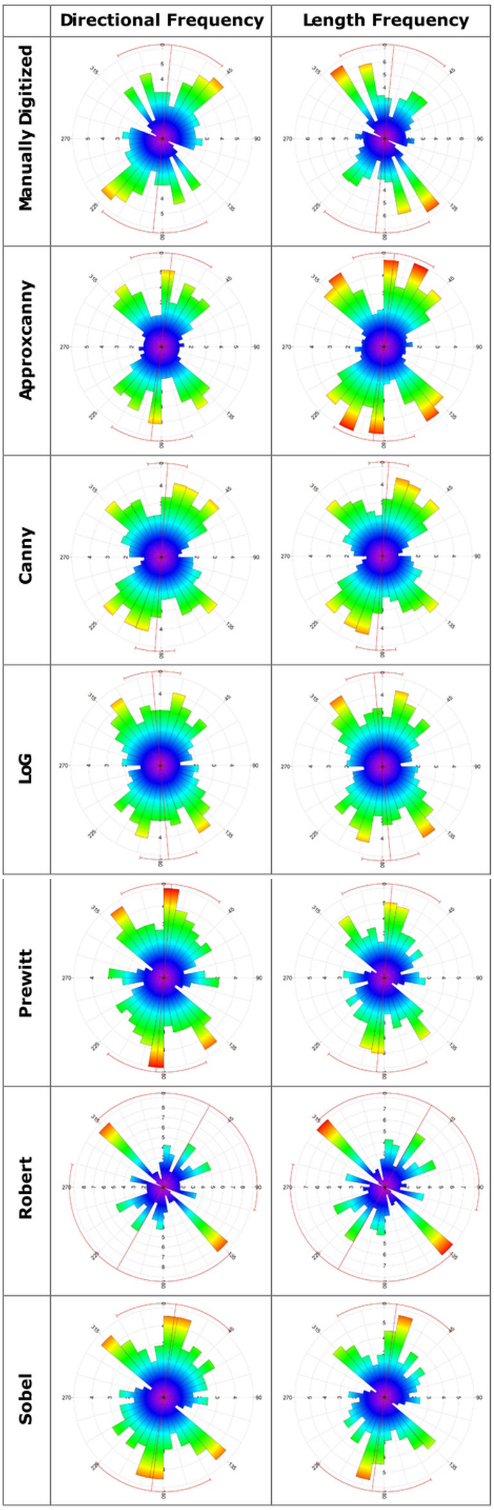

Fig. 3. Directional statistical diagrams of lineaments extracted by different methods

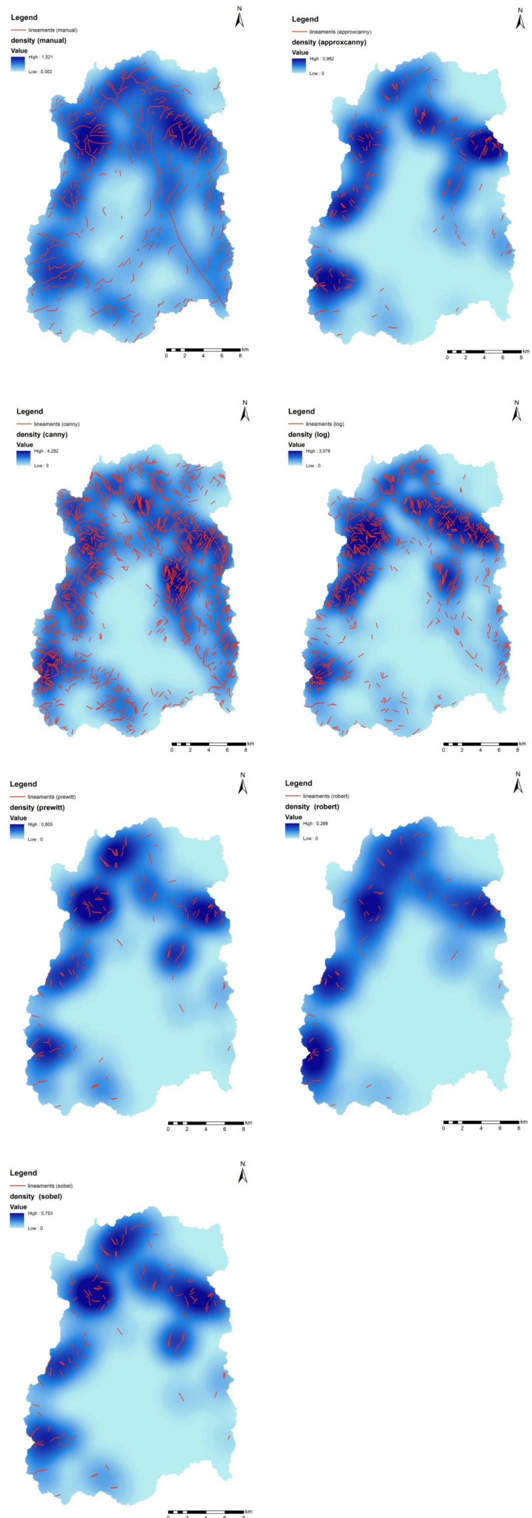

Fig. 4. Lineaments and lineament density maps of the research area (top left: manual, top right: Approxcanny, bottom left: Canny, bottom right: LoG method)

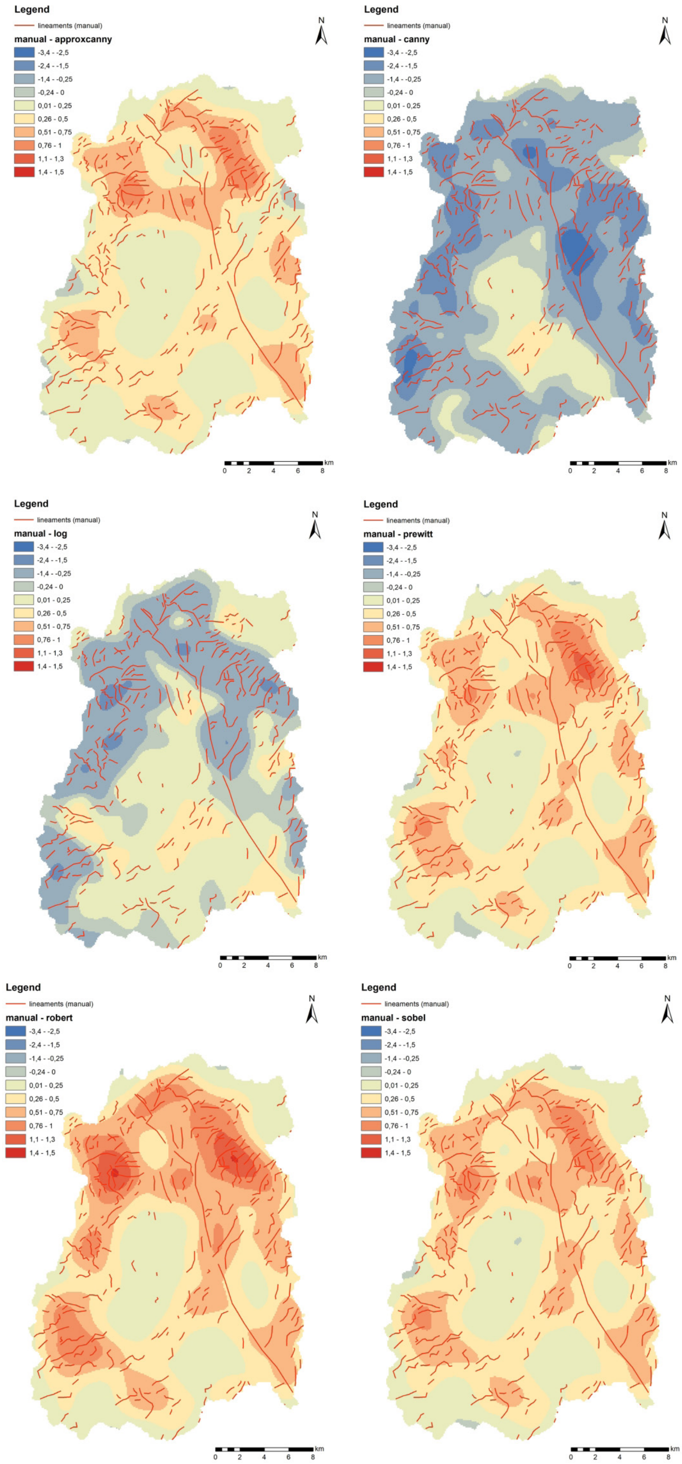

Fig. 5. Differences in lineament density between the MATLAB generated and manual methods (top left: Approxcanny, top right: Canny, bottom left: LoG, bottom right: Prewitt)

Table 3. Correlation matrix of the lineament density maps

Method	Manual	Robert	Sobel	Prewitt	Approxcanny	Canny	Log
Manual	1.0000	0.6450	0.7893	0.7516	0.7361	0.6747	0.8561
Robert	0.6450	1.0000	0.9047	0.8883	0.8389	0.5389	0.7985
Sobel	0.7893	0.9047	1.0000	0.9779	0.9035	0.6413	0.8819
Prewitt	0.7516	0.8883	0.9779	1.0000	0.9030	0.6526	0.8662
Approxcanny	0.7361	0.8389	0.9035	0.9030	1.0000	0.7402	0.8807
Canny	0.6747	0.5389	0.6413	0.6526	0.7402	1.0000	0.7904
LoG	0.8561	0.7985	0.8819	0.8662	0.8807	0.7904	1.0000

When visually analysing the difference maps, it is evident that the Canny and LoG (algorithms generally show negative spatial differences. This confirms that these algorithms tend to detect more lineaments compared to the manual method. In contrast, the other four methods display positive spatial differences, indicating that they tend to identify fewer lineaments than the manual method.

The Table 3. is a correlation matrix for the lineament density maps obtained using different methods. The manual method was the reference method for measuring the correlation. Analysing the table, it can be stated that the manual method shows high correlation with LoG (0.8561), indicating a strong similarity between these methods, suggesting that LoG is a reliable alternative to manual mapping. There are only moderate correlations with Sobel (0.7893), Prewitt (0.7516), and Approxcanny (0.7361), and lower correlations with Robert (0.6450) and Canny (0.6747).

Methods like Sobel and Prewitt exhibit the highest degree of correlation, since they produce very similar lineament density maps, these methods are almost interchangeable. Robert and Canny have the least correlation with each other (0.5389), highlighting a significant difference in the density maps produced by these two methods.

4. Conclusions

The correlation analysis of lineament density maps obtained through various edge detection methods reveals several insights and allows us to categorize the methods based on their similarity to manual interpretations.

The LoG edge detection method exhibits the highest correlation with the manual method, with a correlation coefficient of 0.8561. This high correlation suggests that the LoG method produces results most similar to manual lineament detection. Similarly, the Sobel (0.7893) and Prewitt (0.7516) methods also show strong correlations with the manual method, indicating their reliability in approximating manual interpretations.

Methods such as Approxcanny (0.7361) and Robert (0.645) demonstrate moderate correlations with the manual method. Although they are somewhat close to the manual results, they exhibit more variations compared to the higher correlated methods. The Canny method, with a correlation of 0.6747, shows the lowest similarity to the manual method among the studied techniques.

It is important to highlight that manual lineament mapping is inherently subjective, relying heavily on the expertise and judgment of the specialist. This subjectivity must be acknowledged in any comparison or interpretation of lineament maps.

Automated methods offer consistency and reproducibility, which are significant advantages over manual methods. Combining automated and manual approaches can enhance the robustness of geological interpretations, leveraging the strengths of both consistency and expert judgment.

The results of density mapping suggest the location of areas with higher groundwater potential. However, these findings should be further analysed by incorporating additional field-based geological data, such as hydrogeological surveys, soil permeability assessments, and subsurface geophysical studies. This will provide a more comprehensive understanding of the aquifer systems and ensure accurate identification of high-potential groundwater zones.

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