Site Selection for a new Dam in the Reventazón River, Costa Rica

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ABSTRACT

In this study we used Geographic Information Systems (GIS) to conduct a Multi Criteria Analysis (MCA) in order to locate the most suitable site for building a hydroelectric dam in the Reventazón basin in Costa Rica. As primary data we used elevation data, land use data and satellite imagery. This data was processed in a GIS environment to perform a MCA. Each factor was weighted by using the Analytic Hierarchy Process (AHP) and Rank Order weighting method. The outcome of the study showed that the most suitable site is located 8.2 km southwest of Siquirres. The estimated height of the dam is 100m, which leads to a reservoir capacity of 236.632.969 m^3. The power that the reservoir can generate is 1.087.264.920 kWh.

Keywords: Multi Criteria Analysis (MCA), Analytic Hierarchy Process (AHP), Rank Order, Geographic Information Systems (GIS)

1. Introduction

Electricity generated using the gravitational force of falling or flowing water (hydroelectricity) is the most widely used form of renewable energy. The amount of produced electricity can easily be adapted, which makes it a very flexible source of electricity. Most hydroelectric power is generated using the potential energy of dammed water to drive a water turbine. A dam is the structure, which holds backwater and the construction that holds the volume of water, is called a reservoir (Brassington, 2005). The extracted power depends on the hydraulic of the dam and the stored volume. The hydraulic head of a dam can be defined as the difference in height between the source and the water's outflow. The *Represa de Cachi* is an arch dam located along the Reventazón River in central Costa Rica. It was one of Costa Rica's first hydroelectric projects and produces 102 MW of energy.

The aim of this paper is to locate the best possible site for a dam and a reservoir for hydro-electrical power production. Damming interrupts the flow of rivers and can harm local ecosystems, so the construction of a new dam must be well considered. To find the best site for the dam, Multi Criteria Analysis (MCA) was used. In this method, different criteria are combined to create a suitability map. One of the used factors was the distance of the dam to protected nature. To meet this criterion, a buffer of 300 meters around the protected areas was created. In the method part we will explain all the criteria that were used in the MCA.

The remainder of this paper is as follows. The method section starts with a broad description of the study area. Afterwards, the different data and software that were used are explained. The final part of the method is the explanation of the different criteria and the different methods that were used to conduct MCA are stated. Section 3 is showing the results of the project. Maps, tables and figures are displayed in this section, to help the readers understand the different results. In the discussion part we will give some critical feedback on the results, different methods and the possible further improvements of this study and the research field in broad sense. Section 5 is the final section and will draw some conclusion.

2. Method

2.1 Study area

The republic of Costa Rica is a country in Central America bordering the Caribbean Sea (east) and the North Pacific Ocean (west), between Panama (south) and Nicaragua (north). Approximately 4,8 million people live in Costa Rica, of which 1,5 million live near the capital, San José. Costa Rica covers about 51.000 km² of land. The research is conducted at the Cachi reservoir and the Reventazón River. The river originates in the central parts of Costa Rica and flows down into the Caribbean Sea with an approximate length of 125 km (Brandt, 1999). The drainage basin consists out of a total area of 2,953 km² and can be situated north of Tapanti National Park and to the east-southeast of Cartago between longitudes 83° 20’ W and 84° 03’ W and between latitudes 9° 33’ N and 10° 22’ N (Ramirez et al., 1992).

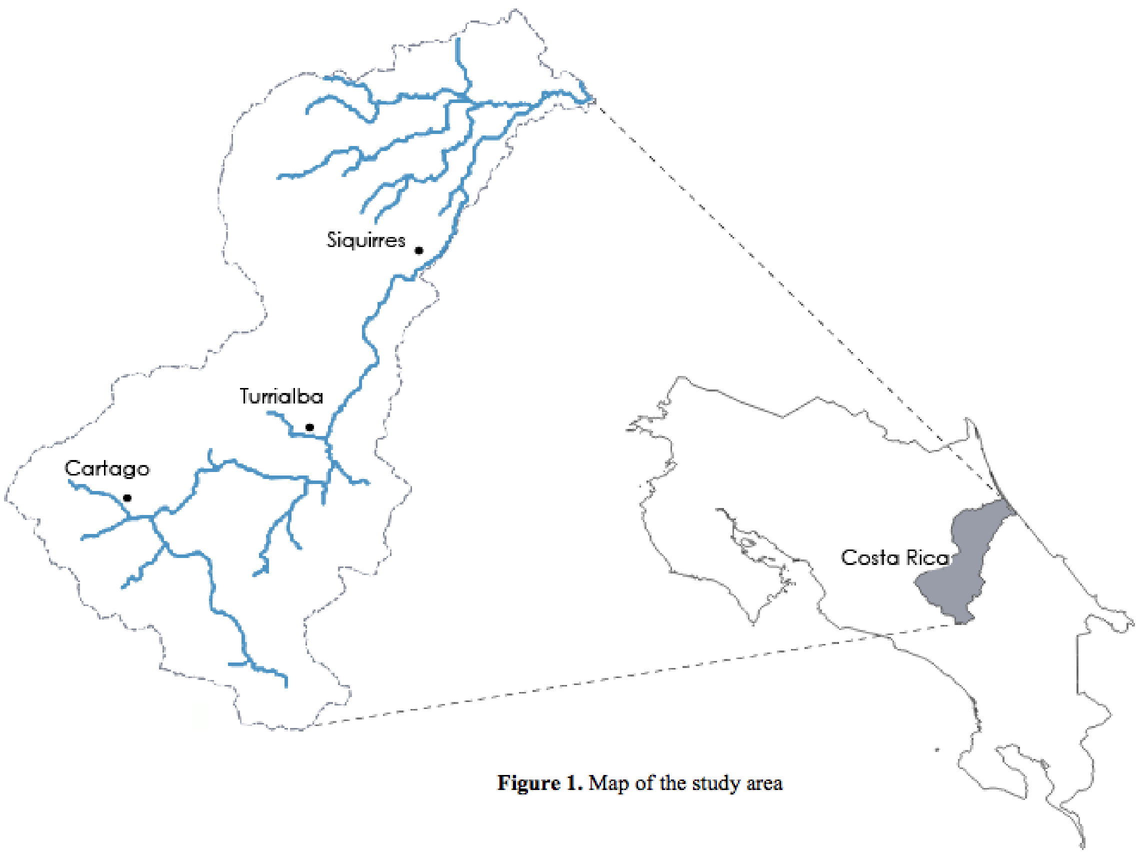


Figure 1. Map of the study area

The Central Valley of Costa Rica is part of the Nicaraguan graben (Bergoeing, 1998). A graben is German geological term that defines a depressed block of land bordered by parallel faults. The deposition of sedimentary rocks in the valley starts before the Upper Eocene and stops in the Lower Eocene. Faulting, folding and intrusion influenced the sediments in a later period. The Cordillera Central was formed by a new period of volcanic activity rocks (Baudoin et al., 2004). The volcanic field in the Central Valley is composed out of two sequences of rocks (Baudoin et al., 2004). In the western valley the volcanic underground consists of andesitic and basaltic lava flows, tuffs and ignimbrites of latitic and andesitic-basaltic composition (Castillo-Muñoz, 1983). Lava flows; breccias, tuffs, mudflow deposits and recent pyroclastic material are the mean components of the eastern valley sedimentary rocks (Castillo-Muñoz, 1983; Bergoeing, 1998). In general, the soils of the Central Valley are highly fertile. There are 11 soil associations in the area, of which 9 belong to main soil types (Pérez et al., 1978). Most soil types were influenced by volcanic activity and can be defined as deep, rich in organic material and well drained. The variation in soil types paints a picture of the diversity in topography, climate and geological history that is typical for the area (Baudoin et al., 2004).

Costa Rica is located within the tropics, with no distinct variations between summer and winter. At a given site, the mean temperature of the warmest month is not surpassed by the temperature of the coolest by more than 5°C (Coen, 1983). As the climate is very dependent on topography, lots of microclimates occur. As Costa Rica is located in the area of the Northern Hemisphere Trade Winds, winds come from the northeast throughout the year. The trades are stronger in the period from December to April and from July to August than in other months (Chacon and Fernandez, 1985). The Rainfall is seasonal, the dry season occurs from December to April. The intensity of the rainy season varies; just before and after July there is typically more rain than during the period itself (Baudoin et al., 2004). This period is called veranillo or little summer (Coen, 1983). Respectively March and September are the months with the lowest and highest precipitation (Protti et al., 1983). Generally, annual rainfall is higher in the western valley than in the eastern valley (Baudoin et al., 2004)

Land use is variable in accordance with soil and topography characteristics. The heart of Costa Rica is the coffee belt, occupying approximately 390 km² around San José, Heredia and Alajuela. It is harvested in the part of the flat lands of the high Central Valley. The soils are deep, friable and rich in organic matter, which make them ideal for coffee (Leon, 1948). At the altitude of about a thousand meters the temperature is mild and without sharp change. These conditions are perfect for growing coffee beans. The presence of stream water benefits the process of harvesting the coffee beans. The coffee industry is the backbone of the economy whist the cultivation of bananas and cacao has come and goes (Leon J. 1948). The region remaining north of the mountains consists largely of pasture and cropland with some fragmented, lowland rain forests (Carlson and Sanchez-Azofeifa, 1999). A different type of land use begins above the upper limit of coffee cultivation, which is about 1100 meters. Pastures are occupying most of the land between the cultivated valleys and the forest (Leon, 1948). Potatoes, highland corn and vegetables can be found in some areas. The deep volcanic soils and fine sandy loams produce good crops, but they are easily eroded. It takes almost an entire year to grow corn, but two crops of potatoes can be obtained per year (Leon, 1948). The soils in the upper Reventazón basin, i.e. upstream from the Cachi

Reservoir are used for the production of potatoes, vegetables and coffee (Sanchez-Azofeifa and Harris, 1994). On the Atlantic coastal plain, banana plantations are common.

2.2 Data

To create different weight layers that represent different criteria we used elevation data, land use data, satellite images and ancillary data. Most weight layers were derived from the elevation data. The main sources for creating the Digital Elevation Model (DEM) were four different sets of elevation data. Two datasets were derived from maps. For the lower part of the basin the contour data was digitized from a 1:50000 map, while the contour data for the upper part of the basin was digitized from a 1:20000 map. To create a full DEM of the study area a grid elevation file (90 m resolution) of the rest of the study area and some elevation data close to the rivers was used. Because all those files represent separate parts of the study area, the files were put together in one file. In order to create a continuous surface we used the Kriging interpolation method.

Next to the elevation data, land information data was used to create criteria layers for different criteria. A relief map was used to see where the terrain is flat, undulating or steep. This data is important, because the dam requires an undulating terrain. Land information data was used to process the different values of suitability according to land use. To calculate the amount water that the new basin can store, we used two types of hydrological datasets. The first one is the average annual rainfall, which contains point measurements of the annual rainfall in the region around the Reventazón catchment. The second one is the surface runoff for the different types of land use. The second dataset can be combined with the land use data in order to map the surface runoff in the basin.

Satellite images and ancillary data were used as reference data. The satellite datasets contained two Landsat images from two different years (2000 and 2001). These maps were used for coordination during processing of the data. The ancillary data consisted of two maps of the study area (1:50000 and 1:200000). These maps are used to check if the creation of rivers by using a DEM is correct. Finally we added an OpenStreetMap dataset of the Reventazón Basin to our project. This dataset was important for created the stream network. Further explanation on this topic will be given in paragraph 2.6.

2.3 Software

The main software packages that we used were: ArcGIS, Surfer and AHP. Surfer (v.10) was used in order to create a Digital Elevation Model of the study area. Surfer is a powerful tool to combine datasets and interpolate different contour lines and point elevation data into continuous surfaces. In Surfer it is possible to select different interpolation methods (Kriging, Inverse Distance to a Power, Nearest Neighbor etc.). ArcGIS (v.10.2) was important for creating a stream network. We used the hydrology toolbox in ArcGIS to create a stream network from a DEM. ArcGIS was also used to conduct the MCA. In ArcGIS different raster datasets can be combined. It is also possible to assign different weight factor to different raster datasets. That is why this software is so powerful to conduct MCA. AHP is a small program that calculated the weight factors of the criteria when you want to conduct the Analytical Hierarchy Process (Brandt, 2006). For this study we used version 2.0.

2.4 Multi Criteria Analysis

Multi-Criteria Analysis is defined as a decision-making tool for complex problems that include qualitative and/or quantitative aspects of the problem in the process of decision making (CIFOR, 1999). It is a tool to help decision makers in acquiring their objectives and help measuring the decision-makers preferences (Strager and Rosenberger, 2006). The goal is to weigh and combine different criteria to find the best possible solution. Ranking methods can be categorized in cardinal methods and ordinal methods. Cardinal methods require a grade of preference for one alternative over another for each criterion (Cook and Seiford, 1978). The Analytic Hierarchy Process is an example of a cardinal method.

Saaty developed the Analytic Hierarchy Process for dealing with quantifiable and/or intangible criteria (Saaty, 1990). The first phase of AHP consists of the creation of a hierarchy, which is then used to frame decisions. The structure goes down from a general goal to criteria, sub criteria and alternatives in following levels (Saaty, 1990). The second phase pertains to evaluation and is based on the concept of paired comparisons. Therefore a criterion and two alternatives are given. Two methods can be differentiated. The first method consists of inputs of relative important ratings and is between factor pairs within the same hierarchical level. Once the measures are computed, they are defined as factor weights. Factor weights are found using top-down factor comparisons and are scaled so that the sum of weights equals one. The second type of pairwise comparison is between pairs of alternatives and is used to determine their advantages against each other (Warren, 2004). The result is a matrix of paired comparisons calculated using the eigenvectors. The final calculated weight could be referred to as the underlying unidimensional scale.

Ordinal methods only require that the rank order of the alternatives be known for each criterion (Lansdowne, 1996). The multiple criteria have to be manually assigned a rank, starting with the most important. Once the order is known, numerical weights are calculated. Depending on the method several equations can be used. The sum of the calculated weights always has to be 1. An example of an ordinal method is the rank order method (1).

Rank order method $$w_i = \frac{n-R_i+1}{\sum_{j+1}^{n}(n-j+1)} \tag{1}$$

n stands for the number of the criteria and R_i is the rank position of criterion i. The weights are calculated using the mentioned equations. When using the rank exponent method, the weight of the most important criterion has to be specified. The equation has to be solved finding a value for p. Finally the other weights have to be calculated.

2.5 Criteria

An important part of MCA is the selection of criteria. Because the selection of criteria always has a subjective part, there will always be discussion about this part. Further discussion about this topic, will take place in the discussion part. In this study we used the following criteria:

- The dam cannot be build close to protected nature areas. To avoid these areas, a buffer of 300 meter must be applied to the large virgin forest above 1400m altitudes.
- The dam must avoid forest areas. The farther away from forest, the better.
- The dam must be built on the river.
- The upstream area must be large enough to provide a mean discharge of 30 m^3/s.
- The dam cannot be built at the existing Cachi Dam and Reservoir
- The reservoir must not flood existing cities. Smaller villages can be flooded, if there are good arguments. However, the generated power I meant for industries and people, so the closer to larger cities, the better.
- The dam must be built on an irregular surface. Mountains on both sides of the river are needed to build the dam.
- To build the dam, the hydraulic head must be sufficient. The bigger the elevation difference for a certain distance, the better it is for building a dam.

2.6 Processing of the DEM

Surfer software was first used to conduct the interpolation from discrete elevation point data. Four types of elevation data were used to perform the interpolation (Appendix I). They were converted into one single text file, which contained coordinates and elevation values. In order to find the best interpolation method for the specific data in this project, we made a comparison between Inverse Distance to a Power, Kriging, Natural Neighbor and Nearest Neighbor methods. The residuals and their statistics were calculated and displayed in table 1.

Table 1. Comparison of interpolation methods

Gridding method	*Sum*	*Mean*	*Standard deviation*	*Processing speed*
Inverse distance	13037.0	0.0091	11.4319	Medium
Nearest neighbor	6551.5	0.0045	8.1014	Quick
Natural neighbor	-10857.8	-0.0076	5.6519	Quick
Kriging	-13653.9	-0.0095	4.8389	Slow

2.7 Hydrological modeling

With the help of the Spatial Analyst tool, we created a stream network out of the DEM. Since the lower part of the drainage area was flat and there was little difference in elevation between the neighboring pixels, the automatically generated stream network may not be realistic. To solve this problem, we downloaded a part of the stream network from Open Street Map (OSM) and converted the OSM data into a raster dataset. The following process is called 'burning in' streams in the DEM. This process is subtracting the pixel values of the OSM data from the DEM. To do this, we firstly converted the stream network (OSM) into raster format with the same pixel size as DEM. Secondly, the no data pixels outside the stream network were assigned value zero. This is an important step, because the raster calculator does not work with pixel values that have no data (Appendix A).

In this project, we set the 'burning' value to 5 meters and subtracted the rivers from DEM using raster calculator. In order to delineate the streams and watersheds, the pits and sinks in the DEM had to be filled. Sinks are the erroneous depressions resulted from the interpolation method. After filling the pits, the flow direction and flow accumulation raster layers were calculated by the hydrologic function in ArcGIS. The stream network was generated from the flow accumulation by setting a proper threshold. In this project, the range of the flow accumulation is 0 to 324475. Finally, we set the threshold to 3000 in order to see the difference between real streams and streams that we generated. This threshold was also used to derive stream links in order to delineate the watershed. The derived raster watershed was converted into a vector polygon. Finally, it was possible to delineate the specific drainage basin by merging the polygons. The stream network was used to create a constraint map. Because the dam must be build on the river, only the river pixels get value 1. The rest of the pixels get value 0.

Another important part in hydrological modeling is the creation of a water discharge map. This map was created, by combining point locations of rainfall and runoff measures for different land use classes. The rainfall measures were interpolated into a continuous surface by using Kriging. The land use map was reclassified by using the runoff rates for land use classes. After creating both raster layers, they were multiplied in order to create an overall runoff map. This overall runoff map was together with the flow direction grid inserted in the flow accumulation algorithm in order to calculate the water discharge along the river. With this resulting dataset, a constraint map and a factor map were created. The constraint map holds a threshold of 30 m^3/s. Because only the areas with a discharge higher than 30 m^3/s are suitable, these areas were set to 1 (Appendix C). The factor map was stretched into values of 0-255. In this case, we can say: the higher the water discharge, the more suitable the site is for building a dam (Appendix D).

The final step in hydrological modeling was to create a hydraulic head raster. The calculations of this raster started with the water discharge constraint map and the DEM of the study area. By processing both datasets, a DEM of the water discharge areas above 30 m^3/s was created. With this new dataset we conducted a neighborhood analysis. This tool assigned the minimum value within a certain distance to the source cell. The output layer of this tool was subtracted from the DEM. The result is the elevation difference along the river (hydraulic head) (Appendix E). A map of the undulation of the area around the river was created in the same way (Appendix H). The minimum was set to maximum and the search distance to 500m.

2.8 Proximity analysis

The further away from forest the better. This kind of analysis can be easily executed by using Euclidean distance. In the case of distance to forest, reclassifying the land use map created a forest raster. The resulting forest map was then used as input for Euclidean distance. The resulting map was stretched into values of 0-255 (Appendix F). The same procedure was used in order to create a map of the distance to cities (Appendix G). In this case there was a positive relation between the distance to cities and the suitability. The three biggest cities in the catchment area (Cartago, Turrialba and Siquirres) were used as input to create the Euclidean distance raster. In order to erase the forested areas above 1400m, a constraint map of these forests was created. Firstly, the DEM was reclassified into a DEM with altitudes above 1400m and then this DEM was multiplied with the forest areas (Appendix B). The result was reclassified into values 0 (forest above 1400) and 1 (the rest of the study area).

2.9 Assigning weights

Last step before conducting the MCA is determining the weight order of the factors. Most of the time this step depends on the experience and knowledge of the researcher who is executing the study. In this study the undulation was set to the most important factor for building a dam. The reason for this is that it is impossible to build a dam on a flat area. Second most important is the water discharge, because there simply has to bet water in order to let the dam function. The hydraulic head is the third factor in the order. Finally, the distance to cities and forest were set to the less important factors. AHP software was used to calculate the weight matrix for the analytic hierarchy process (table 2 and 3).

Table 2. Weight matrix for the AHP method

Feature	*Forest*	*Hydro Head*	*Discharge*	*City*	*Undulation*
Forest	1	0.33	0.25	0.5	0.20
Hydro Head	3	1	0.50	2	0.30
Discharge	4	2	1	4	0.50
City	2	0.50	0.25	1	0.25
Undulation	5	3	2	4	1

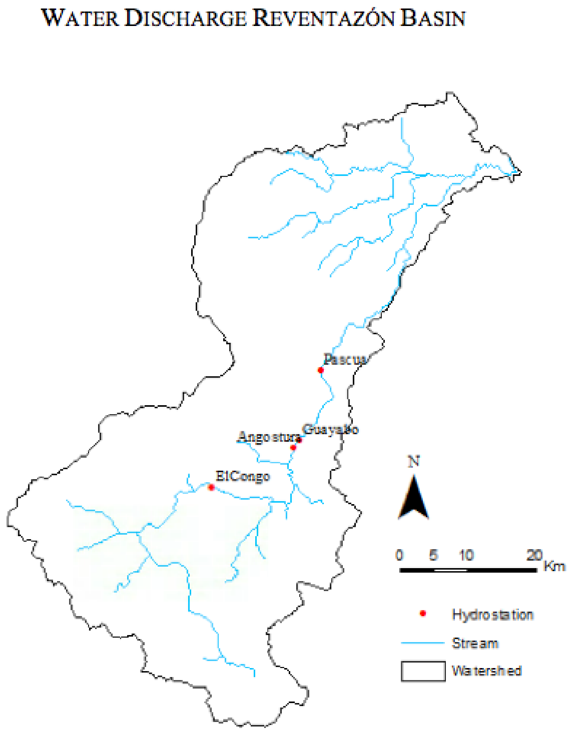
Table 3. Weight factors of the AHP and rank order method

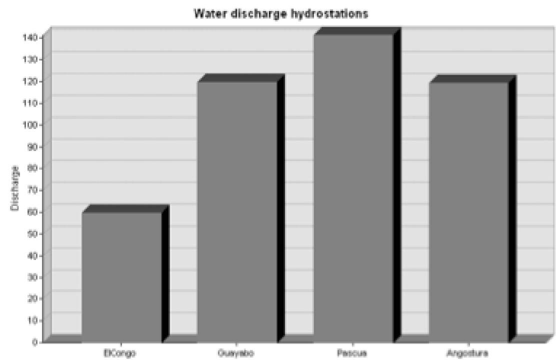
Criteria	*Rank*	*AHP weight*	*Rank order weight*
Undulation	1	0.4116	0.3333
Water discharge	2	0.2752	0.2667
Hydraulic head	3	0.1582	0.2000
Distance to cities	4	0.0931	0.1333
Distance to forest	5	0.0618	0.0667

3. Results

3.1 Hydrological model

To show the discharge along the Reventazón River, four stations were analyzed on discharge. El Congo, Guayabo, Pascua and Angostura are all hydro stations situated in the middle part of the basin. The discharge was calculated with the weighted cumulative flow map. The discharge values are displayed in figure 2.





Station name	Water discharge (m^3/s)
El Congo	59.77
Guayabo	119.82
Pascua	141.26
Angostura	119.29

Figure 2. Hydrological model of the Reventazón basin

3.2 Results of MCA

The results of the MCA with both AHP and Rank Order weighting method indicate that the dam should be built at a bend of the Reventazón River, which is about 5 km southwest of the city of Siquirres. The most suitable site is located in the middle of the river bend, which has the highest suitable value (136). The altitude of this site is around 170 m.a.s.l. and the water discharge is 149.33 m^3/s. The second suitable site is located 3.6 km northeast of the first site with a water discharge of 150.70 m^3/s. The third suitable site is located south of the first site at an altitude of 260 m.a.s.l. The water discharge value at this site is 141.21 m^3/s. The result of the rank order weighting generated different suitable sites compared to the AHP method. The most suitable site of this method is near the second suitable site of the AHP weighting method. Both hydraulic head and water discharge are higher at this site. The reason that we rejected to build the dam here is because the terrain here is not as undulating as it is at the first site of AHP method. Even when this site has more water discharge and it is nearer to a bigger city, a bigger effort is needed to build a dam at this relatively flat area.

We decided to build the dam at a site, which has the highest value according to the AHP method. The green point represents this location, 8.2 km southwest of the city of Siquirres (figure 3). The location coordinates are: 582633, 28542 meters (Cuadricula Lambert, Costa Rica North projection system).

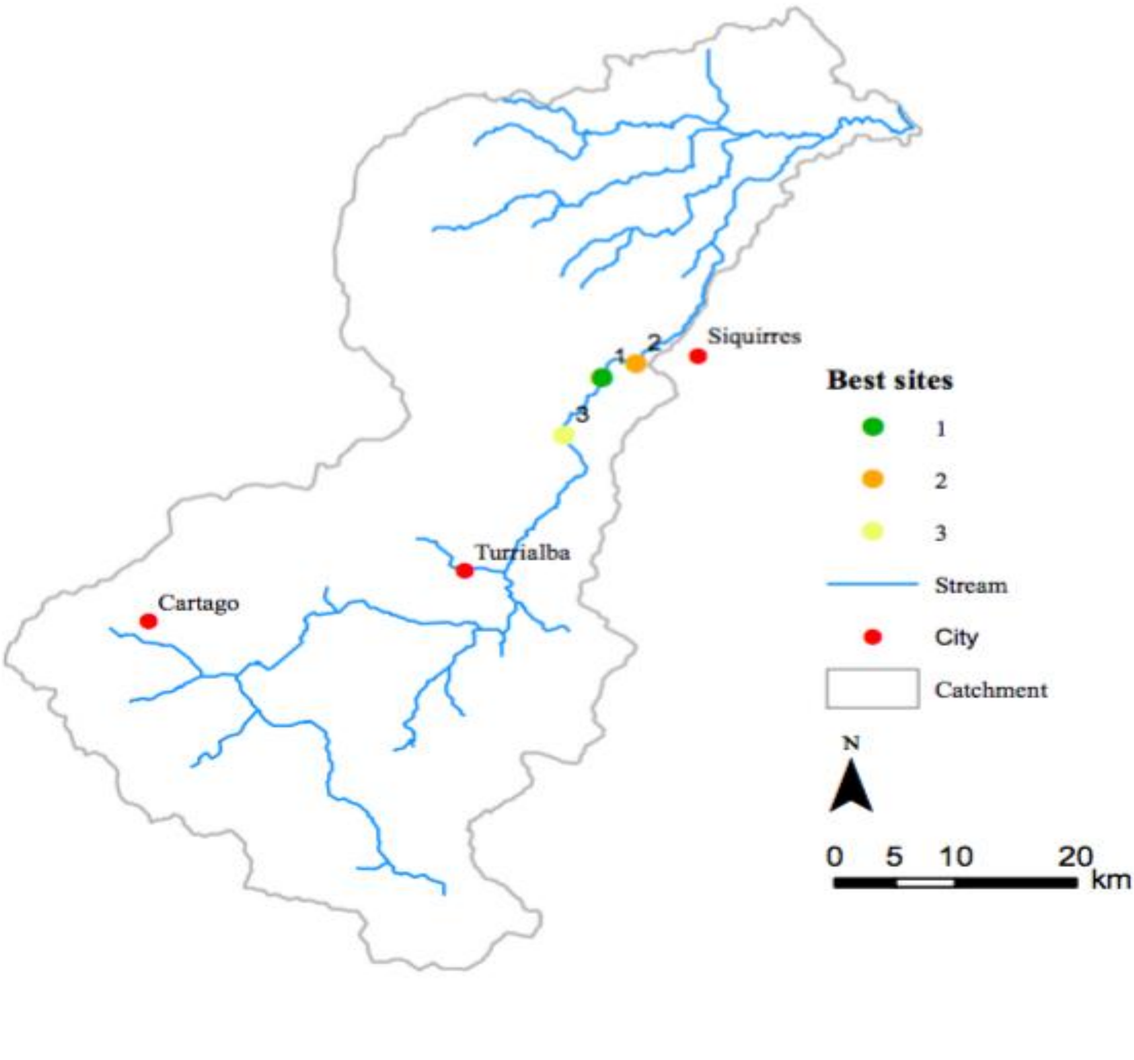


Figure 3. Best sites for building a dam

3.3 Dam height, volume estimation, and energy production

An important decision after selecting a suitable site for the dam is the height of the dam. This height must be well investigated, because it can have a major influence on the flooding of the environment. In this study we tested different dam heights, in order to see what the effect on flooding is. To determine the best height for the dam, a flood analysis was executed. This analysis shows the area that will be flooded in relation to a certain height of the dam. In this case we used a dam height of 100 meters. Figure 3 shows the extent of the flooded area when using a dam height of 100 meter. After choosing the dam height, the volume behind the dam was calculated. With a dam height of 100 meters, the volume behind the dam will be 236.632.969 m^3. The 2D surface flooded surface area is 5.410.484 m^2 and the 3D flooded surface area is 5.580.229 m^2 (figure 4).

In order to calculate the energy that will be produced after building the dam, the following equation was used: E = ρgQtH, where E is the energy in J/h or kWh, ρ is the density of the water (1000 kg/m3, Q is the water discharge $9m^3/s$, g the acceleration of gravitation (9.81 m/s^2), t is time in seconds and H is the hydraulic head in meters. Dealing with an efficiency of 85 %, the total energy that will be generated is estimated on $3{,}914 * 10^{15}$ J or 1.087.264.920 kWh.

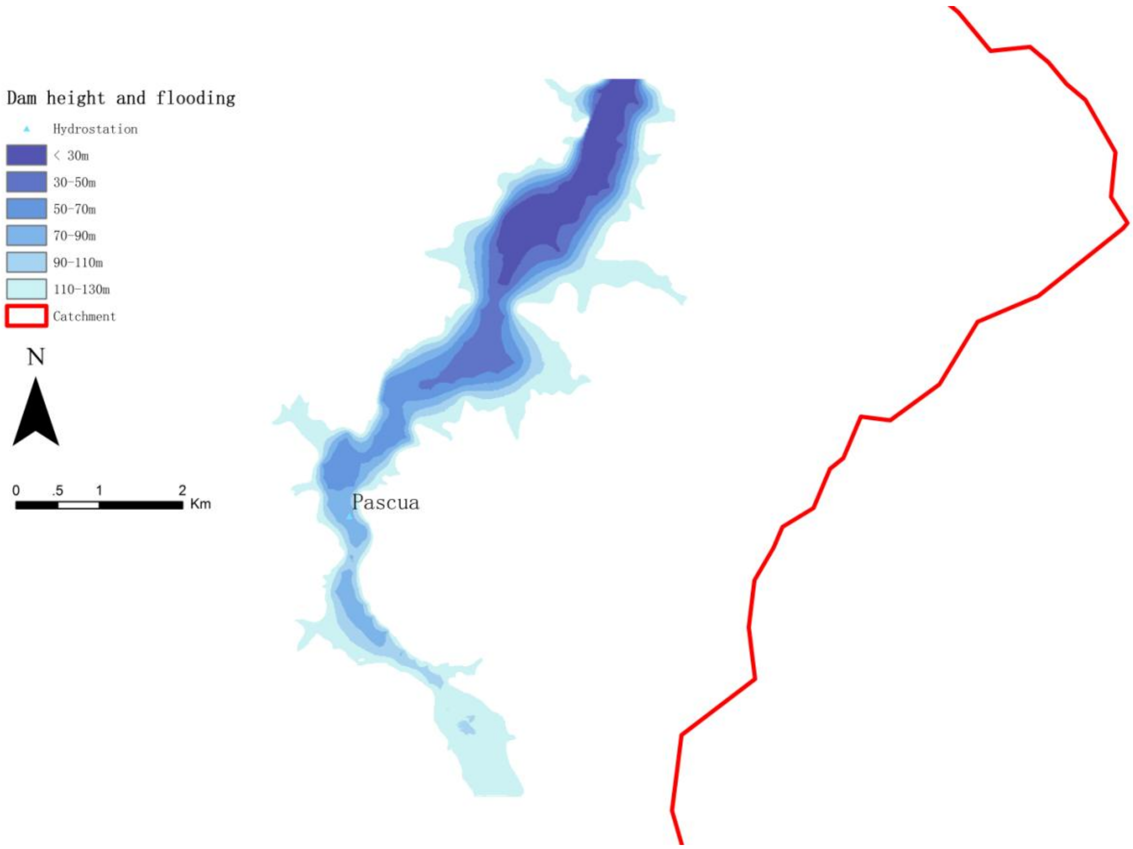


Figure 3. Dam height and the flood extent

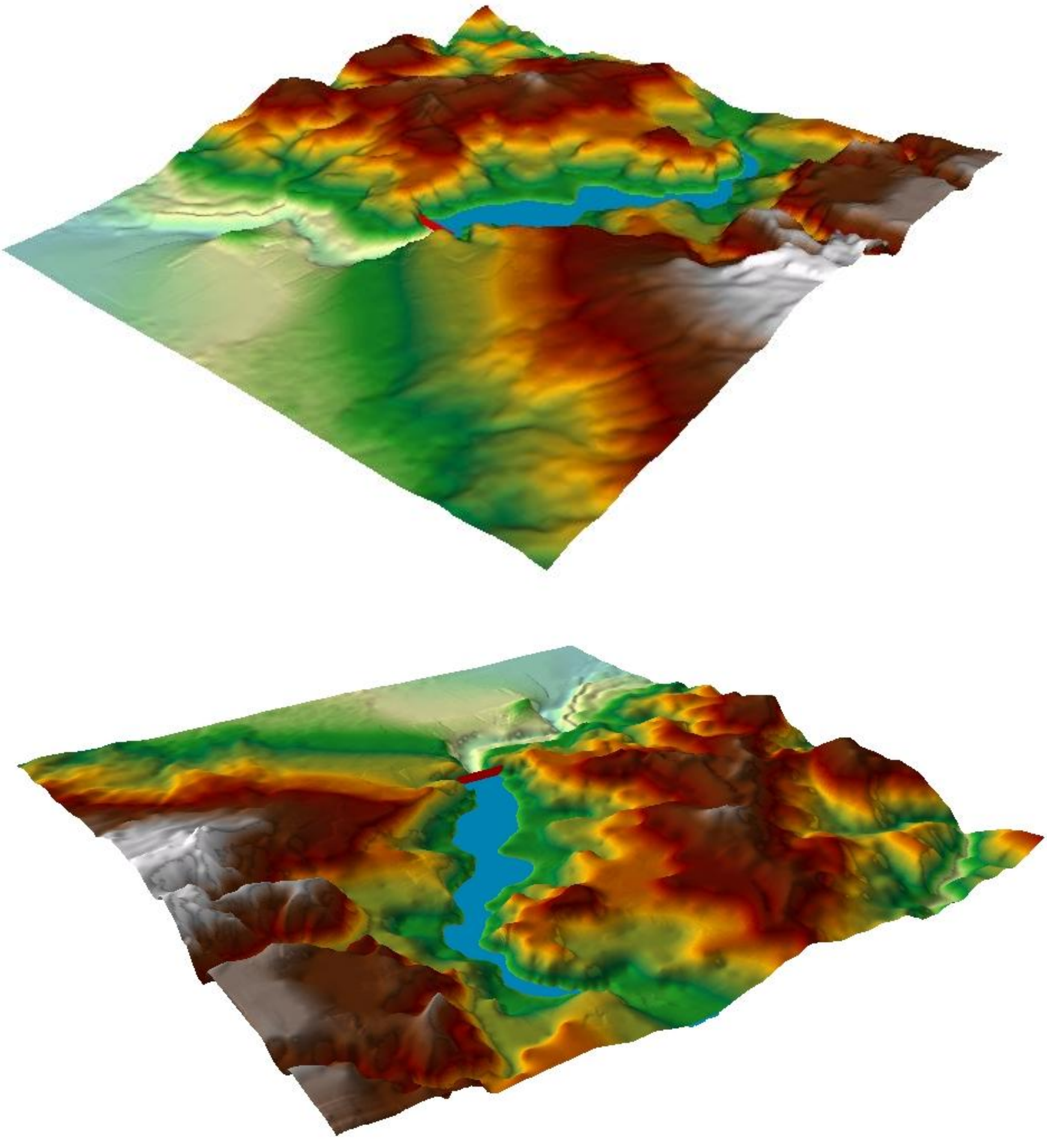


Figure 4. 3D model of the new basin

4. Discussion

4.1 Results of different methods

In this project, assigning weights was a critical step for determining a suitable site for the dam and reservoir. Both AHP and Rank Order methods resulted in three most suitable sites. The locations of those sites are clustered. However, they are not exactly located at the same place. There are several factors that influence the site selection of a dam and reservoir. From economical and topographical perspective, a concrete dam needs to be built at a respectively narrow and undulated valley, with large water flows so that it costs less material and generates more energy (Baban and Wan-Yusof, 2003).

In figure 5, the green triangle shows the most suitable place for the hydroelectric dam. This position is ranked as the third best, when using the Rank Order method. The best position when using the Rank Order is ranked second best by AHP. Different weighting factors result in different locations. This is showing the subjectivity of the ranking methods.

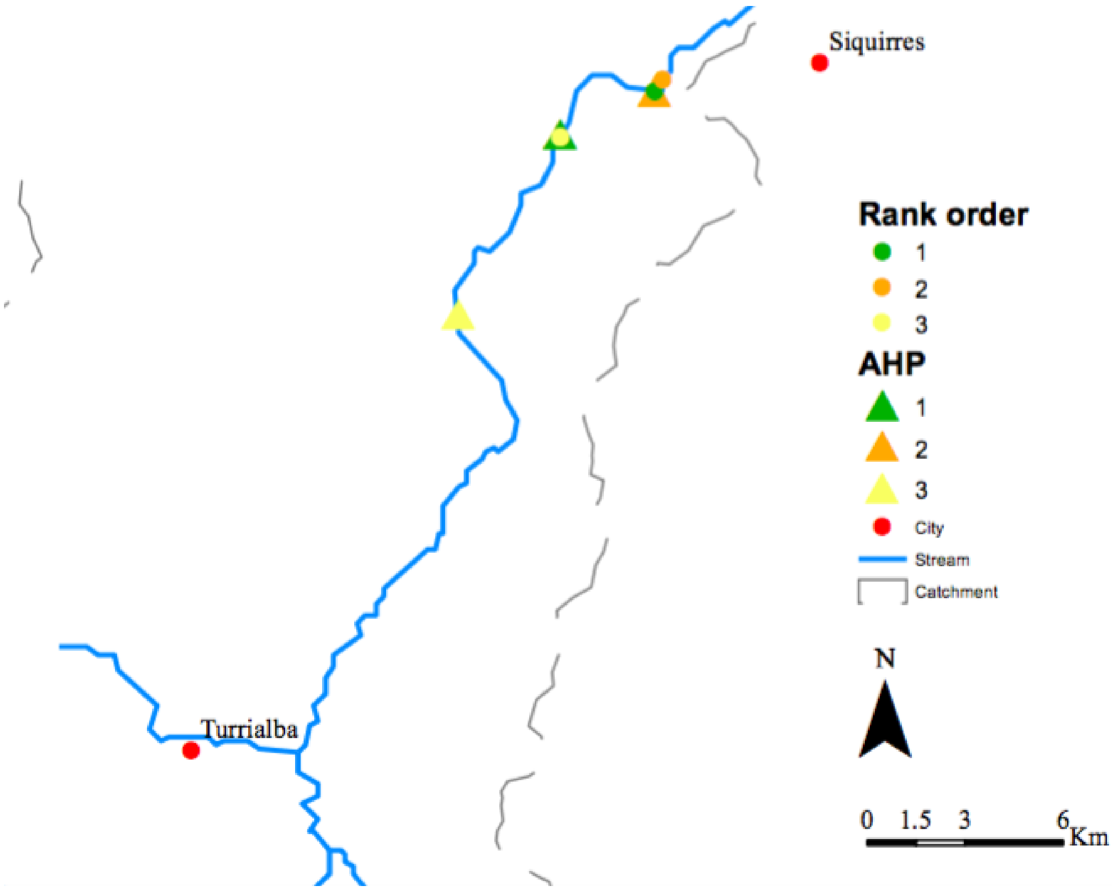


Figure 5. Suitable sites according to the AHP and Rank order methods.

Table 4. Comparison between AHP and Rank Order weighting methods

Weighting methods	*AHP*			*Rank Order*		
Suitable sites	1	2	3	1	2	3
Elevation (m)	171.20	150.82	260.37	153.16	123.31	176.5
Undulation (m)	100.84	39.62	99.38	39.62	38.05	92.2
Discharge (m^3/s)	149.33	150.70	141.21	150.70	150.96	148.94
Hydraulic head (m)	19.97	58.77	26.98	58.77	52.03	26.55

4.2 Further improvements

Elevation data acted as a main data source during this project. To create a DEM, we used four different datasets, with four different resolutions. In order to improve the quality of the DEM, it is better to have one data source with one resolution. It is for example preferable to have a grid of elevation data points over the whole study area. In this case the density of the points will be equal in all the areas. The combination of four data sources that we used consisted of different data types and densities. A constant grid will probably also have positive effects on the accuracy of the interpolation, which is the basis of the research.

The amount of factors is another possible improvement in the process. In this study we used five factors, to meet the minimum requirements of MCA. To improve the model it can be useful to implement extra factors that influence the suitability of sites for building a dam and a reservoir. Example of an extra factor can be the presence of an aquifer or aquitard, which can have a large influence on the hydrological situation in the study area. Next to the selection of factors, the order of factors plays an important role in MCA. To order the factors, we used our experience and knowledge about the study area. In order to improve the arguments for creating the order, more knowledge about the study area is needed. However, the creation of the order will always have some biases.

The model that we created can be adjusted in different ways. A parameter that can easily be changed is the height of the dam. The exact place of the dam was in this case determined by the cross section of the valley. In order to improve the exact location of the dam, a more dense profile analysis is needed. The volume measurement of the reservoirs can be made more accurate, when using a higher resolution DEM. In our case we used the 10m-resolution raster. To create a more reliable exact site further research to the valley profile is needed. This study only selected a site on a regional scale.

The final result will not give a strictly outcome that has to be followed. The outcome gives decision makers a tool to select the possible site for a dam, and provide arguments to build the dam at that place. As mentioned before, more research at the actual site is needed to give more insight into how the dam must be build.

5. Conclusion

In this study we used GIS and MCA to locate the most suitable site for a hydroelectric power dam in the Reventazón basin, Costa Rica. In order to determine the best location, we used two different types of weighting methods: AHP and the Rank Order method. Considering all the criteria, the most suitable location is found 8.2 km southwest of Siquirres. The study showed that GIS is a powerful tool to conduct MCA. However, there are still a lot of subjectivities found in the MCA process. To reduce those subjectivities extra factors, fieldwork and improved data quality are needed.

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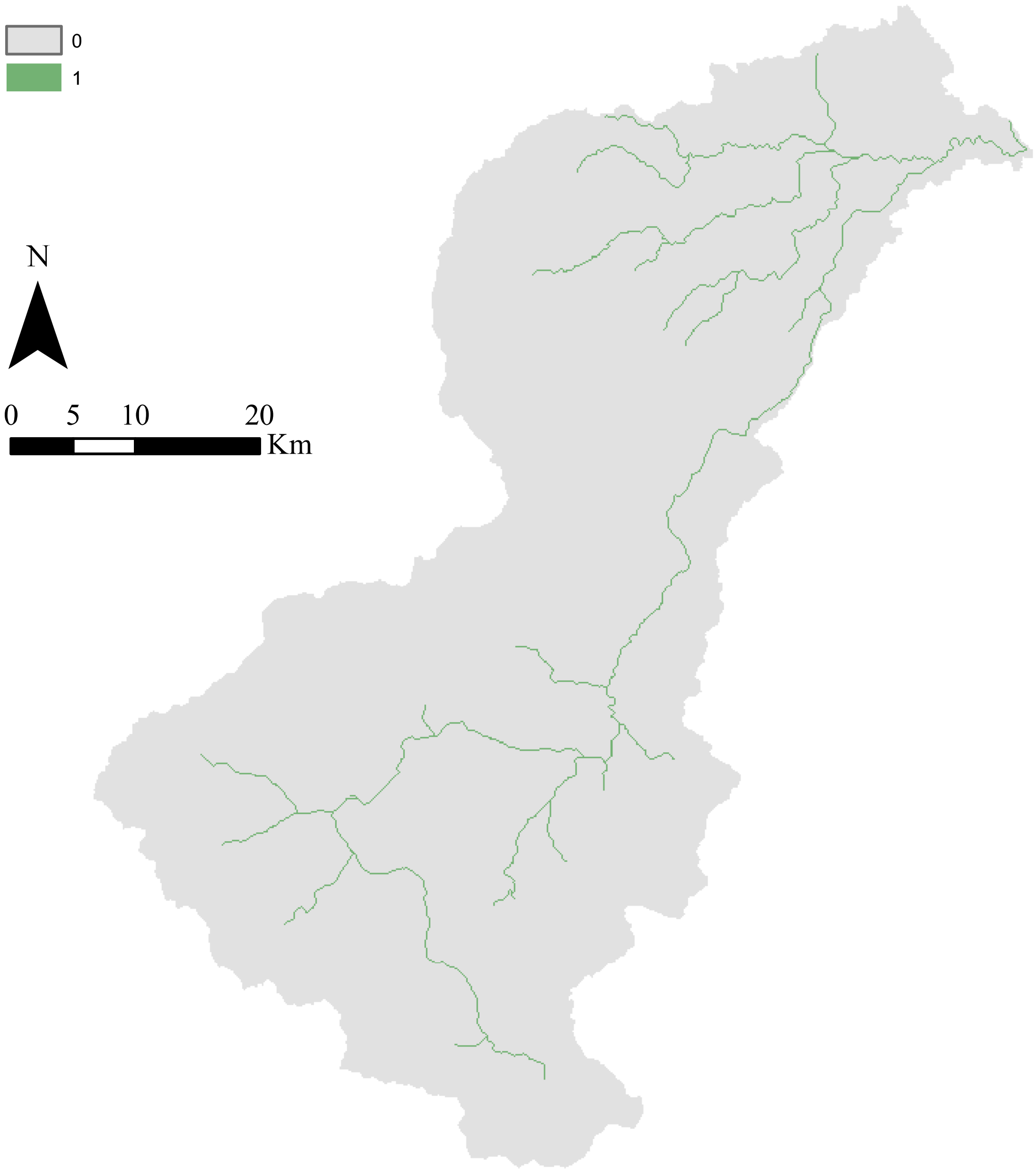
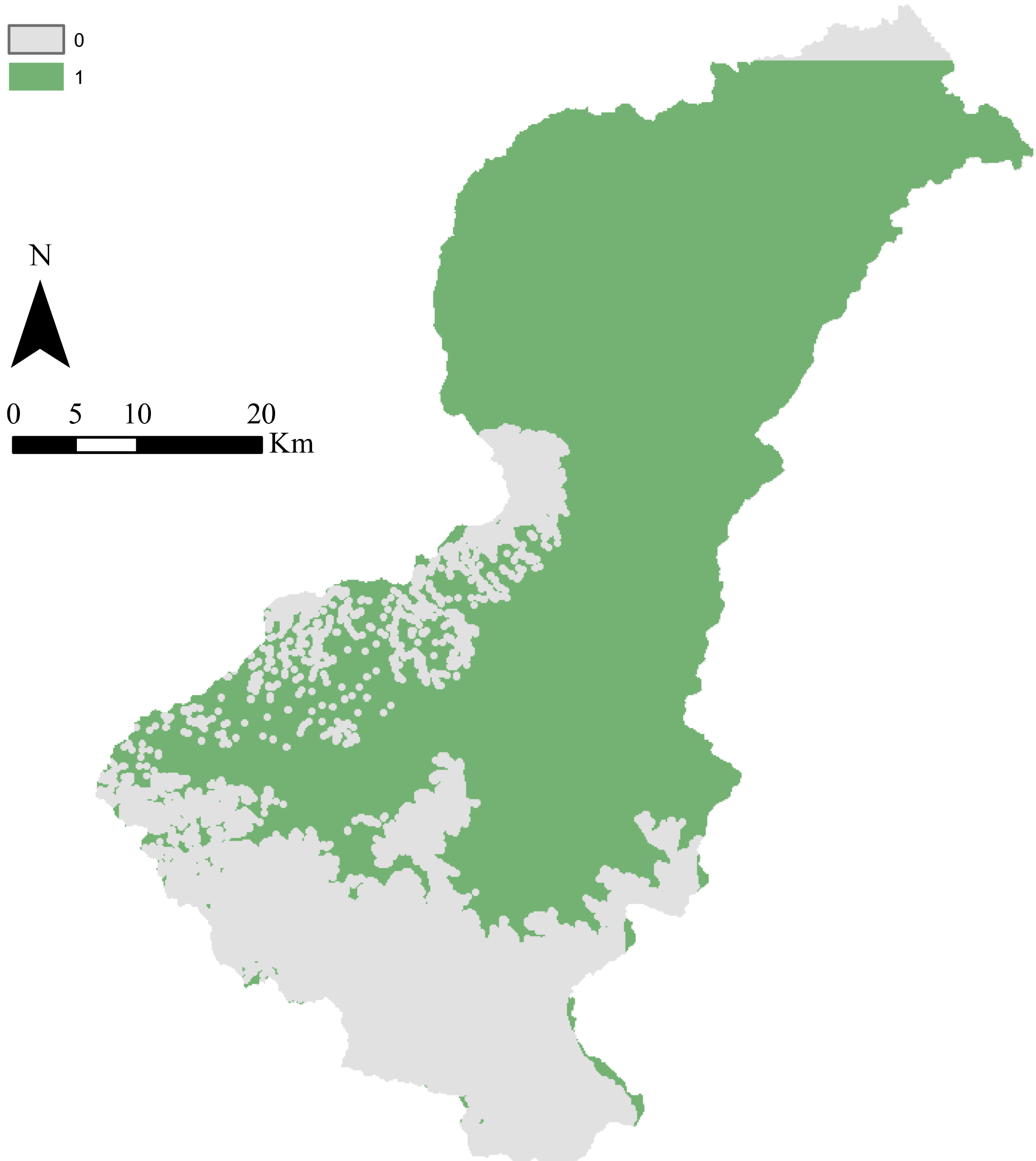
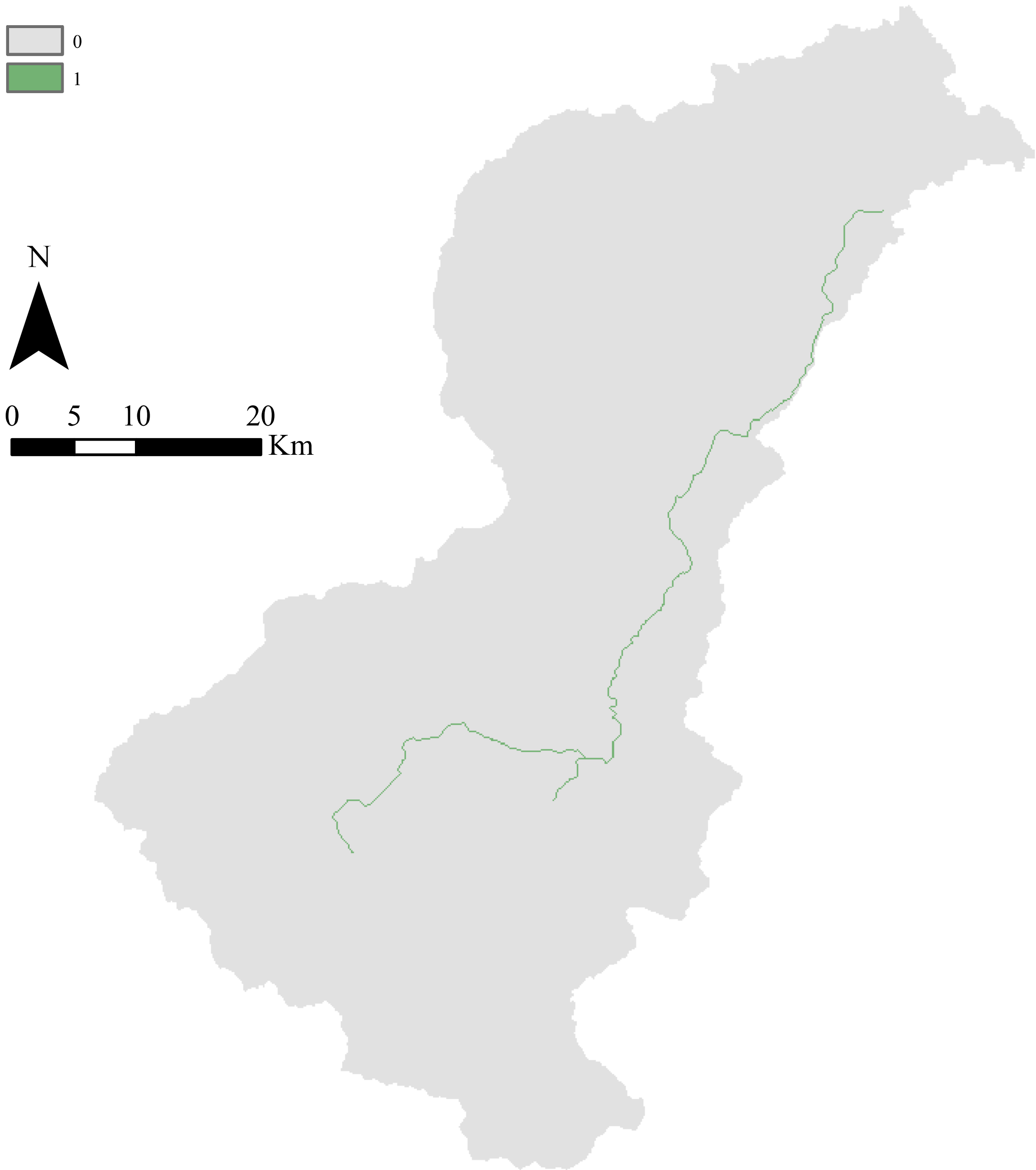
Appendix A. Constraint map of streams



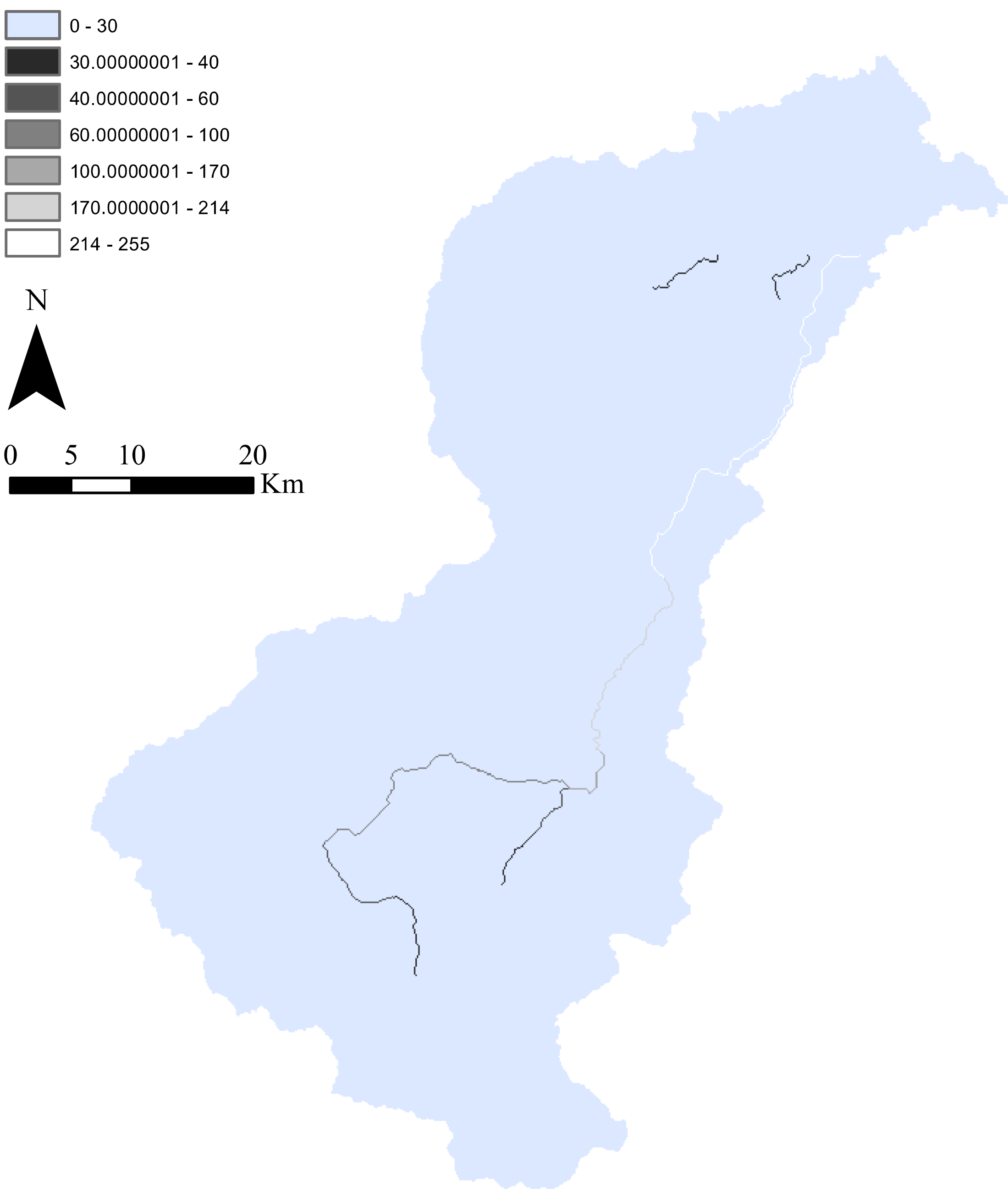
Appendix B. Constraint map of forest



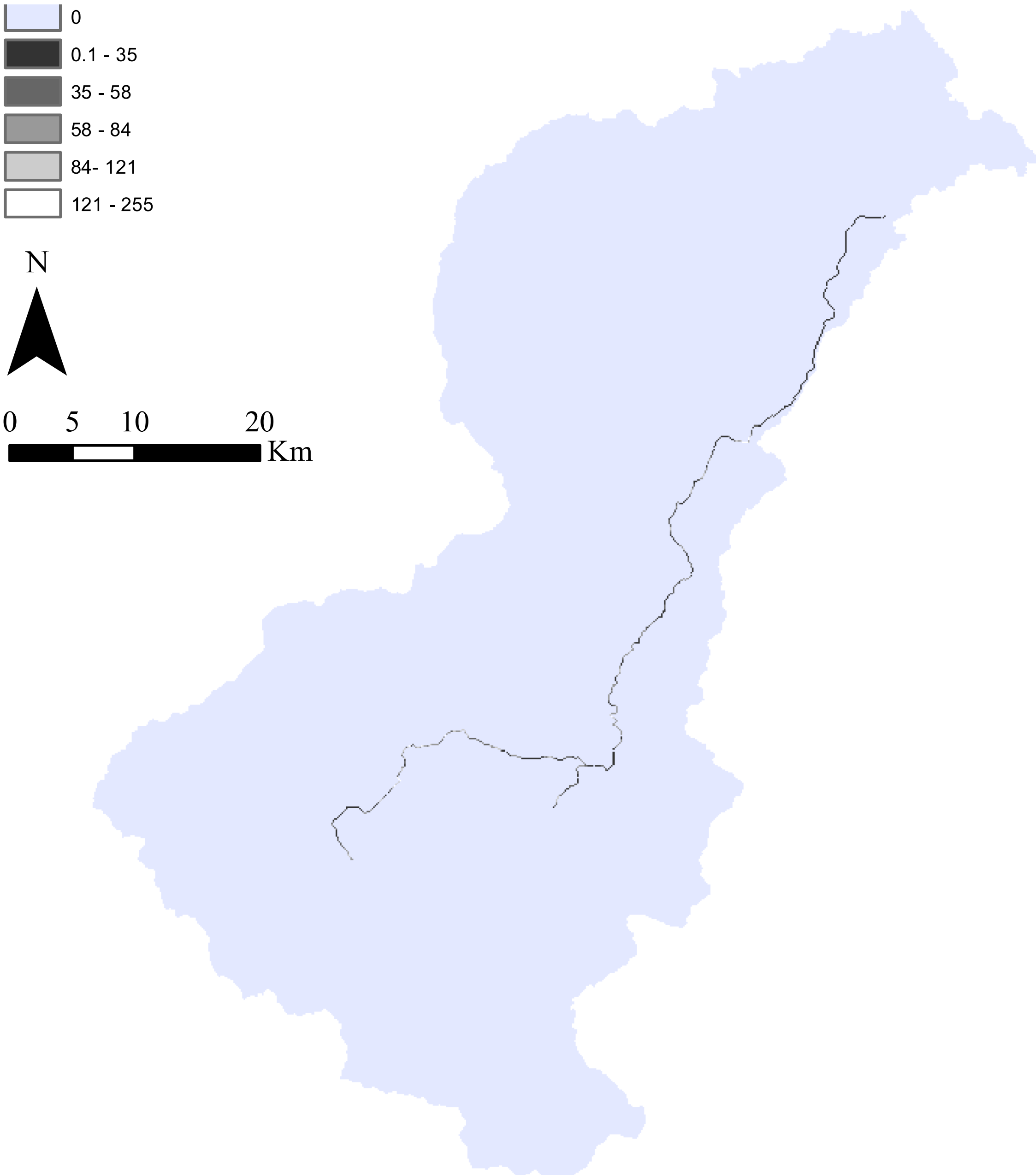
Appendix C. Constrain map of water discharge



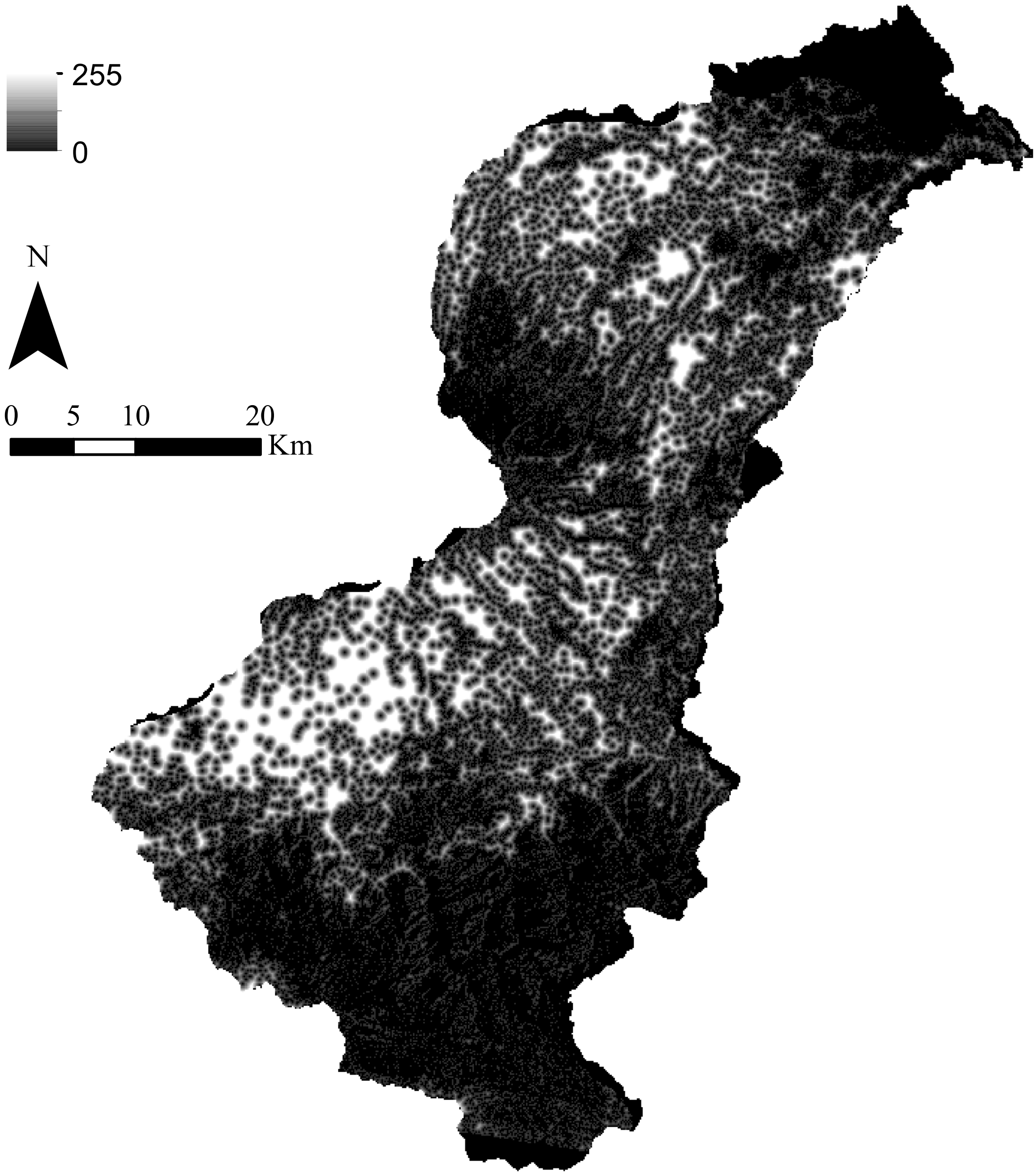
Appendix D. Factor map of water discharge



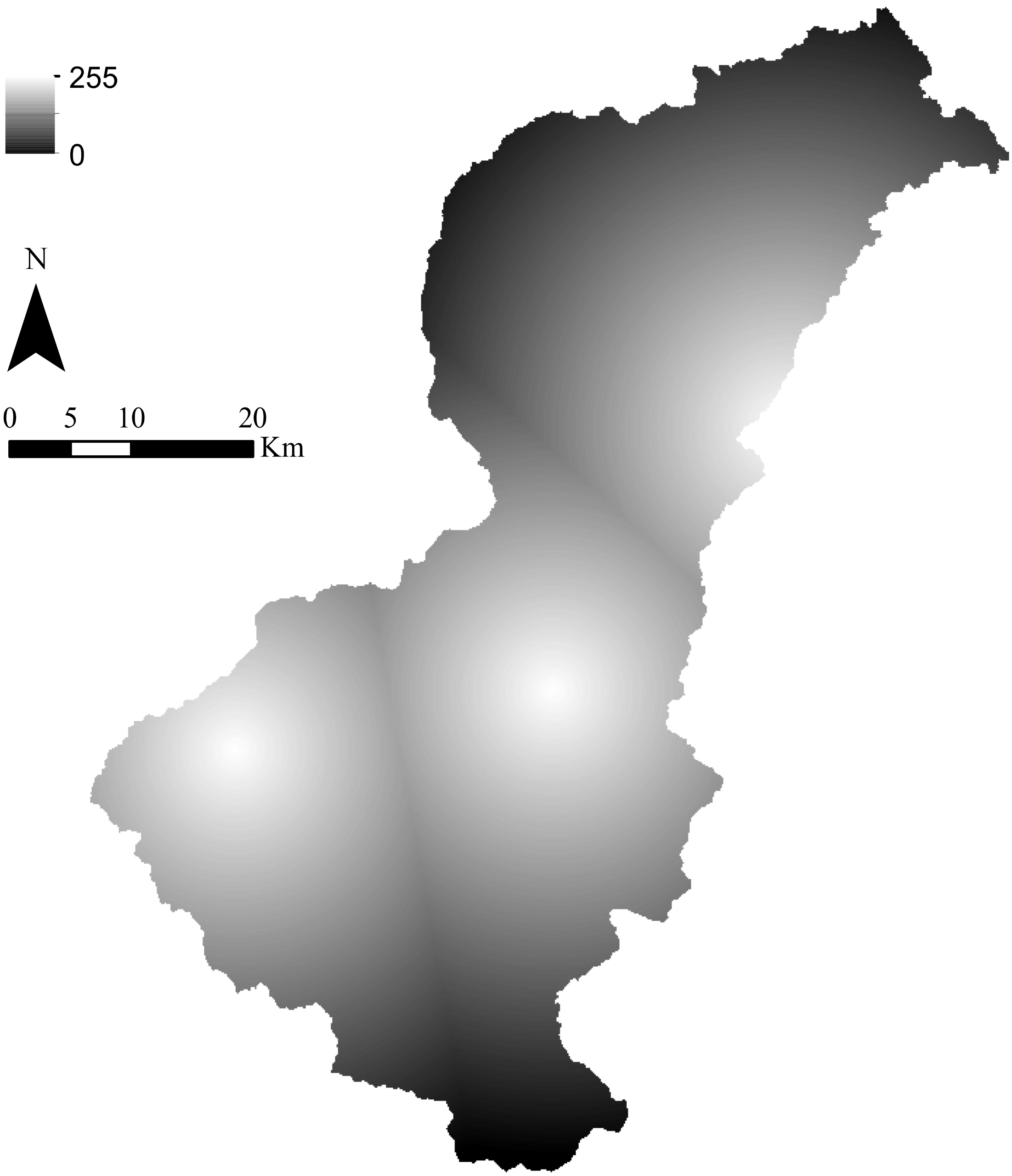
Appendix E. Factor map of hydraulic head



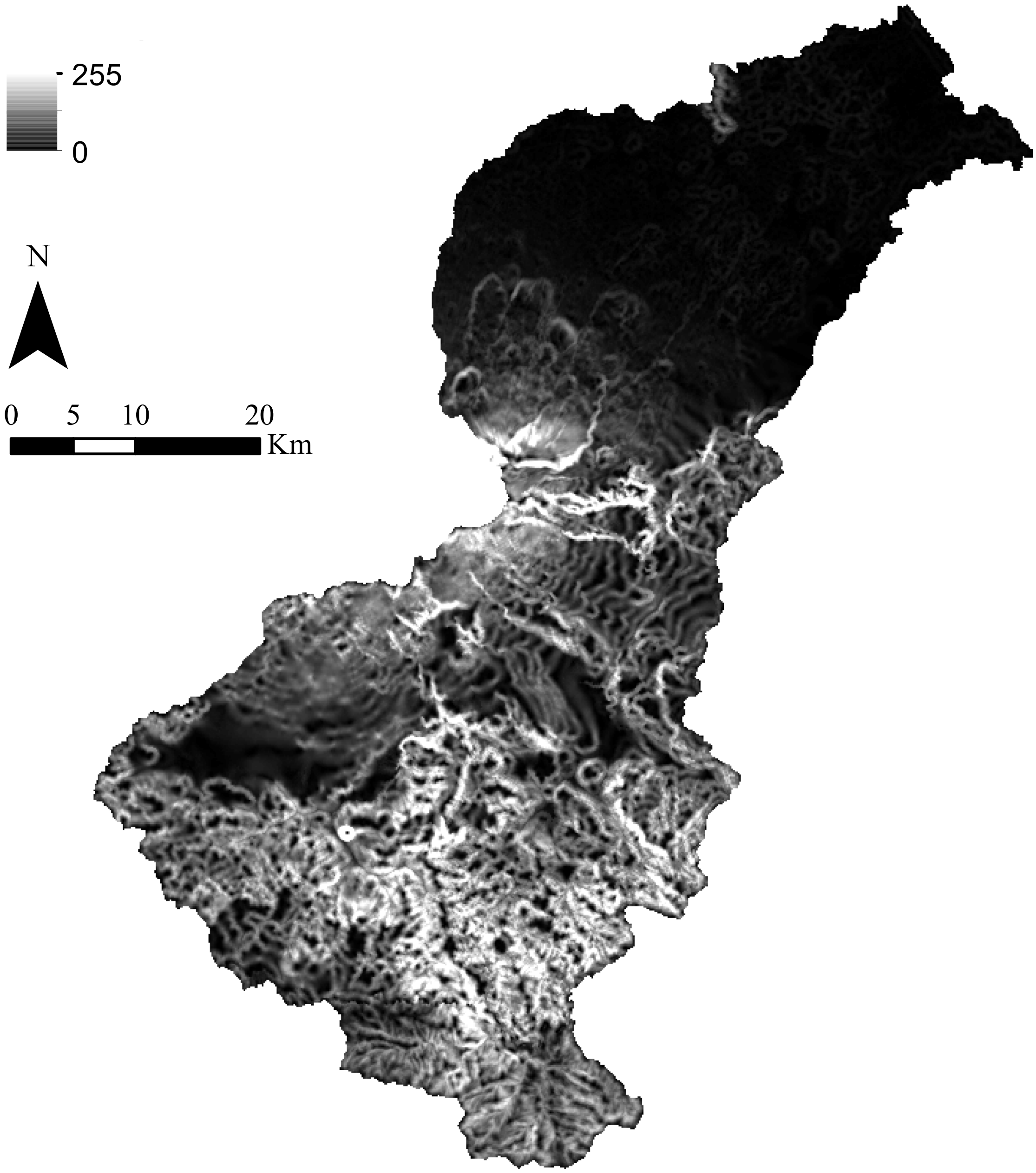
Appendix F. Factor map of distance to forest



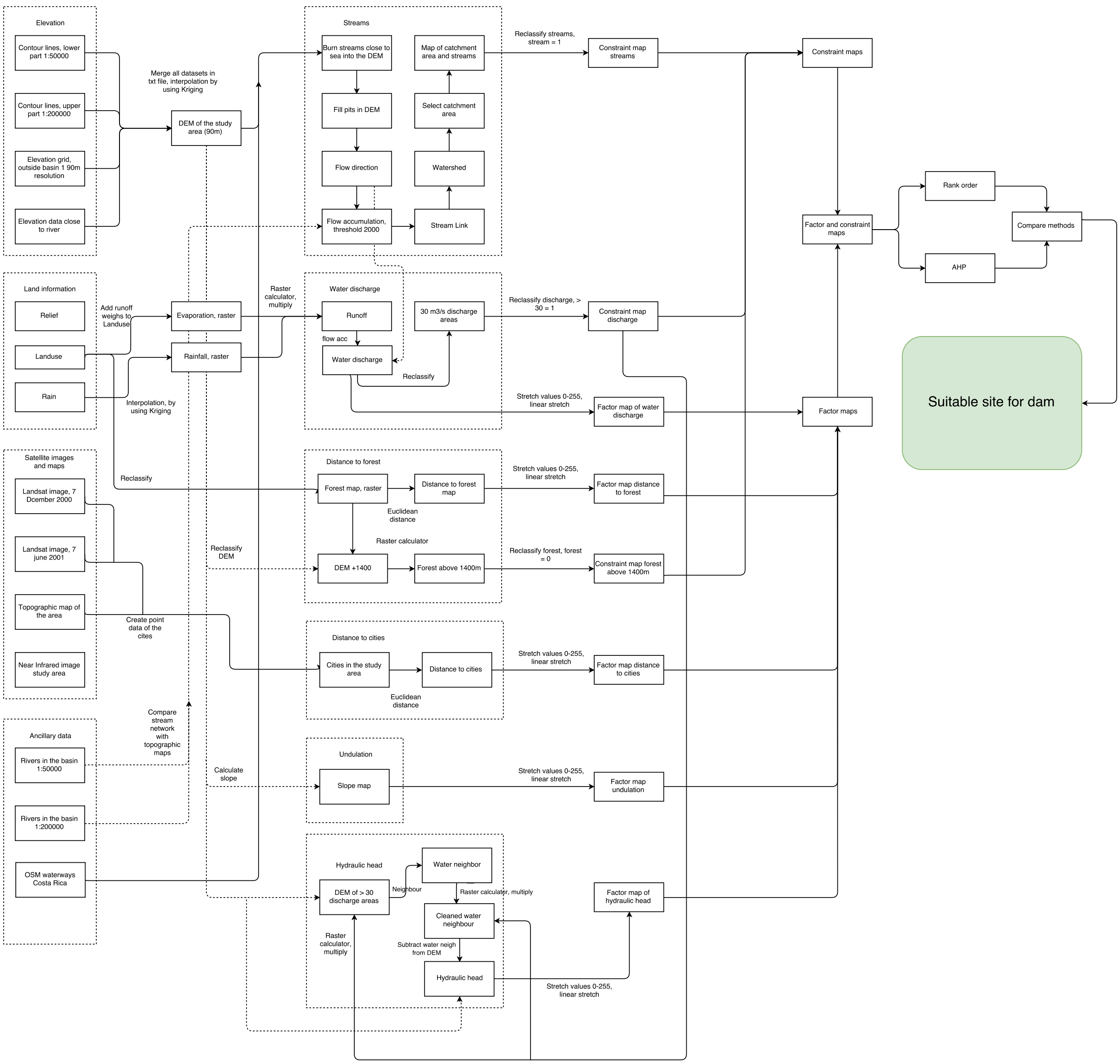
Appendix G. Factor map of distance to cities



Appendix H. Factor map of undulation



Appendix I. Flowchart of the process



Appendix J. 3D model of the Basin