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Application of Remote Sensing in the Hydrotectonic Analysis of Groundwaters, West of Yazd, Central Iran

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Abstract

The faults and fractures play crucial roles in conducting groundwater flow and providing high recharge zones for aquifers. The hard rock formations are exposed on the ground surface of the west of Yazd Province in Iran and build a reliable groundwater source for consumption. This study aims to provide a hydro-tectonic conceptual model of the region using remote sensing techniques and GIS. The geological map, groundwater resource data, geophysical reports, hydrogeological reports, and Landsat ETM satellite images are collected and evaluated by field visits. The lineaments densities of the area have been extracted and projected on various maps. The results demonstrate that the likelihood of groundwater flow is correlated positively with the region's main geological structures and groundwater resource availability. Finally, to conclude, the hydrotectonics model of the area consists of several distinctive and non-distinctive aquifers because of the presence of hydrogeological and tectonic barriers, water-conducting passages, and even neutral fractures.

***Keywords**:* Faults, Groundwater Hydrotectonics, Lineaments, Remote Sensing, Yazd.

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1. Introduction

Groundwater is used for a variety of purposes due to its easy accessibility and low cost. Groundwater levels are declining due to over-pumping. The low recharge rate compared to the high groundwater discharge rate and the extraordinary volume of groundwater consumption has caused the groundwater to fail to compensate for the loss through recharge aquifer. This condition is found in almost all aquifers in Yazd province. Lineaments are frequently surface fractures that affect groundwater recharge. According to (Das, Pal, Malik, & Chakrabortty, 2019), Lineaments such as joints and fractures contribute to the leakage of surface runoff into underground open spaces. Therefore, lineaments are a good potential for groundwater. Kumar, Gautam, and Kumar (2014) believe that lineaments have a good compromise with faults, fractures, joints, layering surfaces, and geological connectivity. And they are valuable for studying the potential of groundwater. In hard rock, the origin and movement of groundwater depend mainly on secondary porosity and permeability caused by faulting, folding and fracturing. The most visible structural element that is important in terms of groundwater is the lineaments (Nag, 2005).

Remote sensing data, which provides a synoptic representation of the large area, helps in understanding and mapping the lineaments both on the regional and local scale. Remote sensing has wonderfully become an extremely valuable tool in exploring, evaluating and managing groundwater resources because of the availability and coverage of spatial and spectral data from large, inaccessible areas in a short time. Remote sensing and GIS are useful tools for mapping groundwater resources and identifying suitable sites for artificial recharge (Jha, Chowdhury, Chowdary, & Peiffer, 2007). Naturally drilling and geophysical techniques are more useful methods for site selection in aquifers, but these are much more expensive and time-consuming. The practical use of remote sensing and GIS in groundwater management such as reliably identifying specific areas with considerable potential for artificial recharge or drilling wells have been reported in many published articles (Ghayoumian, Mohseni Saravi, Feiznia, Nouri, & Malekian, 2007; Kumar et al., 2014). Researchers in the field consider some thematic layers like geology, slope, soil, lineaments, rainfall, land use, and drainage. Numerous thematic layers are integrated into the GIS environment to identify the appropriate groundwater zone. Recent studies have indicated an acceptable correlation between lineament extracted from geological and DEM maps (Chabani, Mehl, Cojan, Alais, & Bruel, 2020). The mapping of linear structures can be performed in various ways. Methods of mapping linear structures include the use of topographic maps, DEM, geophysical information (airborne magnetometry), and radar information. More commons are the use of optical image information such as satellite images and aerial photos for mapping of Linear Structures. Quick Bird and Ikonos satellites with High-Resolution Satellite Imagery (less than 1 meter) are useful but much more expensive. For example, the price per square kilometer of Quick Bird images is about $20, which limits their use in water exploration projects (Sander, 2007). The most common Medium Resolution Satellite Images are Landsat, Spot, IRS, ASTER which are very low priced and have a resolution of 2.5 -30 meters.

By using the remote sensing image interpretation of the information about hydrogeological relevance to images is extracted that depict the terrain. Interpretation focuses in fact, on two interrelated aspects:

1. The hydrogeological subsurface configuration.
2. Surface features which influence recharges and show evidence of groundwater outflow (Meijerink, 1996).

The purpose of this study is to examine the interactions between structures (faults and fractures) and groundwater in the western aquifers of Yazd province that is called Hydrotectonic. The Hydrotectonic mostly is carried out by field work and transferring the field work measurements data onto the maps and interpreting the results. The aim and novelty of this study is to show that hydrotectonic can be done based on the remote sensing image interpretation that can save time and money. In this study, different remote sensing and GIS techniques have been used to investigate and highlight the role of fractures on groundwater in western aquifers of Yazd province.

2. Materials and Methods

2.1. Study area

The center of Iran consists of several closed basins that collectively are referred to as the Central Plateau. Yazd province is located in the margin of the central Iranian desert and about the middle of the central plateau of Iran (Figure 1). Yazd province has desert and semi-desert climate with hot and dry summers and cold and dry winters.

Shirkouh Mountain is the most important factor affecting climate in Yazd province, affecting its surrounding areas. This makes the winters cooler with more rainfall and milder summers as the mountains approach.

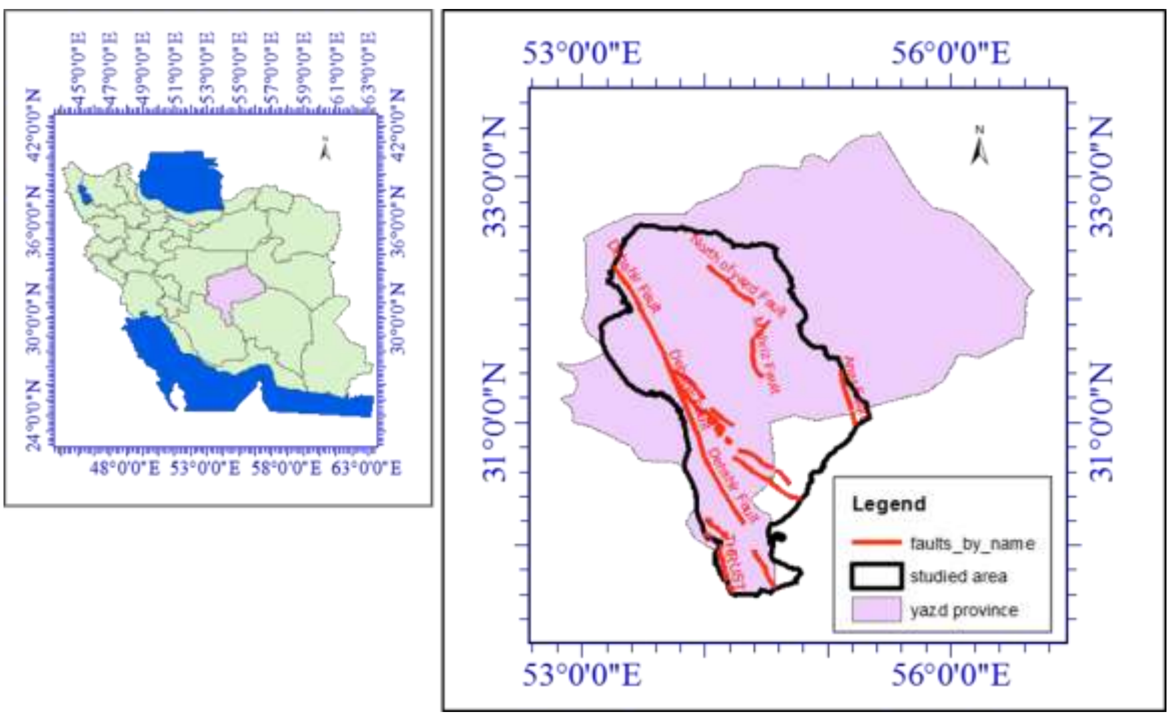


Figure 1. Location of the study area west of Yazd province with major faults in the area

2.2. Geological and Hydrogeological Settings

Yazd province is part of the tectonic zone of central Iran. The initial studies by geologists in the 1950s for the exploration of hydrocarbon materials by the National Iranian Oil Company (NIOC) in this area show that the area is highly faulted and folded. Much of central Iran is a unit that has been severely affected by faulting, thrusting and folding during the Alpine orogenic stages. Explosive volcanic eruptions, emplacement of plutonic intrusions, facies changes, changes in sediment thickness, and development of colored mélanges and ophiolite obduction have increased the complexity of this tectonic unit (Stöcklin, 1968). The study covers an approximate area of 37,000 square kilometres in the western part of Yazd province. The study area consists of Paleozoic rocks to Quaternary alluvial deposits (Figure 2). Alluviums are the most significant aquifer in terms of potential groundwater reserves in the study area. The Cretaceous limestones and intrusive igneous rocks (Shirkouh granite batholith) are also the most important hard formations with significant groundwater reserves.

These formations extend across the center and east of the study area (Figure 2b). The limestones of the Cretaceous (Taft Formation) a thick sequence of carbonate rocks is a dark gray-gray with the appearance of honeycomb and dissolution cavities. Orbitolina is the most important fossil, and occur in the matrix of micrite, and oosparite.

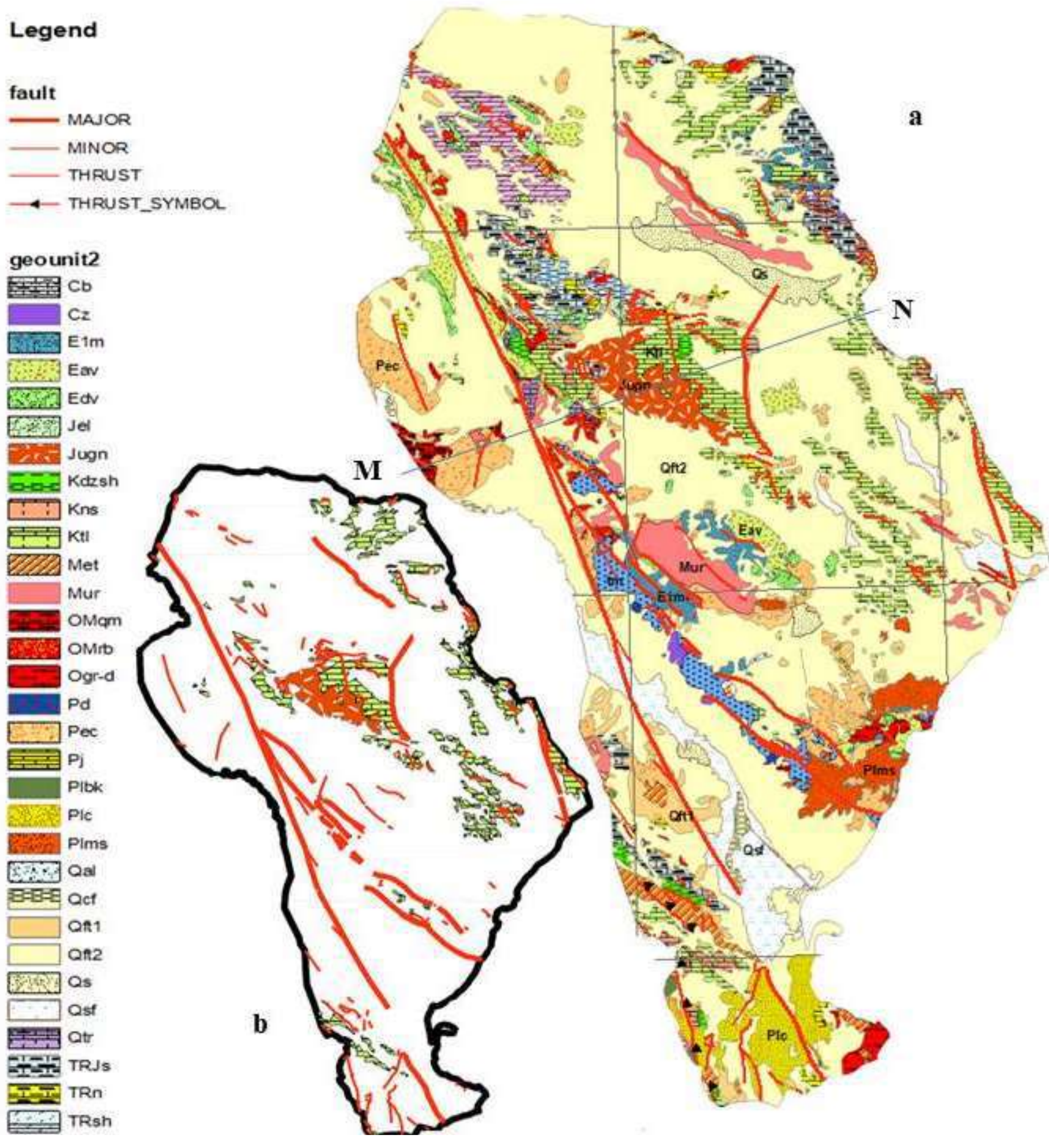


Figure 2. (a) Geological map of the region and location of major faults (b). Limestone and granite position in the study area, most of these formations are in the center of the region (Shirkouh Range). M-N shows the vertical cross-section of Figure 8b in the area

Shirkooh granite is located 40 km southwest of Yazd and is a coarse-grained granite that is characterized by abundant biotite and garnet. The radiometric age of the Shirkouh granite of Yazd has been determined as 176 ± 8 m.y. This batholith belongs to the Middle Jurassic and is the result of the Cimmerian orogeny (Aghanabati, 2004).

There are several faults in the study area, the most important of these faults are the Dehshir Fault, the Mehriz Fault, the North of Yazd Fault, and parts of the Anar Fault and ShahrBabak Fault. This area comprises some catchment areas.

2.3. Remote Sensing and GIS

A lineament is usually defined as a straight or somewhat-curved feature in an image. In a satellite image, lineaments can be the result of man-made structures such as transportation networks (roads, canals, etc.), or natural structures such as geological structures (faults/fractures, lithological boundaries, unconformities) or drainage networks (rivers).

A lineament is distinguishable by the change in image intensity as measured by gradient. By applying edge detection filters to the image, a numerical method for lineament detection can be constructed. This method, however, is not as accurate as the human visual system, which is highly efficient at extrapolating linear features. Thus, to the human eye, a lineament that varies in intensity along its length may be viewed as a single long lineament, whereas to a numerical method, the same lineament may appear as several short lineaments. Thus, a numerical method for extracting lineaments must be robust and allow for gradual or sudden changes in gradient along the lineament, and also for minor changes in direction.

Despite the existence of various satellite data and the development of modified algorithms in lineament analysis as well as lineament detection (Abrams et al., 2018; Bonetto et al., 2015; Masoud and Koike, 2017; Šilhavý et al., 2016; Yeomans et al., 2019), Automatic extraction of lineations from Landsat satellite imagery is also of interest to many researchers (Ferjani et al., 2020; Shiran et al., 2020) because of its cheapness and availability.

In this study, Landsat ETM Satellite Imagery (landsat7 2002) was processed in ENV 5, Arc GIS 10.2 and PCA Geomatica software. Initially, bands 1 to 8 of Landsat 7 satellite images were processed using ENV software. Images of bands 1 to 6 have a resolution of 30 meters. First, with Gram-Schmit spatial sharpening, these six bands were fitted with Data Fusion Algorithms on a panchromatic or Band 8 band with a resolution of 15 meters. After this process, the spatial resolution of all images was 15 meters. Then, using the Layer Stacking tool, all 7 bands were grouped into a single file. The final image is read in the PCA Geomatica software. In PCA Geomatica LINE or Lineament Extraction Module was performed, and the lineaments were extracted from the satellite image.

Lineament extraction extracts linear features from an image and records the polylines in a vector segment. The algorithm of Lineament extraction consists of three stages: edge detection, thresholding, and curve extraction.

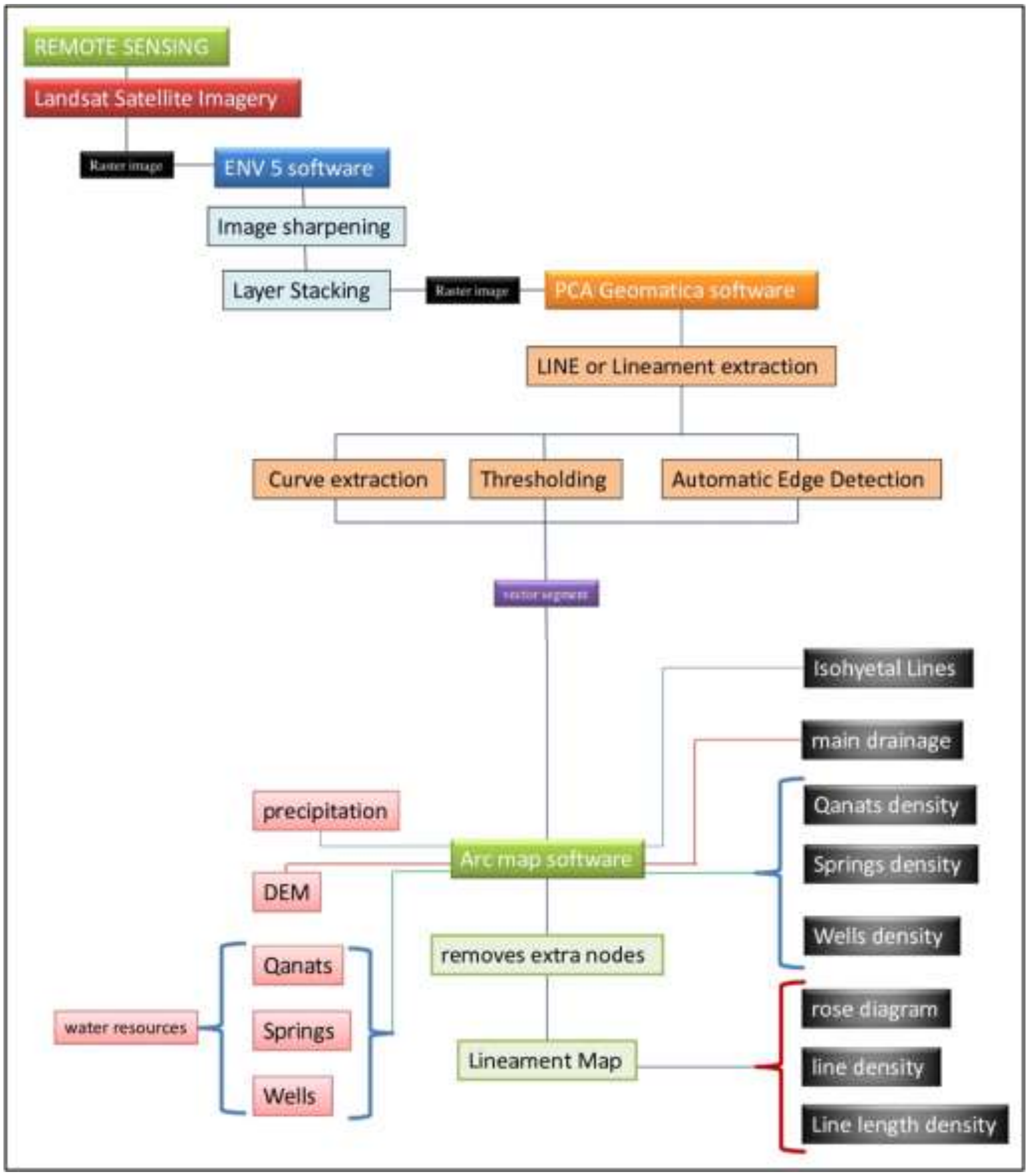


Figure 3. Detailed methodology flowchart of the proposed research

In the first stage, the Canny edge detection algorithm is applied to produce an edge strength image. In the second stage, the edge strength image is threshold to obtain a binary image. Each pixel of the binary image represents an edge element. The threshold value is defined by the Edge Gradient Threshold parameter. In the third stage, curves are extracted from the binary edge image. This step consists of several substep. The final polylines are saved in a vector segment.

The lineaments file was read in Arc map software. This software removes extra nodes on lineaments using the split line at the vertex tool. Finally, the lineaments in the area were extracted. Throughout the region, more than 80,000 lineaments were extracted from satellite images and analyzed. Additional extracts such as line densities and rose diagrams were performed in Arc map software (Figure 3).

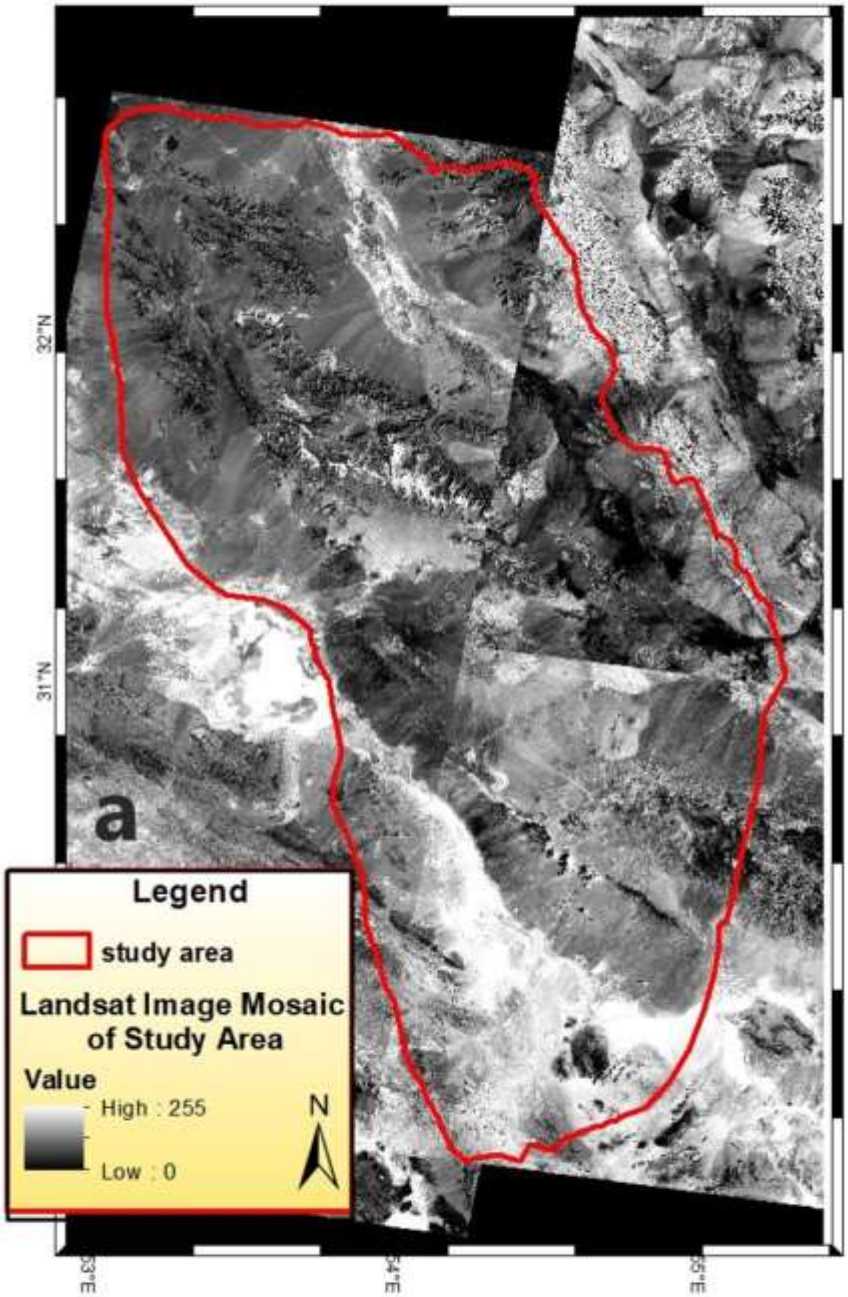
According to Sander (2007), in hydrogeological studies, some projects focus on image processing, some on geology and tectonics and some on geophysics, but it is best to consider all these aspects in hydrogeological studies. According to field mapping and geophysics, the average chance of success for drilling is 57 percent, while the odds of remote sensing success and GIS increase to 70 percent in the previous case.

3. Results

3.1. Lineaments

Lineaments are weak zones, usually acting as conduits for movement or accumulating groundwater beneath the surface lineament is a is an indirect evidence for geological structures such as faults and fractures(Anbarasu, Brindha, and Elango, 2019). (Abdullahi et al., 2013), believes that the mapping of linear features on various types of maps or remotely sensed data is one of the keys to understanding groundwater occurrence, especially in the hard rock area. The Lineaments such as joints, fractures, etc., generally developing due to tectonic forces, provide important surface clues and are responsible for infiltration of surface runoff into the sub-surface as well as for movement and storage of groundwater (Rao, Chakradhar, and Srinivas, 2001). The use of linear features extracted from remote sensing images, in addition to information about the Earth's surface, is also used to study the tectonic status of other planets in the solar system (Vaz, Di Achille, Barata, and Alves, 2012). Therefore, lineaments analysis of an area when extracted from remotely sensed data provide important information on subsurface features that may control movement and/or storage of groundwater.

Figure 4a shows the position of the mosaic images of the Landsat satellite of the study area. Figure 4b show the lineaments extracted from satellite images. Lineaments are abundant in all directions in the region. Rose diagram shows that lineaments have the most expansion in two directions perpendicular to each other. The largest extension of the Lineaments is to the northeast-southwest and the other is to the northwest-southeast, which is the main fault trend of the region, the Dehshir Fault as well as the extension of the Shirkouh Heights. According to Koch and Mather (1997), it is the orientation and length of the lineaments relative to the hydraulic gradient that is important rather than the density of the fracture network. Transverse fractures are usually more open than longitudinal fractures and therefore have an effective role in penetrating water into the karstic system (Charchi, 2015).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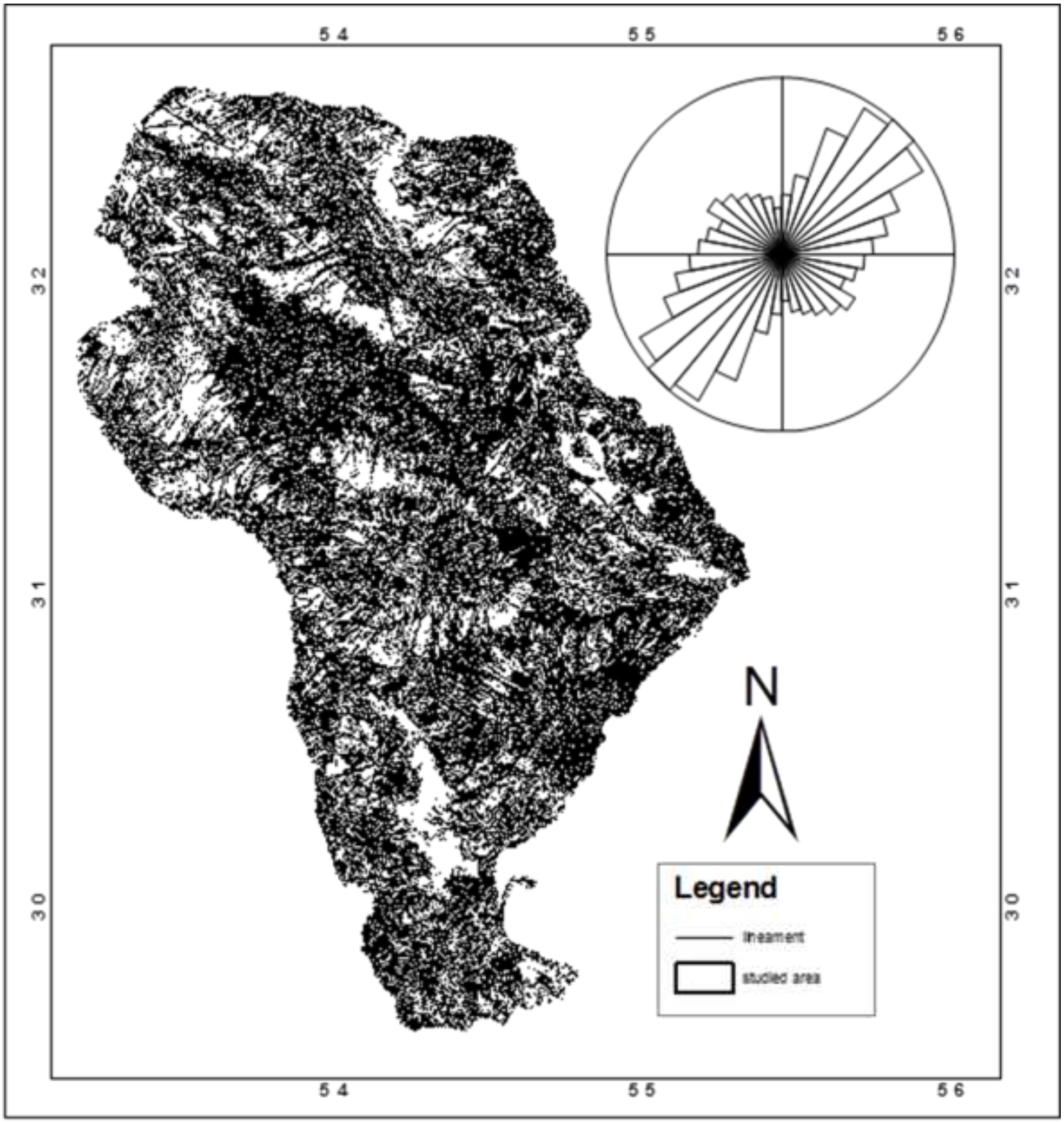

Figure 4. a Landsat image mosaic of the study area and **b** Lineaments extracted from satellite images throughout the study area. Rose diagram of the lineaments shows the main directions of the lineaments.

In hydrological studies, lineaments are the most useful output from satellite imagery. The lineaments demonstrate the weaknesses of the Earth's crust, such as fractures and faults that provide secondary porosity in hard rocks (Singh, Shashtri, and Singh, 2010), However, Different rocks respond to the same overall stress field with different fracture densities (Abdullahi et al., 2013).

Lineament-length density (Ld): This is the total length of the lineaments divided by their area and Lineament Frequency: (Lf) The number of lineaments per unit area, are parameters Used in lineaments analysis (Greenbaum and Directorate, 1985; Sander, 2007).

3.2. Lineament Density

At the center of the study area, the lineaments density map (Figure 5) typically shows good agreement with the distribution of granite formations (Shirkouh granite) and calcareous rocks (Taft Formation). These unique formations, which form the high mountains of Shirkouh in the center of the region, became the principal source of aquifer recharge. Major faults of the area, the Dehshir Fault, the North of Yazd Fault, and to some appreciable extent the Mehriz Fault have established the boundary between the areas of the high density of lineaments and moderate density of lineaments along much of their length (Figure 5).

The density of lineaments plays an important role in the occurrence and movement of groundwater. According to Jhariya, Kumar, Diwan, and Kishore (2016) intersection of lineaments typically creates suitable zones for groundwater recharge. Lineament's density also reveals the relative permeability of a zone, as in specific areas with high relative permeability there is usually a high density of lineaments (Ghazi Salar et al., 2018).

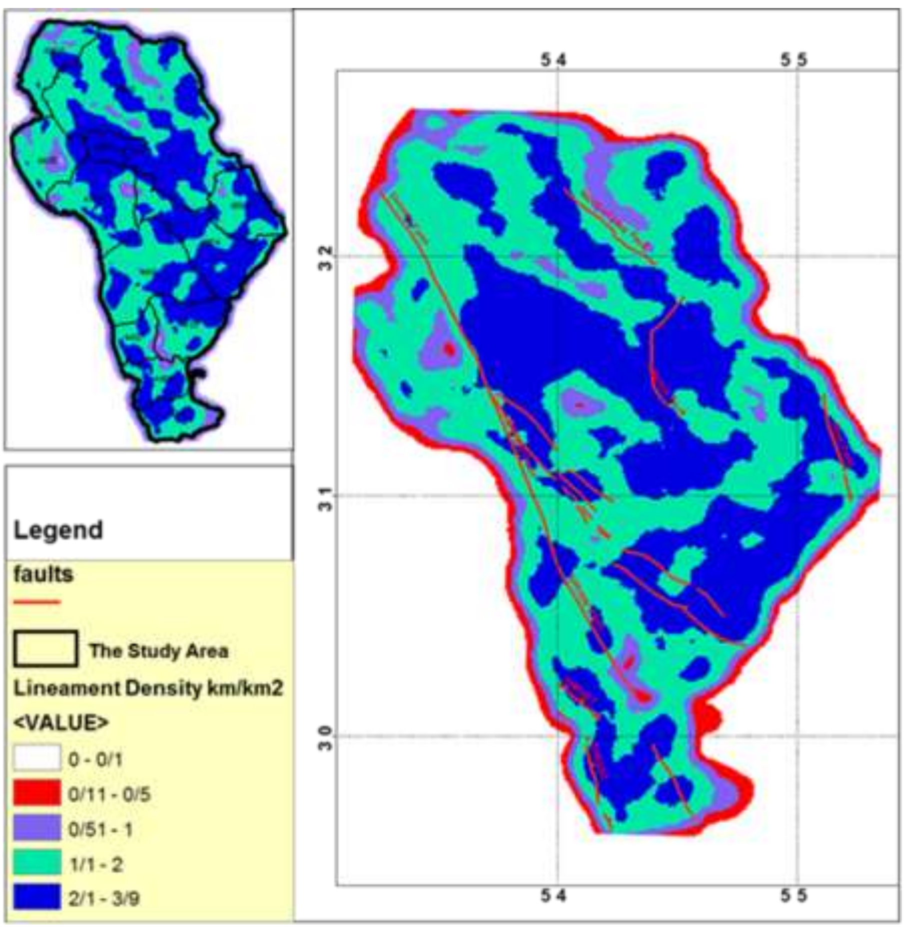

Figure 5. Frequency or density of lineaments in the study area is shown in different colors. The figure on the left shows the density of the lineaments and sub-basins in the study area and on the right shows the position of the major faults on the map of the lineaments density

Distribution of springs can be closely related to fractures. The springs are mainly found in hard rocks. Fracture density in hard formations and their relationship to springs distribution is presented in this paper as the "Hydrotectonic Map of springs" (Figure 5a). The overall interaction between the state of stress, fault structure, and fluid flow is described as hydrotectonics (Brehme et al., 2014).

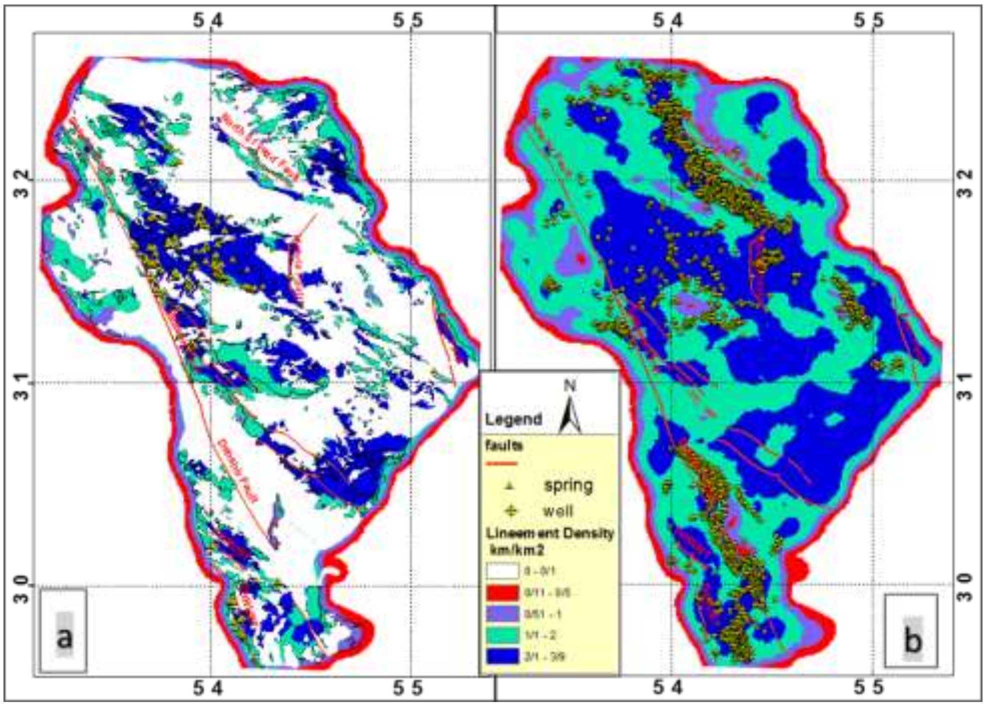

Figure 6. (a) Lineament density map and location of springs, and (b) Location of wells

In Figure 6 (a) Alluviums are displayed in white, and Lineament Density of Alluviums are not shown on the map. The springs of the study area are directly related to rainfall, geological formations (lithology) and structures (fractures and faults). Most springs are concentrated fiercely between the Dehshir Fault and the Mehriz Fault. This district (Shirkouh Mountains) with the highest rainfall within the study area (Figure 1) is considered essentially a vital vein of historical Yazd province. Lithologically the area is composed of local Cretaceous limestones (Taft Formation) and granites of Jurassic age (Shirkouh granite batholith). Limestone due to their karstic and permeable nature naturally produces the considerable potential to store and transport water. The surface of the granites is highly weathered. Therefore, at shallow depths, due to their large area, they can form small local aquifers of groundwater. In addition to rainfall and lithology, structures also play a significant role in the distribution and concentration of springs. According to Figure 6a, springs are located along major faults and are more abundant in areas with the highest fracture density. Such a relationship can equally be observed between the fractures and the distribution of the Qanats in the study area. However, because of the nature and construction status of the Qanats, many of them have been digging in the alluvium.

The wells also demonstrate a significant relationship with the structures in the study area. But their concentration has nothing to do with rainfall. The wells are mostly drilled in alluviums. The highest density of wells can be seen in areas where the density of lineaments is also high.

In addition to density, lineaments equally affect the discharge of wells. The yield of wells on lineament is about 14 times that of wells away from lineaments in the case of Warangal district in India

(Abdullahi et al., 2013). (Lattman and Parizek, 1964) also reported differences in the discharge of wells near fractures in hard rock up to 100 times. Additionally, the major faults in the study area control the distribution and density of the wells. As (Chitsazan and Dehghan Manshadi, 2021) reported that faults affect the groundwater flow, in the form of a barrier-conduit system.

In the north of the study area, distribution and density of wells are in good agreement with the fracture density, this coordination has been introduced as "Hydrotectonic of wells" (Figure 6b). Also, the North of Yazd Fault has acted as a hydraulic barrier so that the density of the wells is high in the west of the fault but in the east of the fault wells are very small and scattered. The linear distribution of wells along the Dehshir Fault also shows the effective role of this fault in the hydrogeology of the study area.

3.3. Line Length Density

Strike and dip of fractures can be effective as basic parameters in guiding water flow to the subsurface. To investigate the continuity of fractures, a map of the sum of fracture lengths per unit area was prepared using line extractions from satellite images (Figure ٧). As shown in Figure ٧ the line length density map in the study area has no particular order, and no significant relationship can be sufficiently established between the major faults in the region and map of the line length density. On top of that, the local distribution of springs was significantly uncorrelated with the line length density map.

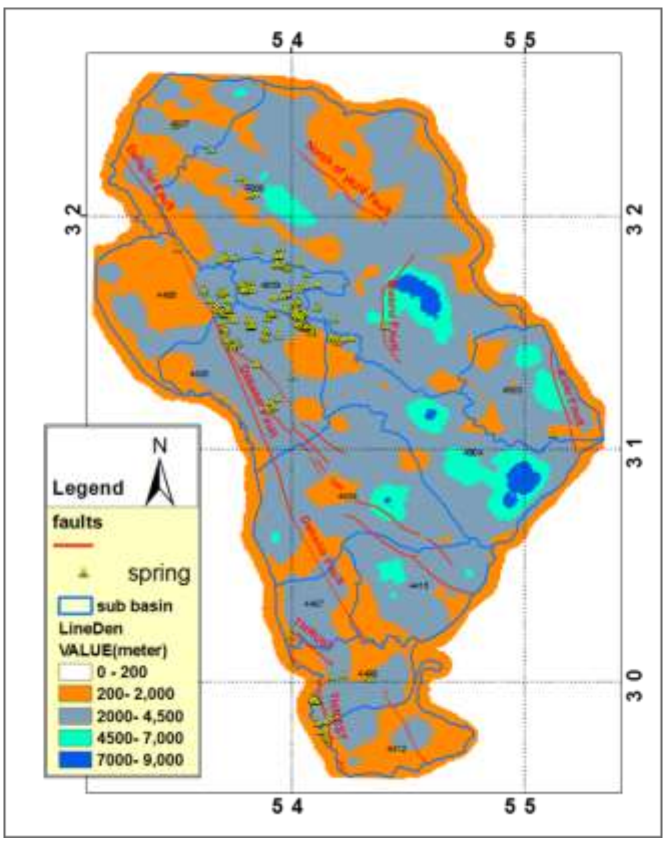

Figure 7. Lineament length density map of the study area

3.4. Hydrotectonic Model of the Study Area

The mechanisms of water and hydrocarbon reservoir formation and the impact of tectonics on their formation (hydrotectonics) have been discussed by various researchers around the world (Brehme et al., 2014; Brehme et al., 2015; Hu, Ngia, and Gao, 2019; Khalil and Santos, 2015; Khalil, Santos, and Farzamian, 2014; Solomon and Ghebreab, 2008).

Based on geological, tectonic and hydrogeological information of the region, the conceptual model of Hydrotectonic of the west of Yazd province was introduced as follows. The placement of the Shirkouh granite batholith occurred during the Middle Cimmerian Orogeny in the Middle Jurassic, which is considered one of the freshwater reservoirs in the region. The Taft Formation limestones were deposited in the Lower Cretaceous.

During the Alpine tectonic events, the Anar and Dehshir faults became active. During the Laramide orogenic extensional phase, Eocene volcanoes occurred east of the Fault. Other phases of the Alpine orogeny have affected the region, producing younger sedimentary and volcanic rocks in the area. During the Pasadenian orogeny, the present geomorphological landscape of the region was formed. Numerous fractures in the rocks during several orogenic phases as well as during the extensional phases created conditions for the formation of alluvial aquifers as well as hard rocks (mainly Late Cretaceous and Jurassic granite). The major faults of the region are the main aquifer boundaries and control how the groundwater resources are expanded (Figure 7).

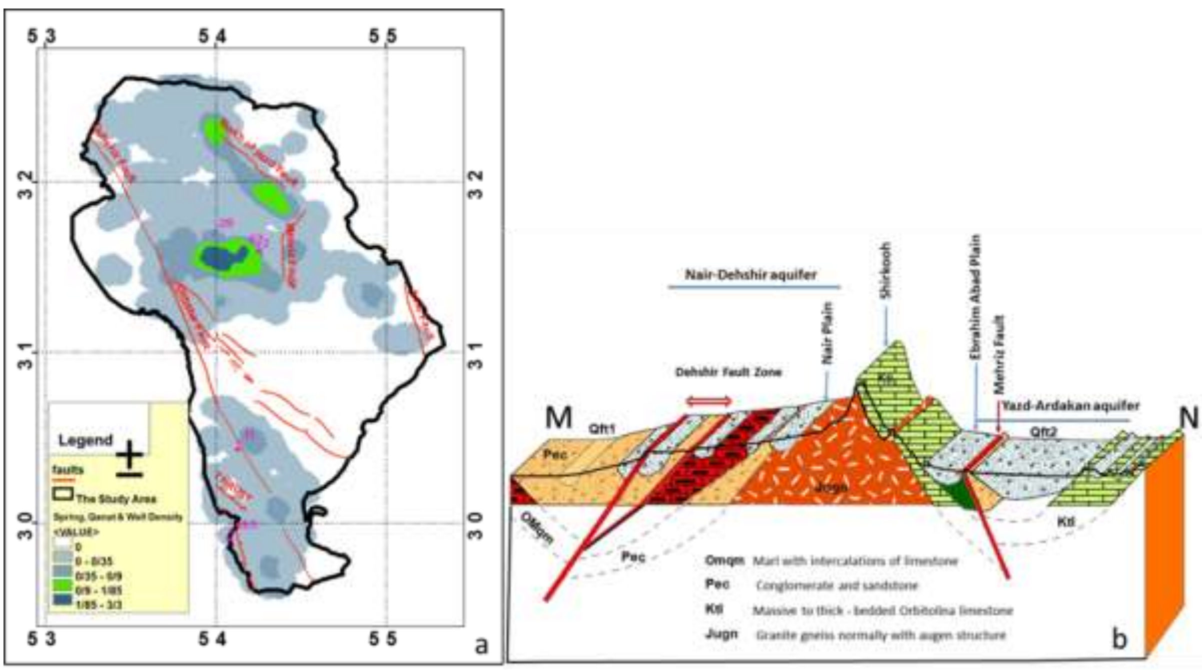

Figure 8. (a) Hydrotectonic map of the study area. (b) Cross-section of the geological map of the region (Figure 2) illustrates how faults powerfully affect the groundwater aquifers

The geological cross-section from the east to the west shows the Yazd-Ardakan (4808) and Dehshir (4405) aquifers, respectively. The Shirkouh Heights is the distinct region's highest mountains and the main hydraulic boundary of the two local aquifers.

On the west side is the Dehshir aquifer, which has the Nir and Dehshir aquifers. The Nir aquifer is elevated and is located on the foothills of the Shirkouh Highlands. Part of the Dehshir aquifer is located in the Dehshir Fault Zone. The distribution of water resources in the Dehshir aquifer depends on the operation of the Dehshir fault. Springs and aqueducts are concentrated on the eastern side and wells on the western side of the Dehshir Fault (Figure 7a). The absence of springs and Qanats in the western part of the Dehshir fault zone is due to the high uplifting rate that this fault has caused. The alluvial accumulation on the west side of the fault has formed a Good alluvial aquifer where the water is extracted by wells. The Dehshir Fault acts as a hydraulic, topographic and structural dam. Naturally, minor faults perpendicular to this fault as well as fractures (lineaments) play an important role in directing water to the Dehshir alluvial aquifer. The aquifer is located as a syncline on the western side of the Shirkouh Mountains.

Yazd-Ardakan aquifer is the largest aquifer of Yazd province, located on the eastern side of the Shirkuh Mountains. The major faults of Mehriz and North Yazd faults are in this aquifer. In the eastern western section of the diagram (Figure 7b), only the Mehriz fault is seen. This fault carries out a significant role in the formation of freshwater zones in the Yazd-Ardakan aquifer (Chitsazan and Dehghan Manshadi, 2021). The dispersion of Qanats and wells in the area is equally affected by faults.

4. Discussion

Artificial recharge is a key technology in the management of groundwater resources in arid and semi-arid regions (Ali et al., 2017). Lineaments, like joints and fractures, usually developed by tectonic forces, are responsible for the seepage of surface runoff into the ground. Of course, lineaments alone are irresponsible for groundwater development, and many factors are important in determining whether a particular area is good or bad for drilling a well or where it is suitable for recharge. As shown in the rainfall map of the study area, most of the precipitation occurs in the center of the region, namely the Shirkouh heights. Precipitation curves are 220 to 340 mm in this area.

There is also significant rainfall in the southwest of the study area (eastern part of the Zagros Mountains), with rainfall ranging from 160 to 280 mm. The floods are expected to be higher in these two locales than in other areas. Figure 9 shows the location of the main hydrometric stations and their annual runoff. In other areas, the hydrometric stations are not shown in the figure because they have little runoff and are not significant. Figure ١٠ shows the density map of groundwater resources (wells, springs, and Qanats) and waterways of the study area. Factors affecting the determination of artificial recharge are, geomorphology, land use, soil type, lineament density, drainage patterns and weathering rate (Saraf and Choudhury, 1998; Senthilkumar, Gnanasundar, and Arumugam, 2019).

Given the location of the hydrometric stations at the beginning of the main alluvial fans of the study area, these sites are admirably suited for artificial recharge in terms of geology, soil type, geomorphology, and slope. On the other hand, because of the lack of rainfall in the area, there are few places where significant amounts of surface runoff can be expected.

Due to the location of hydrometric stations, for the following reasons, natural surface flow paths in the study area are considered the most suitable position and most suitable recharge route for groundwater aquifers.

1. High water drainage is located upstream and at the groundwater recharge area.

2. The distance between the drainage outlet and the seasonal rivers to the water resource gathering point is a long one. On this preferred route, the line density is high. Due to the limited volume of possible floods in this arid region, surface water can easily penetrate natural pores and structural fractures.

3. Groundwater resources comply with the highest density of lineaments, it typically allows percolating floods into the ground to recharge water resources faster.

The Marvast hydrometric station, to the south-east of the study area, is the only measuring station a short distance from the specific location of groundwater resources. The local station passes an average of 11 million cubic meters of flowing water each year. At this site, if the water is released in natural drainage, part of it is discharged into the desert and out of reach. Several completed Recharge dams and flood basins have been designed and implemented at this specific location (Figure 9b). Continuous maintenance and dredging of this system are recommended to prevent runoff and flooding from evaporating.

Several flood spreading structures and artificial recharge systems has been built in others. But their performance is not thoroughly endorsed by the authors of this article. It is more excellent for these necessary structures to store the current water only at the peak of the floods, rather than storing the floods for a long time, and immediately after the floods have subsided sufficiently, release the waters in their normal course with regulated discharge. This prevents the evaporation of floods and maximizes recharge in groundwater aquifers.

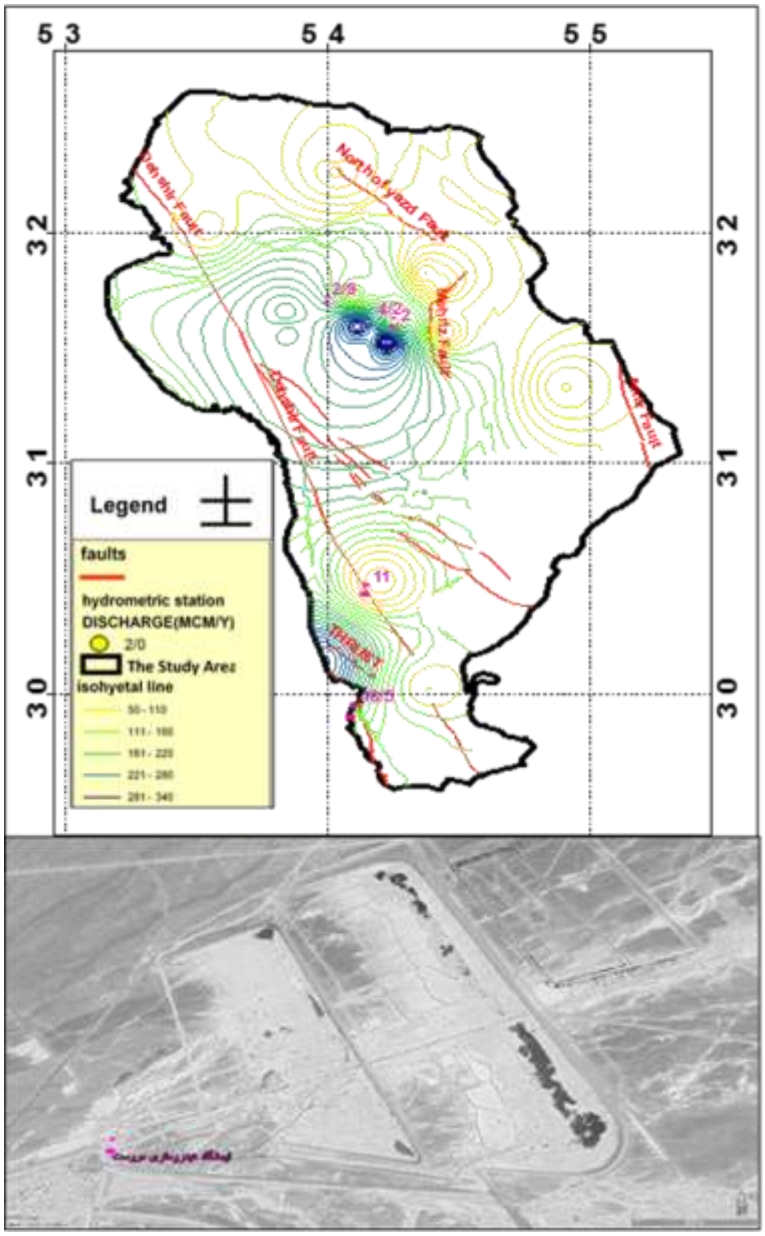

Figure 9. Position of Fault, Isohyetal Lines and Hydrometric Stations (a). The location of the Marvast hydrometric station and the position of its artificial recharge systems (b).

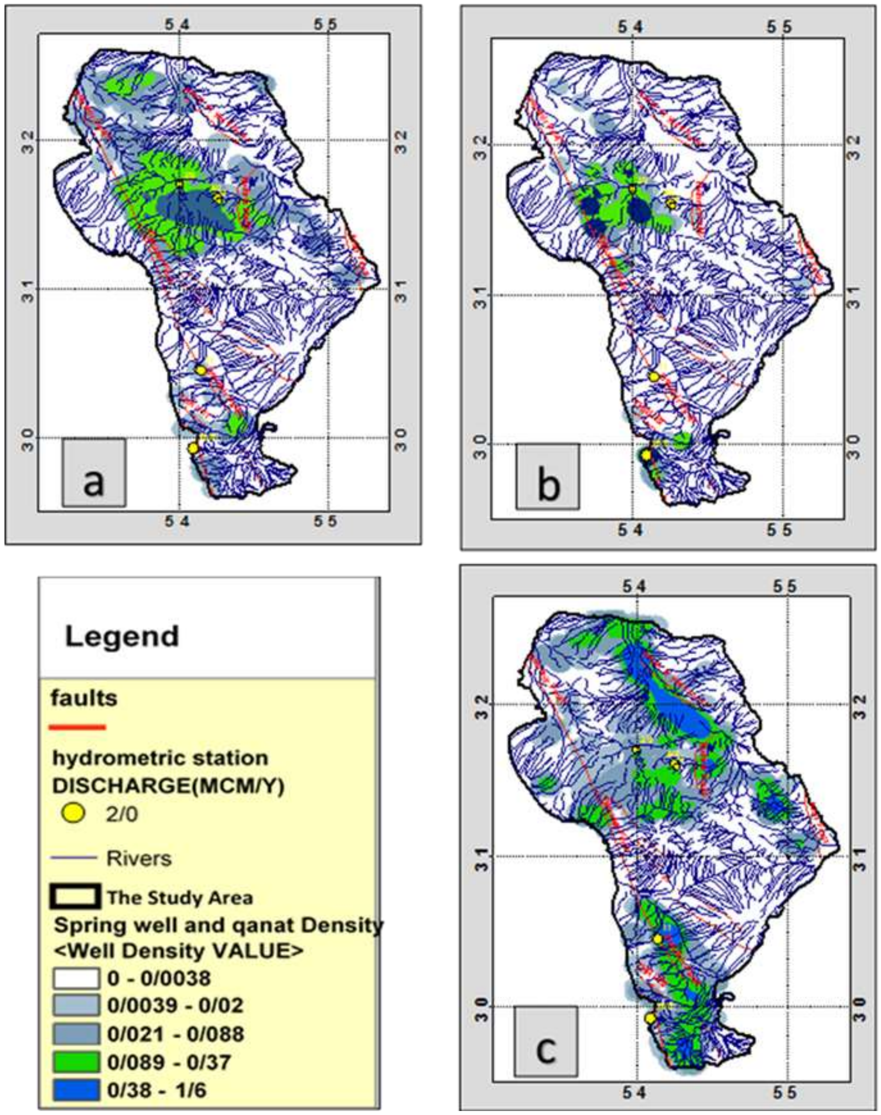

Figure 10. Fault, rivers (main drainage), hydrometric stations, and water resource density map. Qanats density (a) Springs density (b) and comparable Wells density (c)

4. Conclusion

The interaction of active faults as a factor affecting the west of Yazd province (Figure 1 and 2). Most of these faults are northwest-southeast. The faults affect the aquifers in the region as a barrier-conduit system.

The lineaments extracted from Landsat satellite imagery are mostly structural fractures that occur in two directions, one parallel to the main tectonic structures and faults of the region, and the other most perpendicular to these structures (Figure 4).

Various factors such as rainfall, lithology, topography, faults, and fractures influence the distribution and distribution of groundwater resources in the region. Due to the important role of structures (faults and fractures) on the distribution of groundwater resources, especially spring and wells, hydrotectonics in the area have received special attention.

The location and density of water resources in the region can be interpreted as a hydrotectonic model. Based on this model, the Dehshir and Mehriz faults serve as natural boundaries for the pattern of spreading of springs in the study area. Between these two faults, the density of springs is in good agreement with the density of lineaments. In the south of the region, however, Trust faults limit springs.

Wells can also be interpreted with the region's hydrotectonic model. The Great fault of Dehshir in many places it is the border of areas with high abundance and low abundance of wells. The density of the wells on both sides of the Mehriz fault is quite different. The North Yazd Fault acts as a hydraulic boundary and the number of wells on its north side is negligible (Figure 8).

The river's natural paths and drainage pattern are the best places to recharge aquifers. The Marvast River is an exception in this respect and requires artificial recharge systems for better groundwater aquifer recharge.

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