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Feasibility of Groundwater Resources in two Soft and Hard Formations of Shamil-Takht Watershed in Hormozgan Province in the South of Iran

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The current research aims to assess the feasibility of groundwater resources in two soft and hard formations of the Shamil-Takht basin using logic and operators Fuzzy and Boolean in the GIS environment. For this purpose, eight and seven thematic layers in the soft and the hard formations were investigated and analyzed separately. The layers were prepared in a raster format in the GIS environment and then each of the layers was classified according to the values of usefulness obtained with Fuzzy membership degree and 0 and 1 Boolean values. In the next step, AND and Gamma operators for Fuzzy layers and Algebraic Multiplication operators for Boolean logic were used in combining layers. The groundwater potential map of the studied area was obtained from the desired pixels resulting from performing the operations at the output. Based on this, in Fuzzy logic, 77.1% of the area of soft formation and 11% of the area of hard formation, and in Boolean logic, 24.1% of the area of soft formation and 1.74% of the area of hard formation had the possibility of water sources. Areas with high potential of groundwater resources were in areas with low slope and cultivated and areas with weak potential of water resources were in areas with alluvial and sedimentary formations. Also, the field investigations confirm that the emerging springs and existing wells in the Shamil-Takht basin are located in the areas with the lowest slope and high density of the waterway.

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1. Introduction

Groundwater is one of the most essential resources of nature that occurs in pore spaces and rock fractures and sediments under the surface of the earth. It also plays an important role in human well-being, ecological balance, and economic growth (IPCC, 2001). Groundwater consumption is more reliable and sweeter than surface water because it is more convenient and les s vulnerable to pollution (Manap *et al*., 2014).People in many parts of the world rely on groundwater for various purposes. It plays an essential role in the economic development of the world. However, this natural resource is hidden underground and unevenly distributed below the surface of the earth's crust. From this point of view, the assessment of the potential area of underground water is technologically challenging (Anteneh *et al*., 2022).

With the development of agriculture, electrification, and modernization of the pumping system, global groundwater withdrawal has increased from 312 km^3 per year in the 1960s to about 743 km^3 in 2000 (Wada *et al*., 2010). Exploitation of the subsurface area has increased since groundwater took over as the main source of irrigation in the 1980s and currently accounts for about 34% of the total annual water supply and an important freshwater reserve (Magesh *et al*., 2012).

Such uncontrolled consequences of human dependence on groundwater have led to the rapid degradation of the world's main aquifer system (Turner *et al*., 2019). The reasons are to be found in the fact that groundwater development is often done on demand with little attention to hydrogeological considerations. (Foster *et al*., 2006). To solve this problem, we need to know how much water there is underground and how much we can use for different purposes. Groundwater monitoring is very important when it comes to understanding the capacity and facilities of existing reservoirs (Worsa-Kozak *et al*., 2020). So that it has been accompanied by a sharp drop in resources in many areas. Therefore, the search to discover new sources has become more important than before. Identifying places with abundant groundwater is not an easy task (Singh *et al*., 2017). Many methods are used for groundwater exploration, including geological, geophysical, and remote sensing approaches. However, all traditional methods are very time-consuming and expensive to perform accurate groundwater assessment. Hydrological research combined with GIS-based modeling provides more accurate predictions of the groundwater area (Upwanshi *et al*., 2023).

As several researchers have reported the use of GIS techniques in the mapping of potential groundwater areas in the past in different parts of the world (Agbasi *et al*., 2019); (Martínez-Santos and Renard 2020); (Naghibi *et al*., 2017). Recent research has successfully identified potential groundwater areas using GIS and Fuzzy logic (Saravanan *et al*., 2020); (Çelik 2019); (Chaudhry *et al*., 2021); (Radulović *et al*. 2022); (Mallick *et al*., 2019); (Shailaja *et al*., 2019); (Ahmad *et al*., 2020); (Halder *et al*., 2020); (Singh *et al*., 2021) and remote sensing (Singha *et al*., 2021); (Murmu *et al*., 2019); (Ajibade *et al*., 2021); (Kumar *et al*., 2022); (Boughariou *et al*., 2021) has drawn. When these studies were evaluated, it was found that almost all of them used soil characteristics, land use, slope, geology, and lineament. In most studies, personal choices have been prioritized to determine subject matter and class weighting (Agarwal and Garg 2016). Then, the indicators of groundwater potential were weighted and classified based on expert opinion and AHP hierarchical analysis, and finally, maps of groundwater potential were produced for different geographical areas.

Groundwater potential maps maximize the chances of achieving appropriate returns for local communities. Additionally, groundwater potential maps may be used to better understand groundwater flow patterns and ecosystem dependencies, as well as to communicate information to planners and users (Díaz-Alcaide and Martínez-Santos 2019). A common assumption is that groundwater occurrence can sometimes be predicted from surface features. To identify the movement of groundwater through the soil, lineament, slope, geology, landforms, lithology, drainage density (Das 2019); (Díaz-Alcaide and Martínez-Santos 2019), rainfall pattern, faults, land use, and many other things (Mallic *et al.*, 2019); (Das 2019).

By reviewing the sources, we can see that finding the potential of underground water resources is one of the most important solutions for the optimal management of water resources. As remote sensing (RS) and geographic information systems (GIS) are powerful tools in investigating and finding the potential of underground water sources, in the present research, has tried to identify areas with the potential of groundwater in the Shamil-Takht area of Hormozgan province with the help of GIS software and using logic and Fuzzy and Boolean operators.

2. Materials and methods

2.1. Study area

The Shamil-Takht watershed is located in the south of Iran and in the east of Hormozgan province between longitudes 50° 20′ 38″ to 55° 57′ 49″ E and latitudes 27° 20′ 17″ to 27° 55′ 51″ N. The highest point in the northwest of the region is about 3233 m above sea level, and the lowest point with zero height is in the south of the region. The study area of Shamil-Takht is 2850.15 km^2, of which 1984.4 km^2 is hard formation and the rest 865.75 km^2 is soft formation (alluvial areas and plains). The climate of the considered basin is hot and desert. The annual temperature is estimated at 26.3 °C in the highlands and 28.4 °C in the plains. The average annual rainfall is 268.9 mm in the mountains and 217.3 mm in the plain, and the evaporation rate in the plain and the mountains is 3202 mm and 2820 mm, respectively. This watershed leads to the Shamil River from the north, the Jalabi River from the south, the Jamash River from the west, and the Zandan River crosses the watershed (Fig. 1 & 2).

2.2. Methodology

The general characteristics of the study area, such as the location of the region, geological characteristics, climatic characteristics of the region, the state of surface and underground water resources, and the state of alluvial and hard aquifers, through the reports and documents of the Hormozgan Regional Water Company, digital maps received from various organizations and also field visits. Became the desired and effective parameters in determining water sources were defined and each of them was converted into digitalized descriptive information and were classified, weighted, and combined as base maps based on Boolean and fuzzy mathematical logics in the GIS software environment. Finally, after analyzing the output maps, the existing situation was identified and located (Fig. 3 & Table. 1).

Since The desired watershed has a significant size and includes two parts of hard and soft formations, therefore, considering their different nature, different layers were considered for weighting and classification for the two formations, and accordingly, the Scores considered are also different. Thus, in the soft formation there are eight thematic layers including geological formation, soil classification, dissolved solid matter, slope, land use, electrical conductivity, hydraulic conductivity, and the thickness of the unsaturated layer (Fig. 4) and in the hard formation there are seven thematic layers including geological formation, soil classification, crack, slope, land use, electrical conductivity and hydraulic conductivity (Fig. 5) were integrated separately in the GIS software environment based on mathematical operators AND and Gamma in Fuzzy logic and Algebraic Multiplication operator in Boolean logic.

It should be noted that the presence of salt domes in the northern areas outside the basin and the Hormoz series formation in the central parts of the basin has led to high electrical conductivity and dissolved solid matter in this basin, on the other hand, no detailed geological studies were done in this area and in This research was limited to soil classification. Therefore, with the mentioned cases, electrical conductivity layers, dissolved solid matter, and classification of soil in soft and hard formation caused limitations. Therefore, to match the obtained results with what was observed in the field, the three mentioned layers were removed. Again, the remaining five layers in each formation were classified, weighted, and combined in the GIS software environment.

The classification of indicators and numerical ranges considered for the layers, based on the appropriate point of view for feasibility, expert opinions, and the use of previous sources in this field, has been done in the Arc map 10.5 software environment (Tables 2, 3, 4, 5).

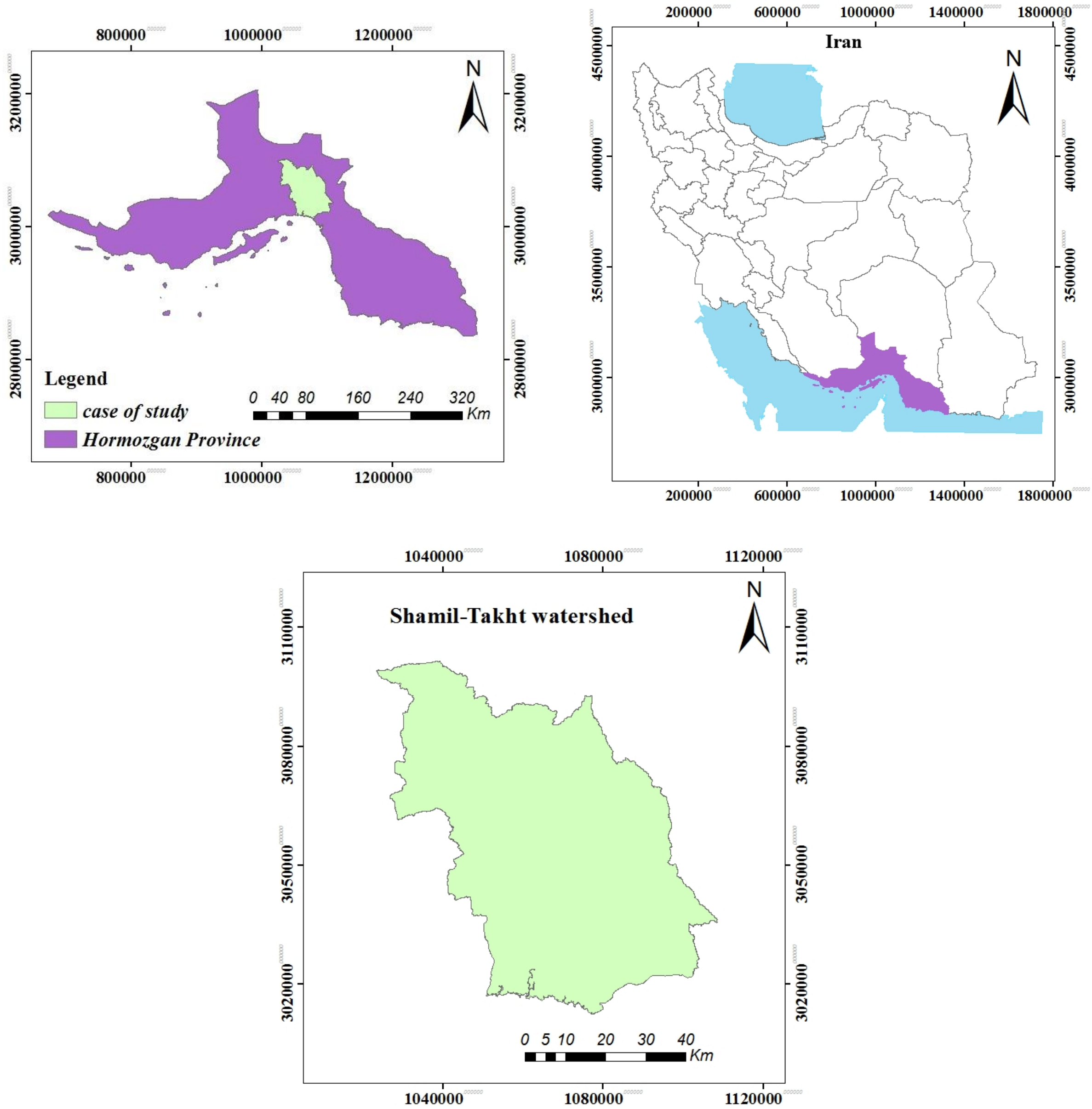


Fig. 1. Location of the studied area in the country and province

2.3. Fuzzy membership function (FMF)

Programming functions are also allowed to be used in a Fuzzy environment. A Fuzzy set is an object class defined through a membership function that assigns a membership value from 0 to 1 to each object and vice versa (Balezentiene *et al*., 2013). Place membership is intended for multiple classes. In this conceptual background, FMFs were dedicated to spatial variance analysis, and their pattern led to the development of Fuzzy boundaries for each potential region. FMFs were assigned variances and their trend resulted in Fuzzy boundaries for each potential developing region. The change from 0 to 1 can be determined by applying any form of FMF (Mallick *et al*., 2019). The Fuzzy logic method has been used to evaluate the interrelationship of the topographic features defining the groundwater table. Thematic layers determining the Shamil-Takht watershed were analyzed and the Fuzzy membership values were determined according to their impact on groundwater. The most important analytical step in Fuzzy logic is determining the criteria for identifying a groundwater potential zone. Each Thematic map was reclassified and assigned Fuzzy logic membership values. Values range from 0 (unlikely or unsuitable for groundwater potential) to 1 (very likely or suitable for groundwater potential). Higher Fuzzy membership values correspond to sites that are more suitable for groundwater potential and vice versa. All 'fuzzified' layers were overlaid using the 'Fuzzy overlay' tool in a GIS environment to help improve location selection for potential groundwater zones (Ahmad *et al*., 2020).

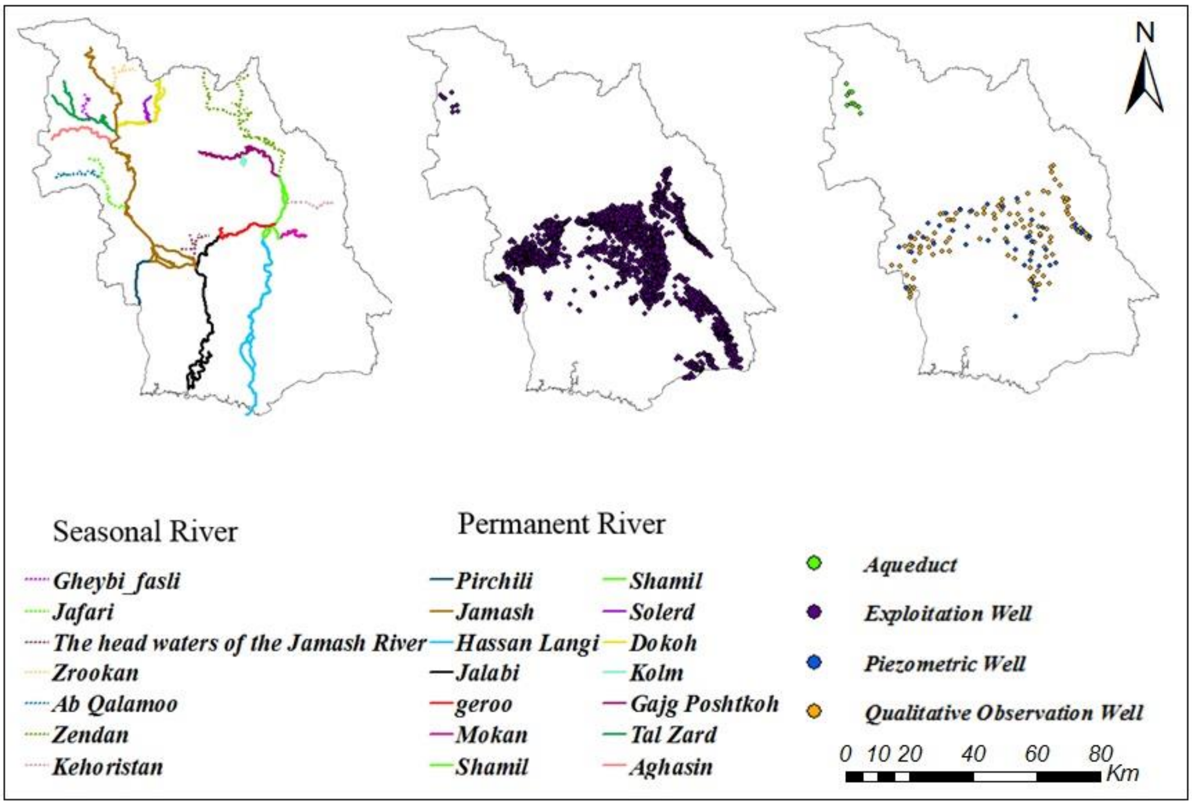


Fig. 2. Location of rivers, aqueducts, exploitation wells, piezometric wells and quality observation wells in Shamil Takht watershed

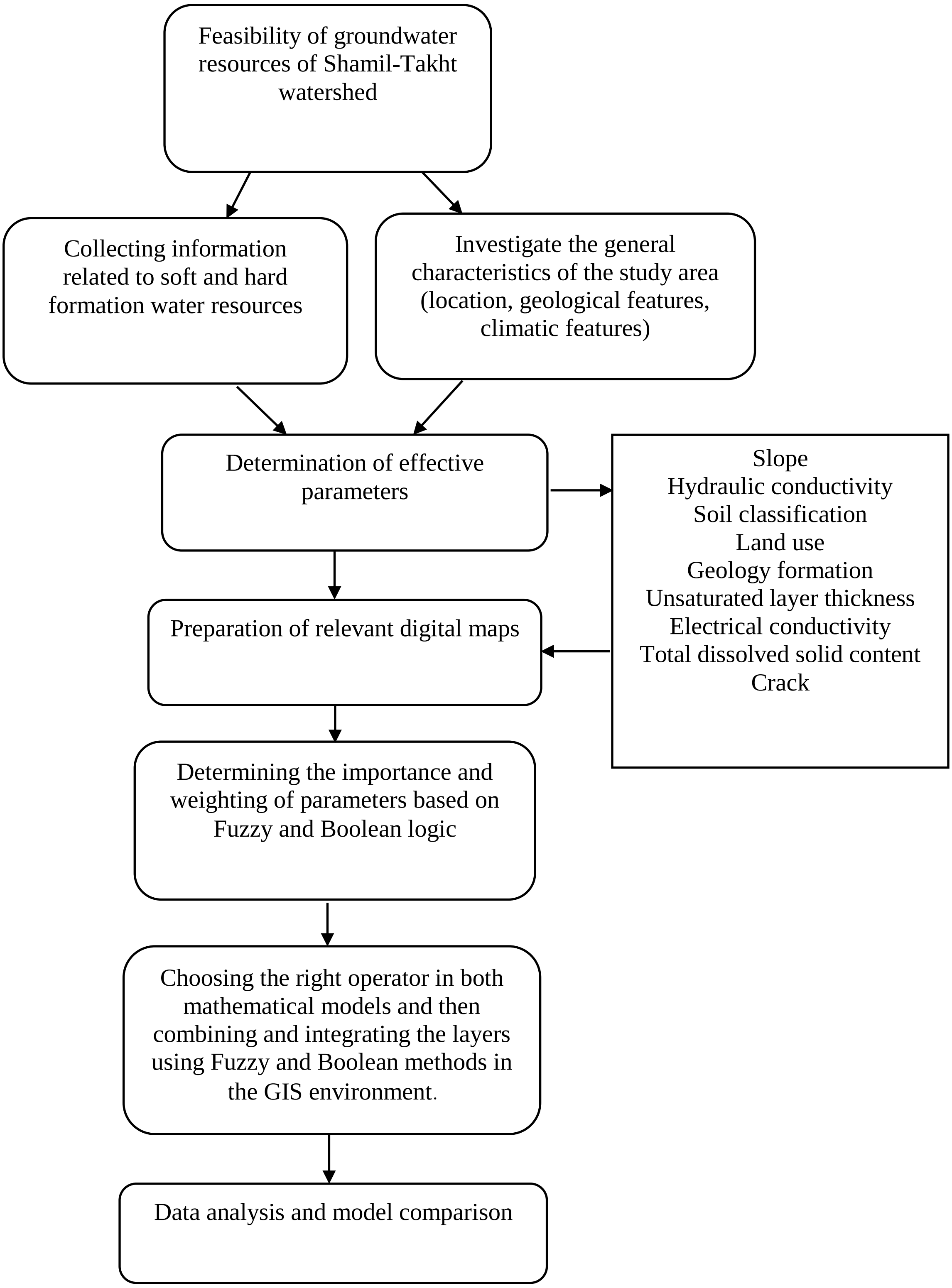
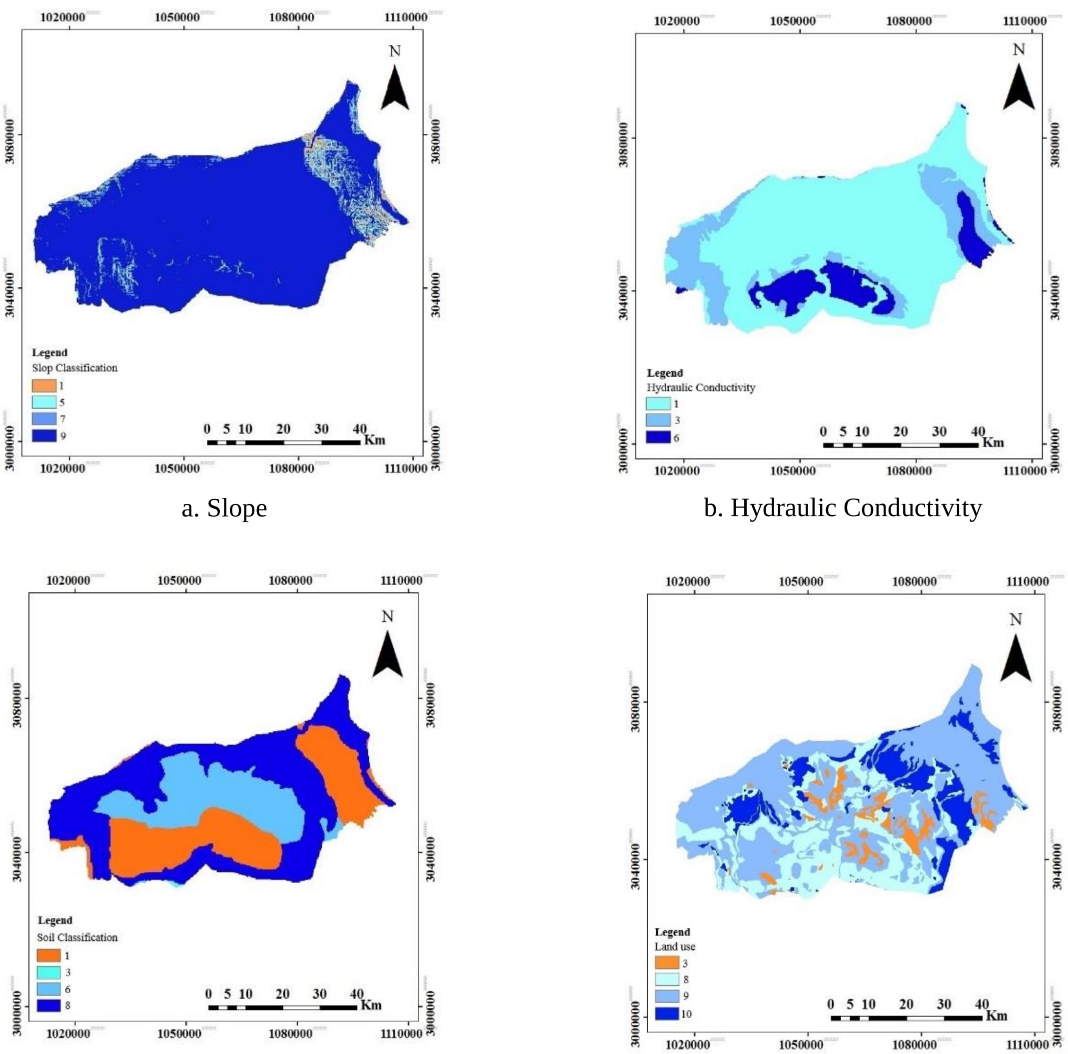


Fig. 3. The flowchart of adopted methodology

Table 1. Factors and resources used

Data	Source
Slope	DEM
Hydraulic conductivity	Pumping information of observation wells
Soil classification	Thematic studies in different parts of the watershed, sampling and measurement
land use	Google Earth Engine, Field visit, available information (preparation of map1:50000)
Geology formation	Geological maps 1:50000
Unsaturated layer thickness	Kriging interpolation on water surface depth data
Electrical conductivity	sampling and measurement, Kriging interpolation
Total dissolved solid content	sampling and measurement, Kriging interpolation
Crack	Geological maps 1:50000



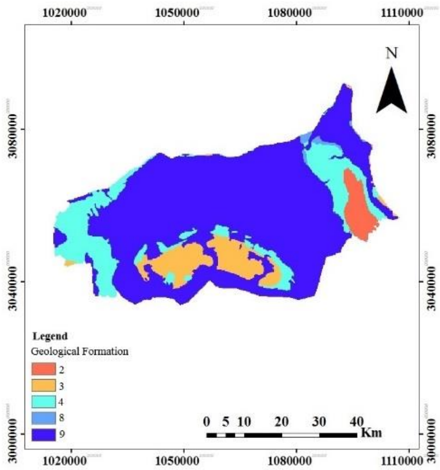
a. Slope

b. Hydraulic Conductivity

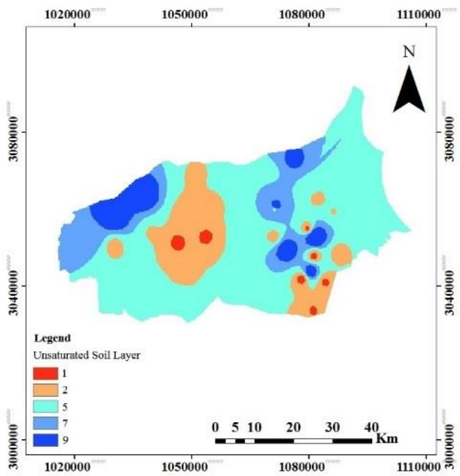
c. Soil Classification

d. Land Use

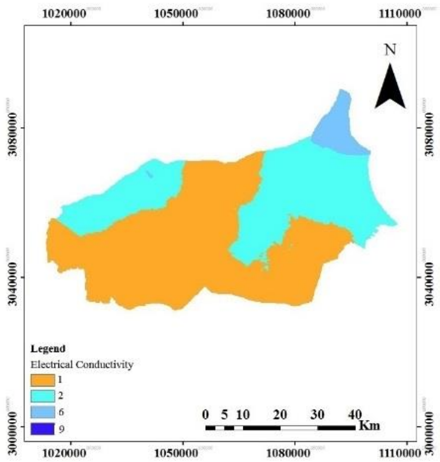
Fig. 4. Thematic layers used for the feasibility of water sources in the soft formation of the Shamil-Takht watershed



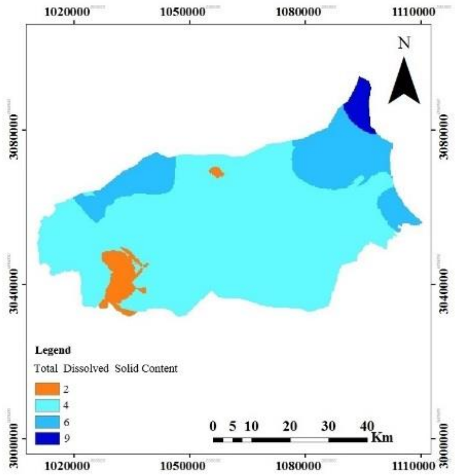
e. Geology formation



f. Unsaturated Layer Thickness

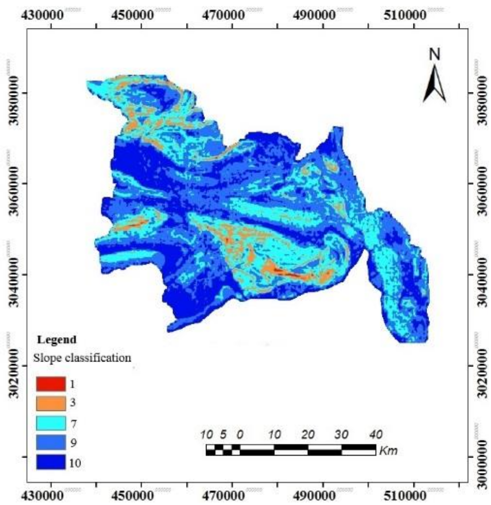


g. Electrical Conductivity

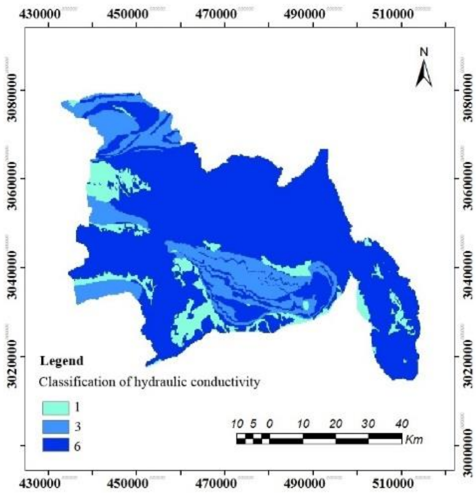


h. Total Dissolved Solid Content

Fig. 4. Continued

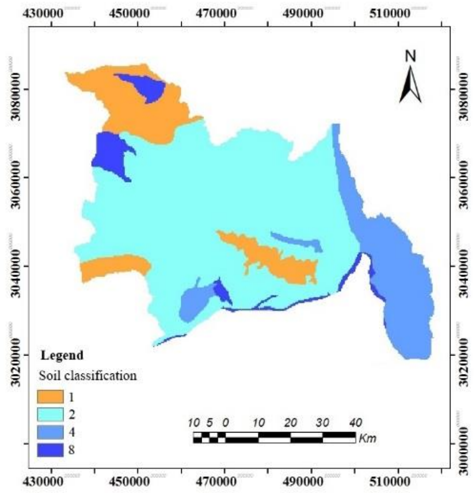


a. Slope

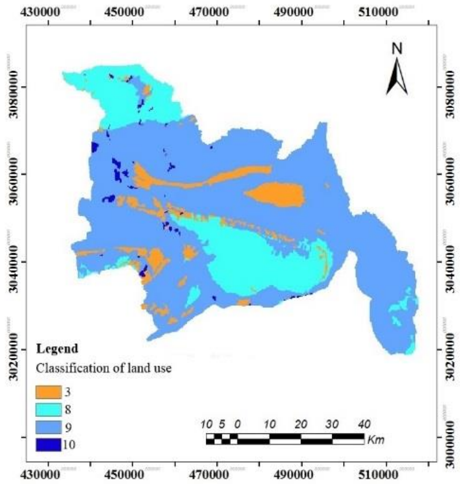


b. Hydraulic Conductivity

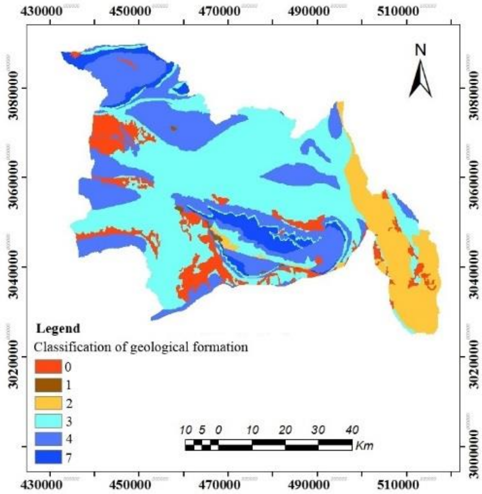
Fig. 5. Thematic layers used for the feasibility of water resources in the hard formation of the Shamil-Takht watershed



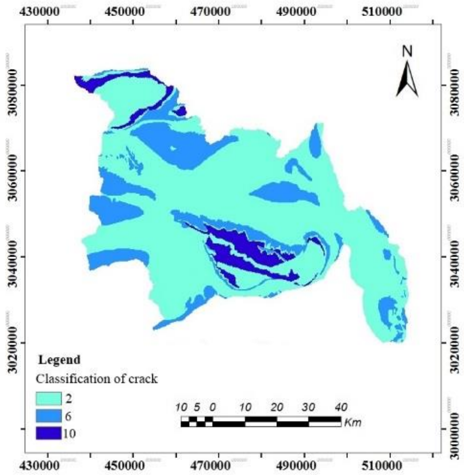
c. Soil Classification



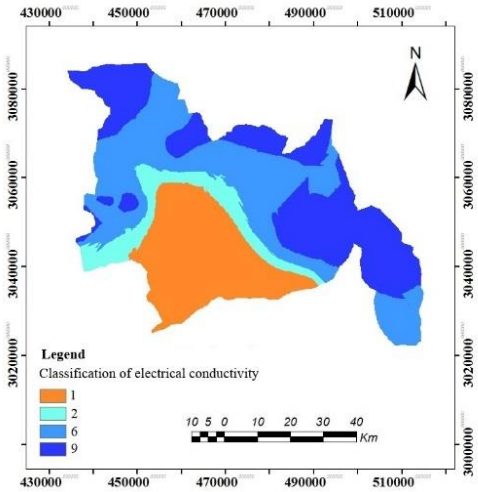
d. Land Use



e. Geology formation



f. Crack



g. Total Dissolved Solid Content

Fig. 5. Continued

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2.4. Delineation of potential groundwater zones using Boolean logic

The Boolean logic approach is the most basic type of GIS model for integrating thematic layers using a binary code classification system. Each pixel from different subject layers was considered zero for inappropriate locations and one pixel for appropriate locations. Boolean logic consists of its Boolean AND and Boolean OR operators, which work with two or more sets of data. Thematic layers and their subclasses were assigned based on their importance when delineating groundwater potential zones, with appropriate thresholds of 0 and 1 (Ponnusamy *et al*., 2022).

3. Results

The results of the classification and weighting of each of the thematic layers based on Fuzzy and Boolean logic in soft and hard formations are shown in Figures 6, 7, 8 and 9. The layers of different parameters in soft and hard formations were classified into four categories: very suitable, suitable, moderate, and unsuitable according to the statistics and information given in tables 2 and 4 based on the Fuzzy scoring logic and finally the groundwater potential map. Based on the statistics and information given in Tables 3 and 5, the layers of different parameters are scored as zero and one (Boolean logic). As a result of this scoring, there will be only two classes suitable and unsuitable.

The results obtained from combining thematic layers in soft and hard formation, which were weighted, classified, and combined in a Fuzzy way, are given in Tables 6 and 7 and Figure 10. The obtained results showed that in terms of the possibility of groundwater resources, about 51.6% (445.81 Km^2) of the total area of soft formation is very suitable, 25.5% (220 Km^2) is suitable, 6.8% (58.41 Km^2) is moderate and 16.2% (140 Km^2) is unsuitable (Table 6). Based on this, 0.2% (3.29 Km^2) of the hard formation area was found to be very suitable, 10.8% (213.49 Km^2) suitable, 1.9% (38.53 Km^2) moderate and 87.1% (1728.89 Km^2) unsuitable (Table 7).

The results of combining thematic layers in soft and hard formations, which were Boolean weighted and classified and combined, are presented in Tables 8 and 9 and Figure 11. The results showed that in terms of the possibility of groundwater sources, 24.1% (207.28 Km^2) of the total area of the soft formation is suitable and 75.9% (653.76 Km^2) is unsuitable. Based on this, in hard formation, 1.7% (34.6 Km^2) was found suitable and 98.3% (1949.6 Km^2) unsuitable.

In the Fuzzy logic, the suitable areas in the soft formation, which indicated the existence of underground and surface water sources in the region, were obtained in parts of the southwest, the end of the Jamash River, the east of the basin near the Jamash River, and the south of the basin of the end of Jalabi. Suitable areas in the hard Formation, parts of the northwest located in the Tal Zard River from Jamash's headwaters, as well as the southeast, the end of the Zandan River (corresponding to the suitable areas resulting from Boolean logic), and moderate areas in terms of water resources in the north, west and in the form of It is scattered in the southeast of the basin (Fig. 12a).

In the Boolean logic, the suitable areas in the soft formation, which indicates the presence of underground and surface water resources in the region, are located in parts of the southwest, south, and southeast of the end of the Shamil River and the junction of Jalabi and Jamash. Also, there is a very small part in the southwest part at the end of the Jamash River. Suitable areas in the hard formation, which indicates the existence of groundwater sources in the region, are located in parts of the east of the basin located in the Zandan River (Fig. 12b).

Table 2. Classes weighting criteria and area with the Fuzzy method in soft formation

Index	Class	Area (Km^2)	Area (%)	Score
Slope (%)	0-2	12.8	1.5	9
	2-5	24.6	2.8	7
	5-8	51.8	6	5
	>8	776.2	89.7	1
Hydraulic conductivity (m/day)	1-8	614.4	71	1
	8-12	151.1	17.5	3
	12-19	99.7	11.5	6
Soil classification	Without soil or with very shallow to shallow gravelly soil in some slopes and valleys	400.9	46.3	1
	Very deep soil with medium to heavy texture and high salinity	33.2	3.8	3
	Very deep soil with medium to heavy texture and low salinity	340.5	39.4	6
	Shallow to semi-deep gravelly soil with light to medium texture	90.5	10.5	8
Land use	Stone outcrops - sandy areas - water bed - salty lands - residential areas	91.3	10.5	3
	Low density forest , hand-planted forest , grove and shrubland	228.1	26.4	8
	Low-density and semi-dense pasture, riverbed	420.1	48.5	9
	agriculture	126.1	14.6	10
Geology formation	Zandan formation, sandy silty flysch - Razak formation, marl, and sandstone - gypsum marls - Derpahn unit	29.5	3.4	2
	Aghajari formation, sandstone marl	74.7	8.6	3
	Bakhtiari Conglomerate	146.7	17	4
	Alluvial terraces, Jahrom Formation	6.1	0.7	8
	Alluviums of the present era	608.4	70.3	9
Unsaturated soil layer thickness (m)	0-20	9.6	1.1	1
	20-30	154.5	17.8	2
	30-40	126.7	14.6	7
	40-50	62.2	7.2	9
	>50			
Electrical conductivity (µmhos/cm)	0-1000	504.87	58.31	9
	1000-2250	322.78	37.28	6
	2250-4000	38.21	4.41	2
	>4000	0.01	0.001	1
Total dissolved solid content (mg/l)	500-1000	30.7	3.5	9
	1000-2000	661.3	74.4	6
	2000-4000	156.7	18.1	4
	4000-6000	17.3	2	2

Table 3. Classes weighting criteria and area with the Boolean method in soft formation

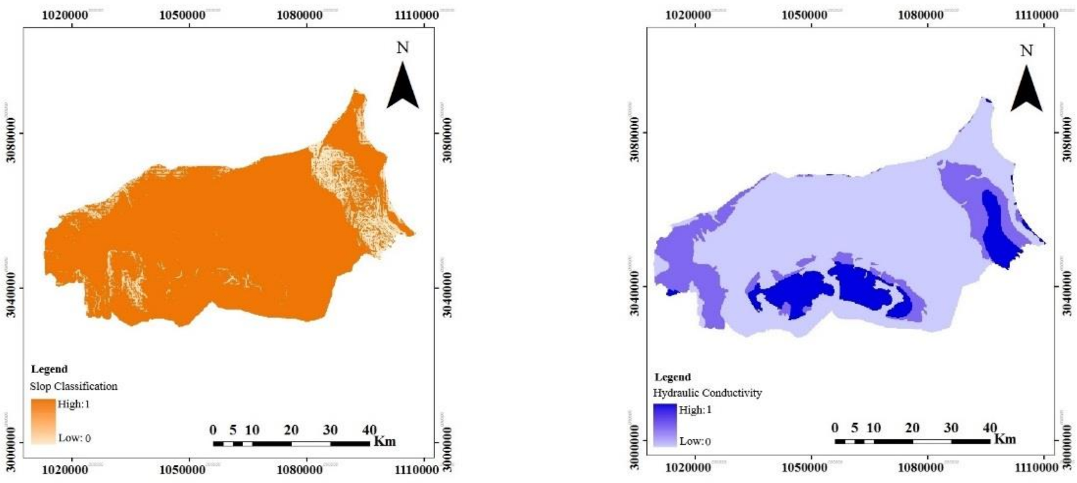
Index	class	Area (Km^2)	Area (%)	Score	Fitness class
Slope (%)	0-5	828	95.7	1	suitable
	>5	37.46	4.3	0	unsuitable
Hydraulic conductivity (m/day)	>10	250.79	29	1	suitable
	0-10	614.25	71	0	unsuitable
Soil Classification	Light to medium	449.51	52	1	suitable
	Medium to heavy	415.53	48	0	unsuitable
Land use	Forests, agricultural lands, pastures, man-planted forests, thickets, shrublands, and riverbeds	818.42	94.5	1	suitable
	Rocky outcrops and salty lands	47.33	5.5	0	unsuitable
Geology formation	Jahorm formation, Aghajari, sandstone marl, Bakhtiari conglomerate, Zandan formation, sandy silty flysch - Razak formation, marl, and sandstone, alluvium	864.26	99.91	1	suitable
	other	0.78	0.09	0	Unsuitable
Unsaturated layer thickness (m)	<20	807.36	93.3	1	suitable
	0-20	57.96	6.7	0	unsuitable
Electrical conductivity (μmhos/cm)	0-2000	16.86	1.9	1	suitable
	>2000	849.01	98.1	0	unsuitable
Total dissolved solid content (mg/l)	0-2000	173.95	20	1	suitable
	>2000	691.92	80	0	unsuitable

Table 4. Classes weighting criteria and area with the Fuzzy method in hard formation

Index	Class	Area (Km^2)	Area (%)	Score
Slope (%)	45-70	3.9	0.2	1
	30-45	138	7	3
	18-30	531	26.8	7
	8-18	840	42.3	9
	0-8	472	23.8	10
Hydraulic conductivity (m/day)	1-8	195.19	9.8	1
	8-12	35.37	18.7	3
	12-19	1430.12	72.1	6
Soil classification	No soil with too much salt and too much gypsum	293.24	14.8	1
	Often without soil or with very shallow soil in some slopes and valleys	1269	63.9	2
	No soil and very shallow to semi-deep and often gravelly soil	320.63	16.2	4
	Shallow to deep soil with light to medium texture	102.09	5.1	8
Land use	Stone outcrop	158.14	8	3
	low density Forest - semi-dense forest - thicket and shrubland	424.63	21.4	8
	Low density pasture, riverbed	1382.50	69.7	9
	agriculture	19.27	1	10
Geology formation	River alluvium	185.53	9.3	0
	Hormuz series	5.23	0.3	1
	Series of colored mixtures - old fan sediments - Niriz formations - Zandan formation	229.39	11.6	2
	Mishan Formation - Aghajari Formation - Setang Formation - Surme Formation	893.17	45	3
	Gouri, Pabde-Gori, Bangistan, Bakhtiari route	571.85	28.8	4
	Jahrom formation	99.46	5	7
Crack (%)	0-1	1416.89	71.4	2
	1-1.5	436.94	22	6
	1.5-3	130.4	6.6	10
Electrical conductivity (µmhos/cm)	>4000	499.92	25.2	1
	2250 – 4000	184.2	9.3	2
	1000 – 2250	680.24	34.3	6
	0 - 1000	620.11	31.2	9

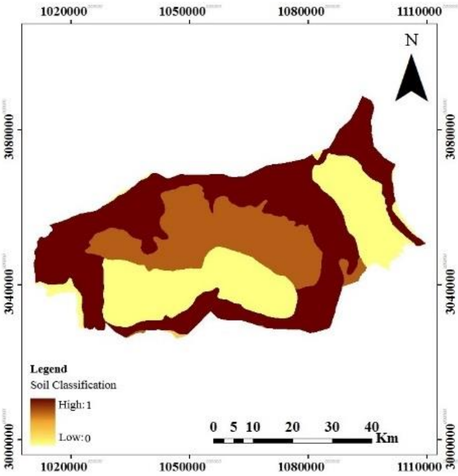
Table 5. Classes weighting criteria and area with the Boolean method in hard formation

Index	class	Area (Km^2)	Area (%)	Score	Fitness class
Slope (%)	0-18	683.6	34.4	1	suitable
	>18	1300.8	65.6	0	unsuitable
Hydraulic conductivity (m/day)	>10	680.25	34.3	1	suitable
	0-10	1304.6	65.7	0	unsuitable
Soil Classification	Light to medium	1272.58	67.13	1	suitable
	Medium to heavy	711.89	35.87	0	unsuitable
Land use	Forests, agricultural lands, pastures, man-planted forests, thickets, shrublands, and riverbeds	144.31	7/3	1	suitable
	Rocky outcrops and salty lands	1840.371	92.7	0	unsuitable
Geology formation	Jahrom Formation, Aghajari, Marl, Sandstone, Bakhtiari Conglomerate, Zandan Formation, flysch Silty Sand - Razak Formation, Marl, and Sandstone	784.5	39.5	1	suitable
	alluvium	1200.36	60.5	0	unsuitable
Crack (%)	>1.5	1328.4	66.9	1	suitable
	0-1.5	655.8	33.1	0	unsuitable
Electrical conductivity (µmhos/cm)	0-1800	1194.65	63.4	1	suitable
	>1800	690.231	36.6	0	unsuitable

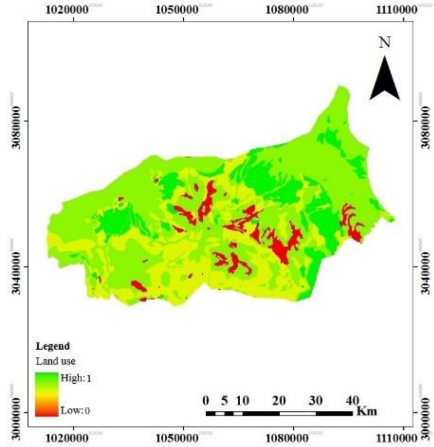


a. Slope b. Hydraulic Conductivity

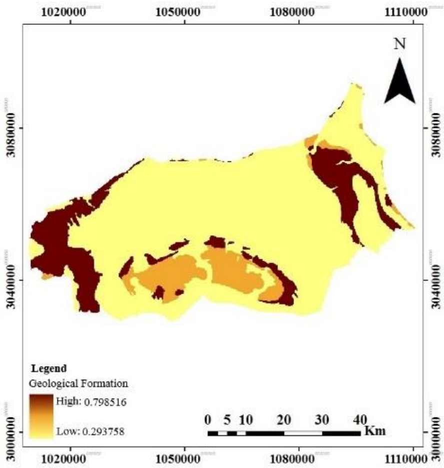
Fig. 6. Thematic layers classified by Fuzzy membership degree in the soft formation of the Shamil-Takht watershed



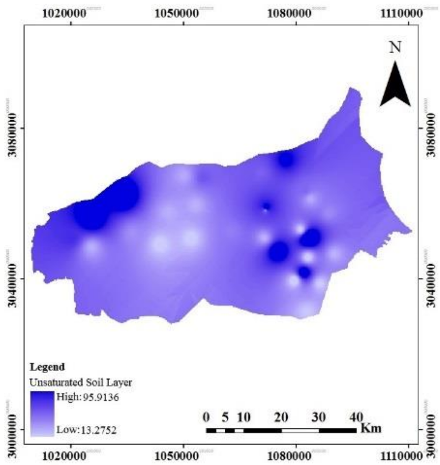
c. Soil Classification



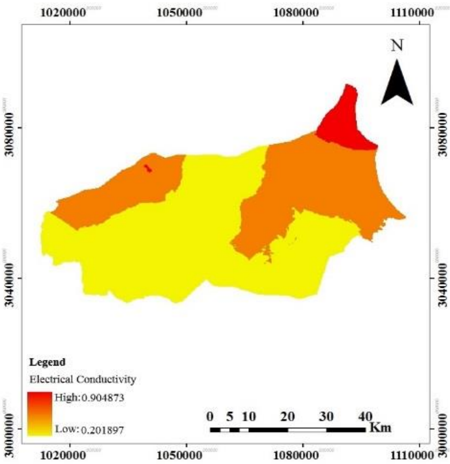
d. Land Use



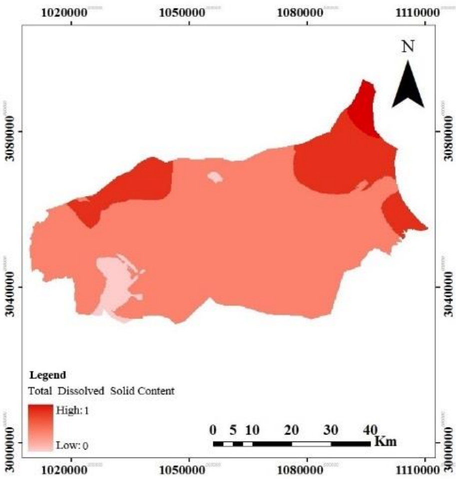
e. Geology formation



f. Unsaturated Layer Thickness

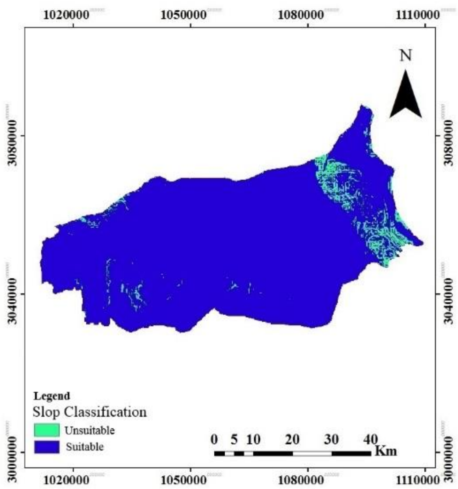


g. Electrical Conductivity

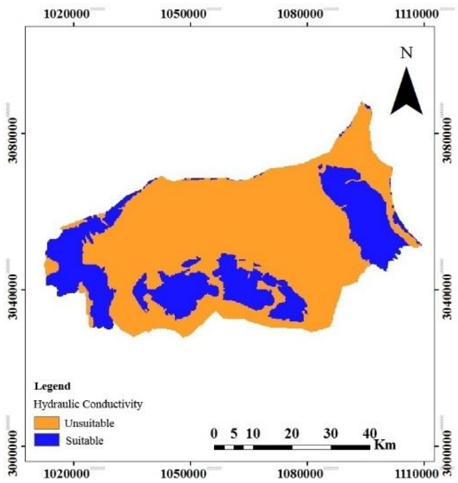


h. Total Dissolved Solid Content

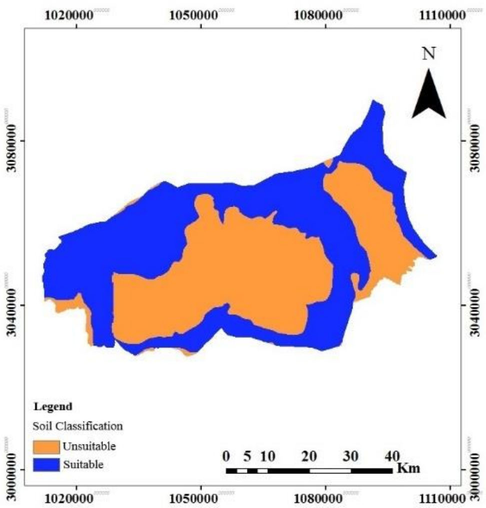
Fig. 6. Continued



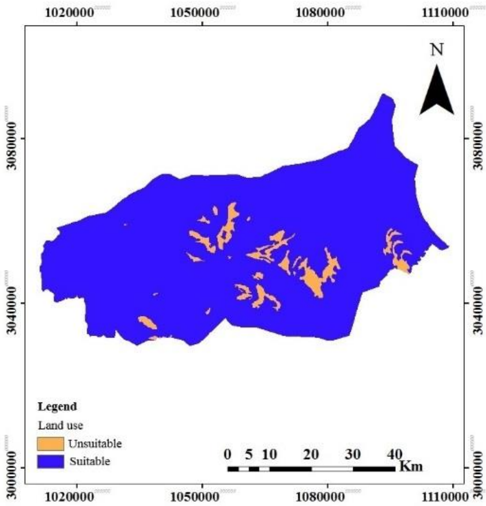
a. Slope



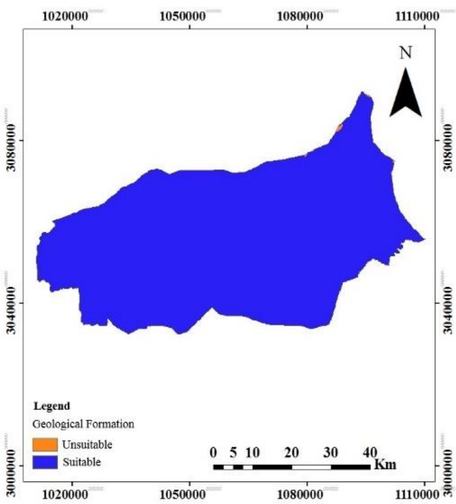
b. Hydraulic Conductivity



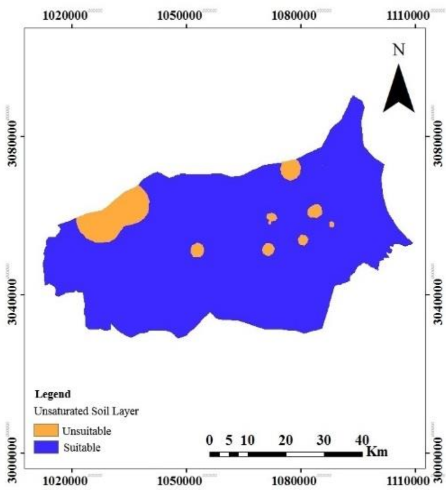
c. Soil Classification



d. Land Use



e. Geology formation



f. Unsaturated Layer Thickness

Fig. 7. Thematic layers classified by the Boolean method in the soft formation of the Shamil-Takht Watershed

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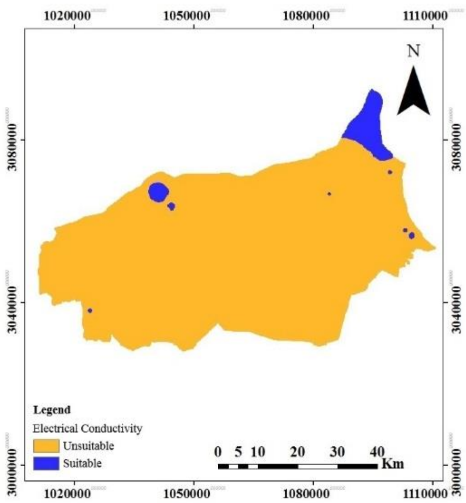
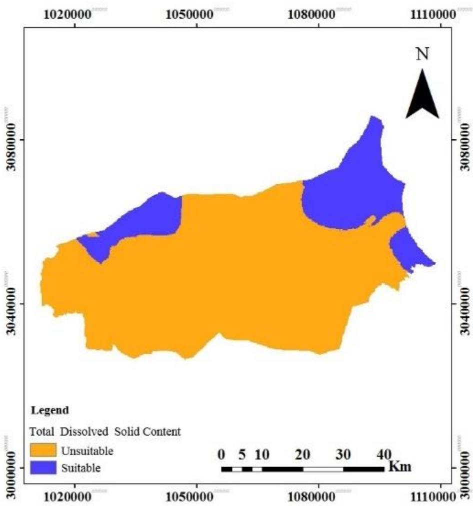
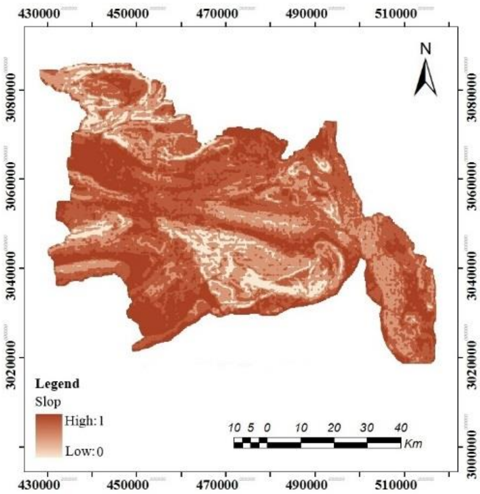


g. Electrical Conductivity

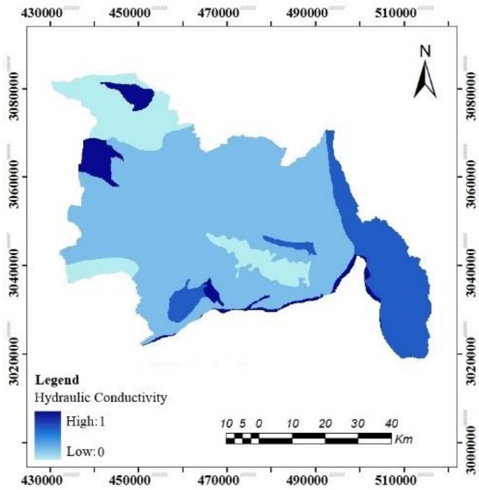


h. Total Dissolved Solid Content

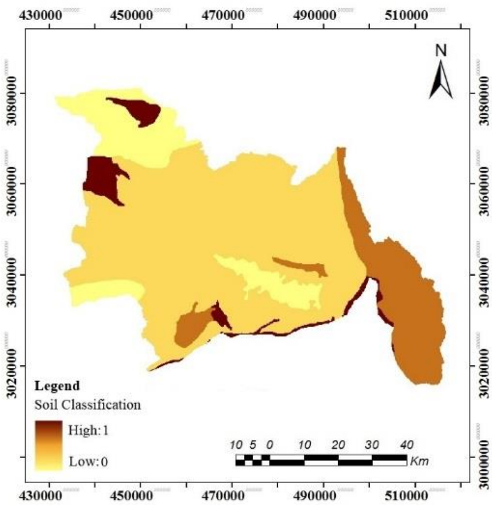
Fig. 7. Continued



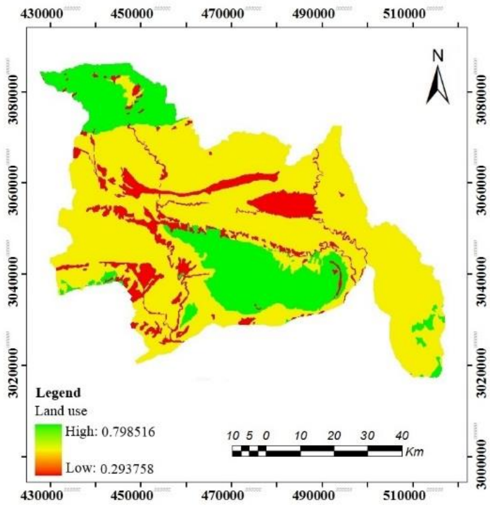
a. Slope



b. Hydraulic Conductivity

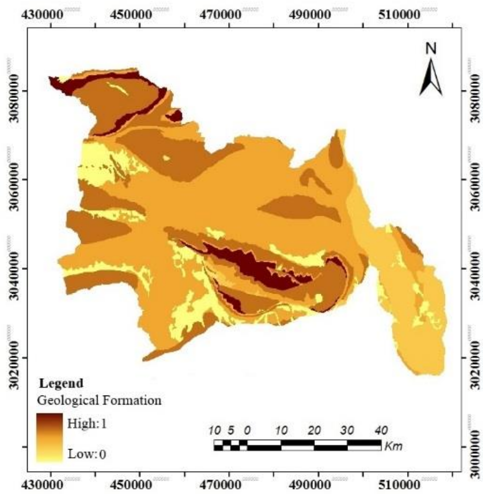


c. Soil Classification

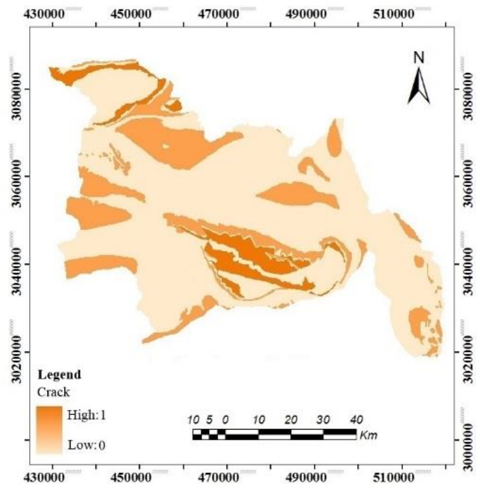


d. Land Use

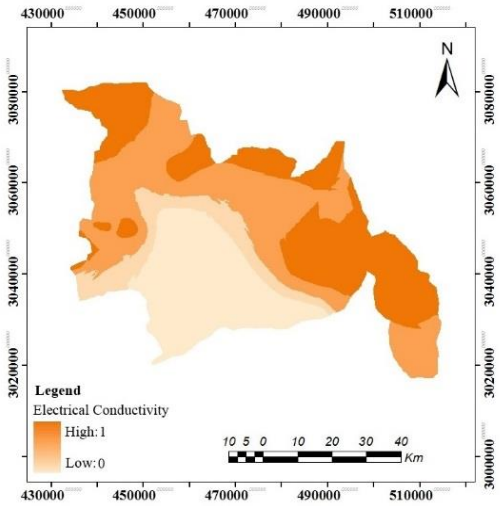
Fig. 8. Thematic layers classified by the degree of Fuzzy membership in the hard formation of the Shamil-Takht watershed



e. Geology formation

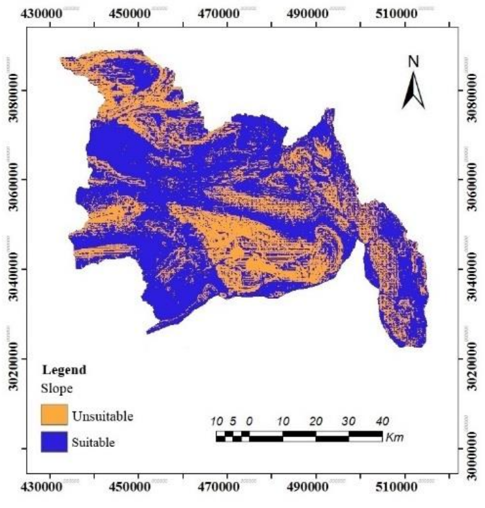


f. Crack

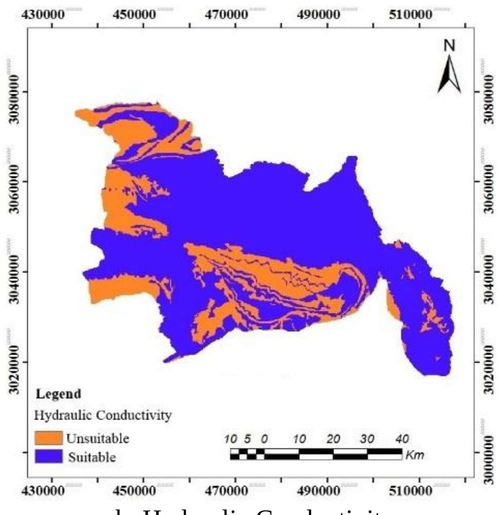


h. Total Dissolved Solid Content

Fig. 8. Continued

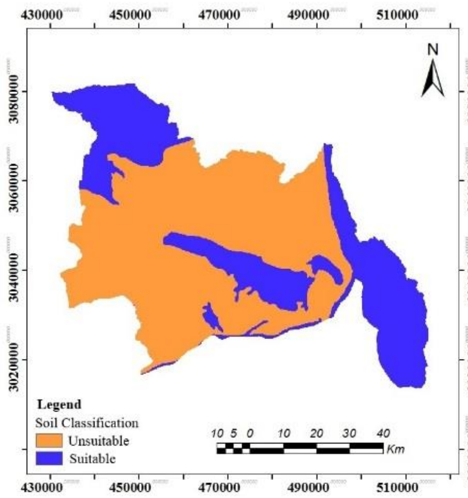


a. Slope

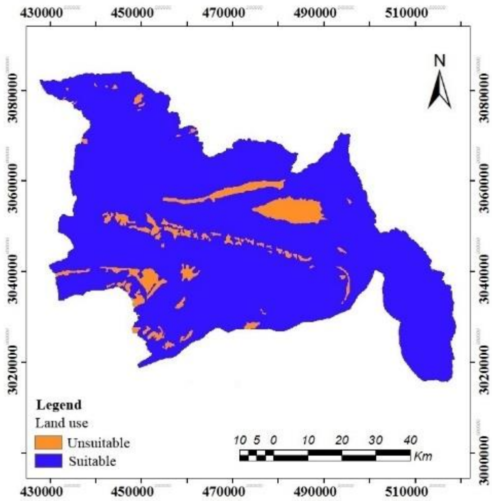


b. Hydraulic Conductivity

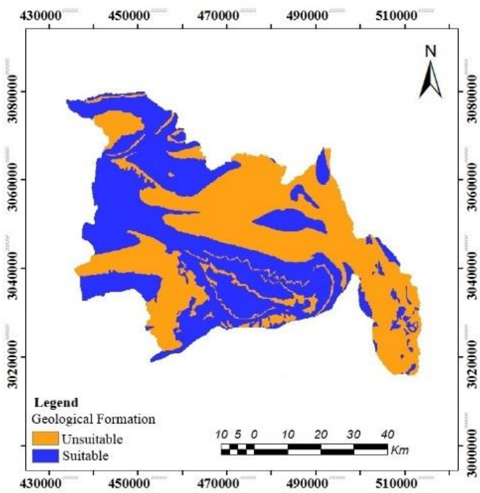
Fig. 9. Thematic layers classified by Boolean method in the hard formation of Shamil-Takht watershed



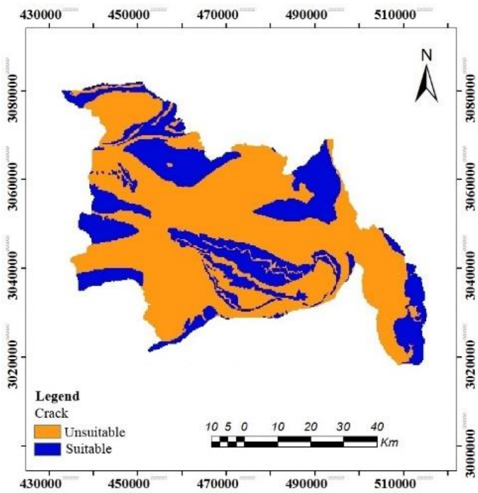
c. Soil Classification



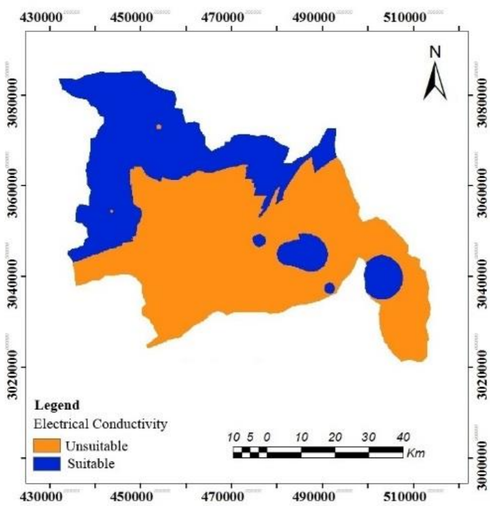
d. Land Use



e. Geology formation



f. Crack



h. Total Dissolved Solid Content

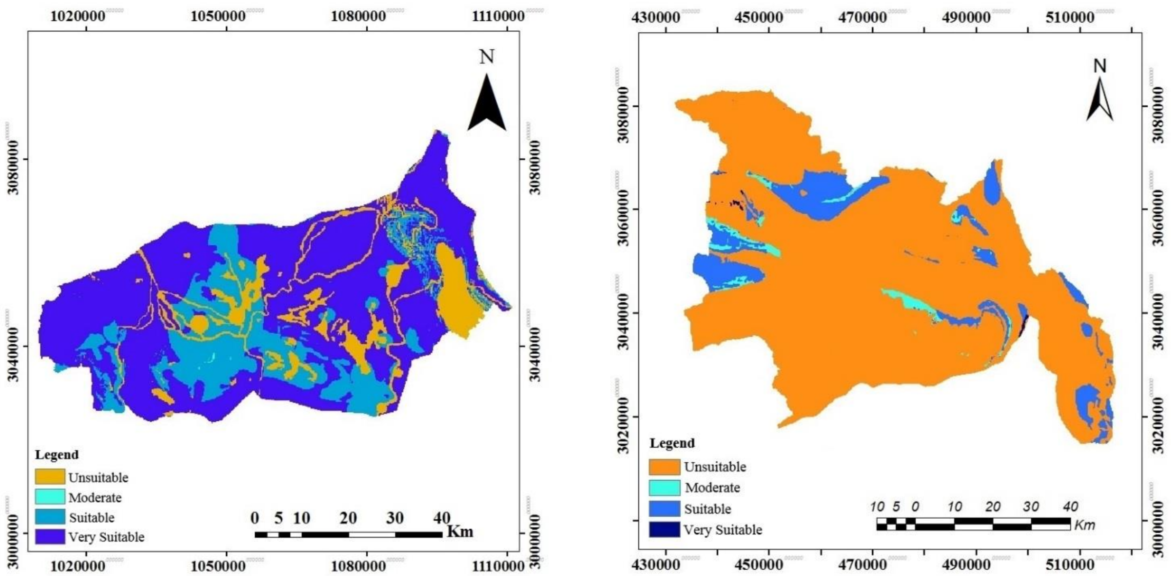
Fig. 9. Continued

Table 6. The area and percentage of the area of the groundwater potential classes in soft formation by a Fuzzy method

Classes of utility	Area (Km^2)	Area (%)
very suitable	445.81	51.6
suitable	220	25.5
Moderate	58.41	6.8
Unsuitable	140	16.2

Table 7. The area and percentage of the area of the groundwater potential classes in the hard formation by a Fuzzy method

Classes of utility	Area (Km^2)	Area (%)
very suitable	3.29	0.2
suitable	213.49	10.8
Moderate	38.53	1.9
Unsuitable	1728.89	87.1



a. Soft Formation b. Hard Formation

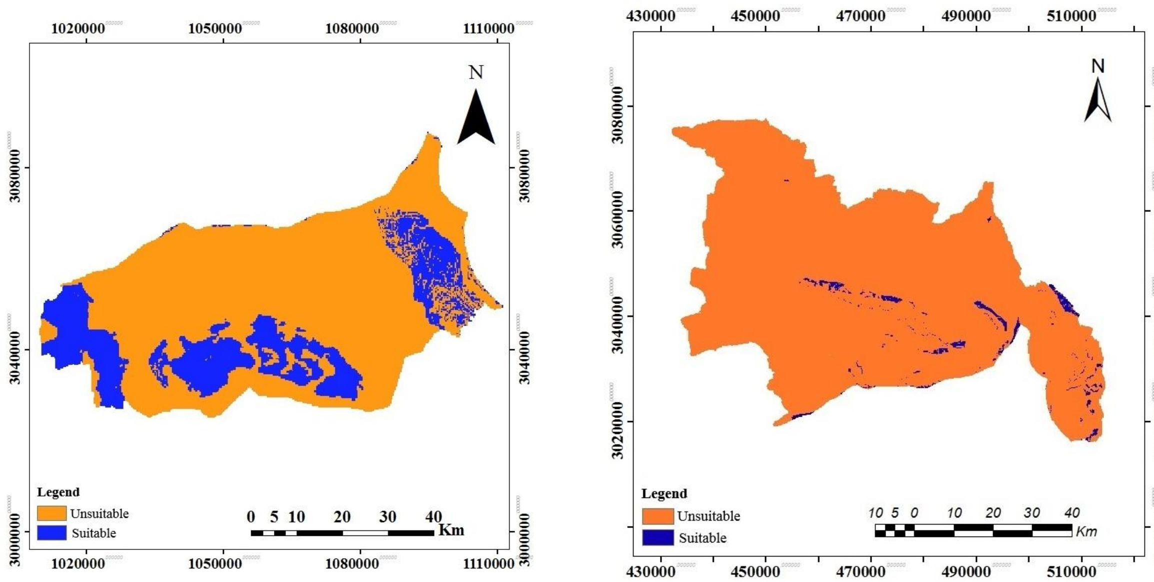
Fig. 10. The map resulting from combining thematic layers by the Fuzzy method in the soft and hard formations of the Shamil-Takht watershed

Table 8. The area and percentage of the area of the groundwater potential classes in the soft formation by Boolean method

Classes of utility	Area (Km^2)	Area (%)
suitable	207.28	24.1
Unsuitable	653.76	75.9

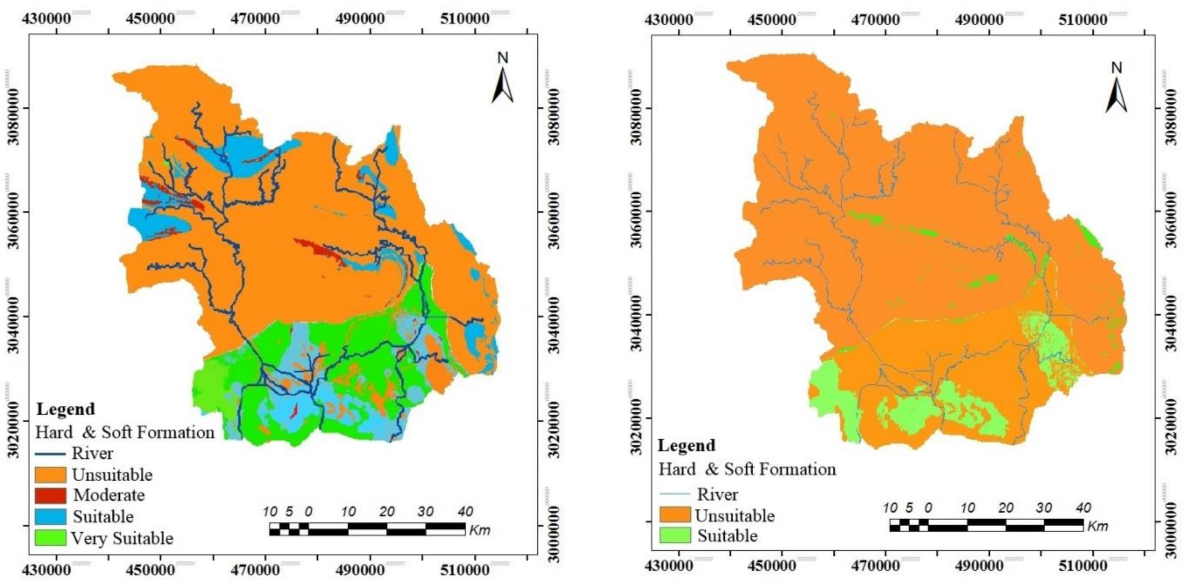
Table 9. The area and percentage of the area of the groundwater potential classes in the hard formation by Boolean method

Classes of utility	Area (Km^2)	Area (%)
suitable	34.6	1.7
Unsuitable	1949.6	98.3



a. Soft formation b. Hard formation

Fig. 11. The map resulting from the combination of thematic layers using the Boolean method in the soft and hard formations of the Shamil-Takht watershed



a. Fuzzy b. Boolean

Fig. 12. Map resulting from combining thematic layers using Fuzzy and Boolean methods; and waterway network in the entire Shamil-Takht watershed

4. Discussion

The results show that the use of various surface and subsurface groundwater controlling factors in the Fuzzy spatial technique can be a powerful approach to mapping the groundwater potential zones in a very accurate way (Singha *et al*., 2021). The selection of criteria for mapping the groundwater potential of the region requires a good knowledge of the site and basin data, the accurate weighting of the criteria by hydrogeologist experts, and careful cooperation between the selected factors. One of the most important steps in the decision-making process is determining the weight of the criteria and, in other words, their importance. The weights given directly to the criteria are the result of the decision analysis. The accuracy of the analysis depends on determining the weights with sufficient accuracy. There are different methods to determine the weights of the criteria and since these methods differ from each other in terms of accuracy, ease of use, clarity, and theoretical structure, according to the decision maker's priorities, which method is used to determine the weights? Although ranking and scoring methods are easier to use, binary comparison and preference analysis methods provide more accurate results (Çelik, 2019).

The current research proves the better efficiency of the Fuzzy logic tool compared to the Boolean logic in demarcating the potential areas of groundwater. As it has been successfully used in other places with suitable modifications. (Saravanan et al. 2020); (Çelik, 2019); (Chaudhry *et al*., 2021); (Radulović *et al*., 2022); (Mallick *et al*., 2019); (Shailaja *et al*., 2019); (Ahmad *et al*., 2020); (Halder *et al*., 2020); (Singha *et al*., 2021); (Murmu *et al*., 2019); (Ajibade *et al*., 2021); (Kumar *et al*., 2022); (Boughariou *et al*., 2021). In the Boolean method, only two categories of 100% suitable and unsuitable areas are obtained, so a percentage of the area that is considered suitable must have water sources (surface or underground) without risk. By comparing the percentage of the area of the identified suitable parts, from both methods, it can be seen that Fuzzy logic has worked similarly to Boolean logic in terms of calculating 100% suitable and without risk areas. However, in the Fuzzy method, a percentage of the area is expressed as an average, which means that there is a chance of finding water resources in these parts with a higher risk and lower probability. This distinction is very useful in Fuzzy logic, in the sense that it gives the user a wider part of the region as an answer, compared to Boolean logic.

Of course, geographic techniques such as GIS and Boolean logic can also provide a platform for mapping potential groundwater areas (Ponnusamy *et al*., 2022). However, it is said that the Fuzzy logic approach is very related to human thinking because it gives a value based on the amount of truth (Pal *et al*., 2020). Previous research studies using AHP and other methods have the limitation of expert bias when assigning weights to factors; The weighting method is discrete, which does not provide a clear picture of reality. Fuzzy logic removes bias and weight allocation is continuous so that a picture closer to reality is obtained. Fuzzy logic solves the generalization problem. It provides specific details for every single factor considered. The Fuzzy logic approach is significant and provides consistent results that can be applied to other locations with comparable hydrological characteristics with appropriate modifications (Ajibade *et al*., 2021).

In such research that faces limited data, the use of these approaches can be used as the most appropriate tool to solve various groundwater management issues (Radulović *et al*., 2022). The current research is not only important for water resources management, but can also help regional land use planning, creating future wells, and protecting groundwater (Boughariou *et al*., 2021).

The results obtained from the integration of thematic layers showed that the points with the lowest slope and cultivated in the soft formation have a high potential for groundwater sources, which is in line with the results of the research of (Ponnusamy *et al.*, 2022) and (Radulović *et al.*, 2022). As agricultural lands are flat and porous, the amount of runoff is small, but the amount of infiltration is high, which is a good condition for maintaining groundwater (Ponnusamy *et al.*, 2022) and provides the possibility of feeding groundwater; This shows that soil, geology, geomorphology, lineament density, land use, and slope play a vital role in mapping groundwater potential zones (Ponnusamy *et al.*, 2022). The results obtained from the integration of thematic layers in the hard formation showed that the areas with a high potential for the existence of groundwater correspond to the areas with the lowest slope and high density of waterways. Since movement and infiltration in some areas depend on drainage density. Higher drainage density indicates lower groundwater potential. Low drainage density indicates high infiltration and hence contributes more to groundwater potential. (Radulović *et al.*, 2022). Of course, the values of the potential areas of groundwater resources in a region are different according to the hydrological and hydrogeological conditions (Çelik 2019). These cases indicate the lower potential of the groundwater resources of the hard formation compared to the soft formation. On the other hand, the existence of water resources with good quality in hard formations, especially carbonate formations, has resulted in frequent requests from those responsible for providing drinking water, in this sense, the importance of knowing and being aware of the water potential of hard formations is felt more and more day by day.

5. Conclusion

The purpose of the present study is to determine the areas with groundwater potential in two soft and hard formations of the Shamil-Takht watershed with the help of Fuzzy and Boolean logic. In the present study, five thematic layers of the geological formation, slope, land use, hydraulic conductivity, and thickness of the unsaturated layer were used in the soft formation, and in the hard formation, the layers of the geological formation, crack, slope, land use, and electrical conductivity were used. Based on the final potential map of Groundwater resources, in the Fuzzy method, the studied area was classified into four distinct areas with very suitable, suitable, medium, and unsuitable groundwater potential, and in the Boolean method into two suitable and unsuitable areas.

The results obtained from the integration of the Thematic layers in the soft formation in the Fuzzy and Boolean regions showed that 77.1% (665.81 Km^2) and 24.1% (207.28 Km^2) of the total area of the formation had the possibility of water sources, which corresponded to the points with the lowest slope and cultivated. Based on this, the number of 2626 operating wells and 31 piezometer wells in this formation indicates compliance with reality. The results obtained from the integration of thematic layers in the hard formation in Fuzzy and Boolean regions showed that 11% (216.78 Km^2) and 1.7% (34.6 Km^2) of the total area of the formation had the possibility of water, which corresponded to the areas with the lowest slope and high density of the waterway. The emerging springs in the northwest of the basin indicate the high potential of groundwater sources in this formation.

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