Locating suitable sites for Hydroelectric Power Production:
The case of Reventazón Basin, Costa Rica

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Abstract
The area chosen for this study is a region within Costa Rica where most of the existing power plants are located, this region contains many of the Costa Rican rivers, which makes it suitable for further development of hydropower. Within this paper, suitable locations for new development of hydroelectric power production sites in Costa Rica are presented. The proposed locations are based on a spatial Multi-Criteria Decision Analysis considering environmental, economic, and social factors. Two methodological approaches were used for assigning weights, Analytical Hierarchy Process and the Ranked Order method. Two suitability maps of dam sites were produced out of these methods. The results were evaluated and for each suitable site, technical specifications were proposed.

Keywords: Multi-Criteria Decision Analysis, Analytical Hierarchy Process, Hydroelectric power, Costa Rica

1 Introduction
The area of interest is the Reventazón basin, located in the central parts of Costa Rica (Figure 1.). The basin is approximately 55 000 meters wide and 90 000 meters long and within it, many of Costa Rica's hydropower plants are located. Most of the rivers within this area are flowing outwards in a north-east direction into the Caribbean sea. This area is approximately 3800 km^2. The study area is based on the basin generated from the DEM, extended towards the ocean, so the basin contained the entire Reventazón river. Costa Rica is located in the tropics which means that the temperature in the summer does not change drastically from the temperature in winter (Brandt, 1999).

The city of San José is the capital and the biggest city within Costa Rica and is located partly within the Revantazón basin in the south-west. San José has approximately 340 000 inhabitants (INEC, 2011). 25 kilometres south-east of San José is another city called Cartago which is completely within the basin and it is estimated that around 150 000 people live there (INEC, 2011). Cartago is also the name of the region that covers most of the basin area, and within this region, there are around 500 000 inhabitants (INEC, 2011). The borders of the Reventazón basin and the Cartago region does not align completely but the number of inhabitants in the region gives a good estimation on how many people live in the basin area. Smaller villages and settlements are spread out across the basin as well.

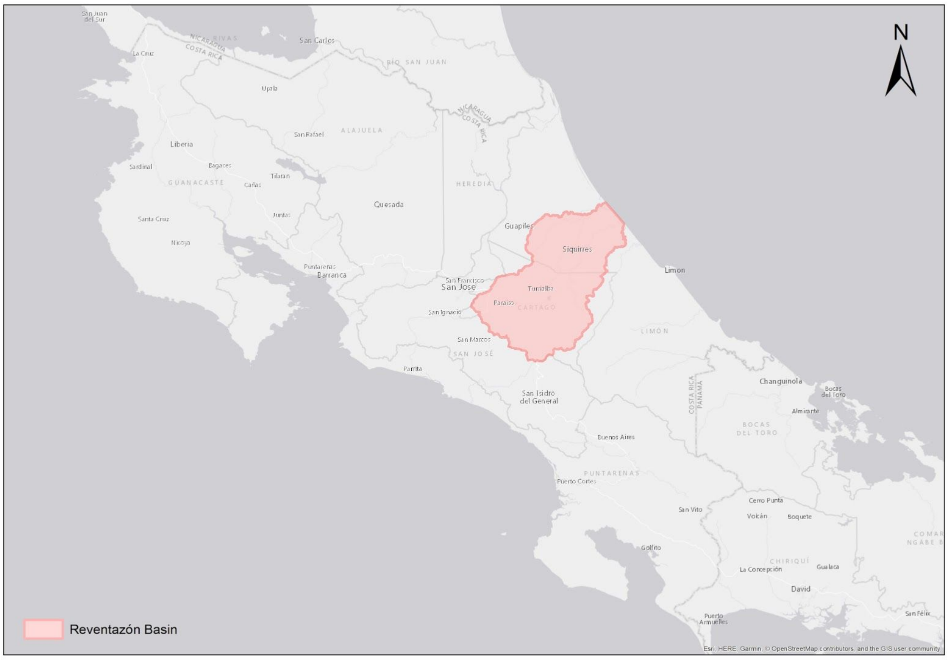


Figure 1. Reventazón basin in Costa Rica

During the 70s and 80s, Costa Rica went through an extensive deforestation period. Forests used to cover more than 50% of the country in the 70s but 20 years later that number had dropped below 35 % (Lutz & Daly, 1991). This trend of extensive deforestation met some objections in the form of forest restoration programs and institutions that were founded during the same time period (Calvo-Alvarado et al., 2009). The restoration programs were in many cases successful in making the deforestation less extensive and in creating a public opinion that valued the forest. So within the study area conservation values are regarded highly.

Water contribution in the Reventazón basin is mainly affected by relatively high mean annual precipitation of 3,780 mm (Brandt 1999, Vahrson 1992). One of the important contributors in precipitation are Caribbean tropical cyclones (Waylen et al. 1996) The precipitation is transferred to the water by run-off process, where the percentage of the rain precipitation is absorbed to the ground the rest end up in the water bodies and rivers due to the steepness of the terrain. Different surfaces have different types of run-off coefficients. Thus, thus the water contribution is also highly dependent land type or land use. Another important factor in the water contribution process is the evapotranspiration cycle. The annual average value of the evapotranspiration in the Reventazón basin is approximately 100 mm per month (Brandt 1999, Vahrson 1992).

The surface in the Reventazón basin freely passes from the mountainous areas to the hilly sites and then to the flat area around the coast within north-east direction. A major part of the area is covered by rainforests (Sanchez-Azofeifa and Harriss 1994). Other land types include agriculture, pastures, or plantations such as cocoa, banana, sugar cane, or coffee (León 1948). Nonetheless, rivers, reservoirs and lakes have their own place in the Reventazón basin as well, and it is indeed noticeable due to the high annual precipitation. The steepness of the terrain and high occurrence of water bodies makes Reventazón basin an oasis for hydropower plants.

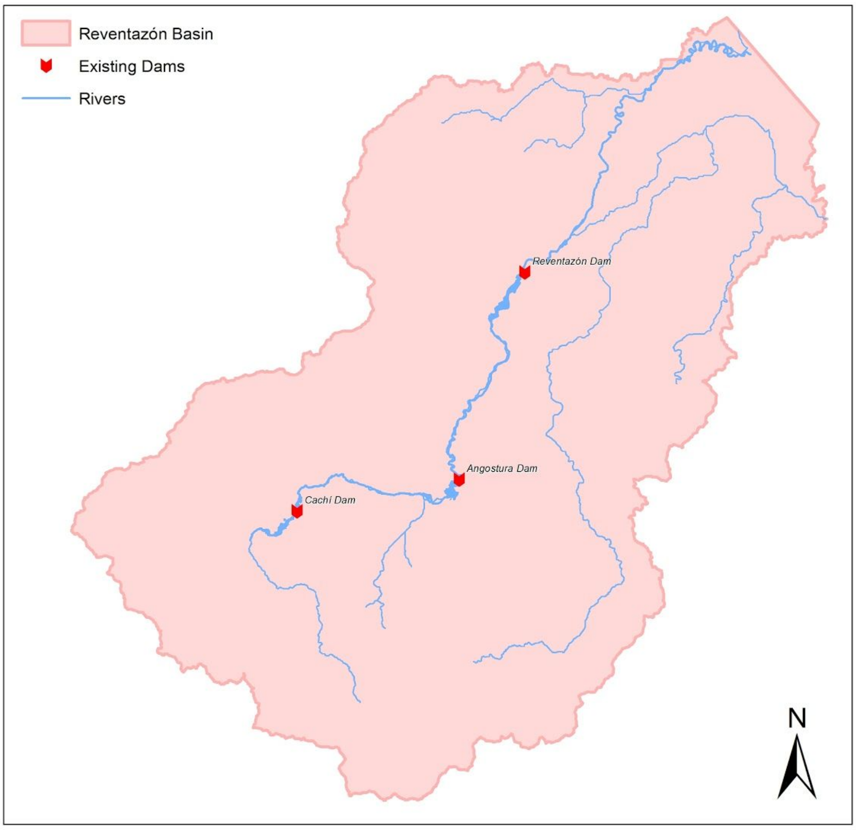


Figure 2. Reventazón basin and its existing dams.

Costa Rica has set a goal of having 100% renewable energy by 2030 (IHA, 2017) and in 2003 around 90% of the total energy come from renewable sources. In 2003, 71% of Costa Rica's total energy production comes from hydroelectric power sites (Nandwani, 2006) and at the end of 2016 Costa Rica had used nothing but renewable energy for 271 consecutive days (IHA, 2017). The many rivers in Costa Rica make extraction of energy from hydropower possible in this extent.

Conflicts of interest can arise in the development of new hydropower. Building new dams and reservoirs often limit the possibilities for land conservation due to the flooding that comes with it. The aim of this paper is to propose suitable areas where it is possible to locate a dam and its reservoir with a minimum impact on the environment. The new dam should also not limit other factors as well for example the proposed dam can not flood existing urban areas. Thus, environmental and social factors need to be accounted for in this analysis. Due to the nature of this problem i.e. many factors that need to be accounted for the method of choice fell on Multi-Criteria Decision Analysis.

The main aim of this paper was to locate suitable areas for further development of hydroelectric energy. In order for the proposed sites to be as good as possible social, environmental and economical factors were taken into account. Important environmental and social effects include information about how big the reservoirs will be and if it will flood existing cities. With this paper, suitable areas for further development of hydroelectricity are located as well as additional information about what kind of damn that can be built there are provided. This paper could in extension work as decision support for developers who want to develop hydroelectric power plants in the Revantazón region.

2 Methods

First, the primary methods used in this project are presented, then a more detailed workflow for this project is described. The pre-existing data that was used in this study include a Digital Elevation Model (DEM), Landsat Images and precipitation data for different stations within the basin. Additional information in the form of vector data was downloaded from OpenStreetMap (OSM). Data from OSM included existing water bodies within the area of interest and information about roads in the area.

2.1 MCDA

Macoun and Prabhu (1999) define MCDA as *"a decision-making tool developed for complex multi-criteria problems that include qualitative and/or quantitative aspects of the problem in the decision-making process."* In this definition, MCDA is a toolset for making a decision when facing a problem that is based on many different criteria. In this case, the environmental, social and economic criteria need to be accounted for. An MCDA can consist of both factors and constraints. Constraints are places that are not suitable at all and thus a restriction in the decision (Kordi and Brandt, 2012). These constraints are represented with a boolean scale where 0 indicates not suitable and 1 indicates a suitable location. Factors, on the other hand, represent different criteria, it can, for example, be the distance to or from different features that are of interest. A map for each factor/constraint is produced and weights for the factors are calculated. The weights represent how important each factor are. A higher weight means a higher impact on the final map. The constraint maps are multiplied with each other resulting in a map representing all of the constraints. The factor maps are multiplied with its weight and then added together resulting in a weighted factor map.

Since there are several factors, some of them might not be as much important as the others. The hierarchy of criteria weights determines the result. Thus, the study must have stated priorities, whether it is the protection of natural environment, reduction of costs, or maximising the production. Either way, there should always be an effort to minimise impacts on the environment and surrounding. MCDA done in proper manner provides sustainability and minimising environmental impacts in the environmental sciences.

The MCDA has been used in several scientific fields for a couple of decades already. Therefore, there is much literature written on this topic providing many framework models. Nevertheless, not all of these studies and approaches are complex enough to describe and solve proposed issues. Vassoney et al. (2017) contributed to the MCDA application field with the list of necessary phases and descriptions of complex study. According to these phases, a proper MCDA study should contain a detailed description of the study area, extent or either scale of the study area (national, regional, local, area units or distances); detailed description of study case, implemented software, circumstances regarding the problem solution, or participants of the decision-making. These parameters provide a better description and help to understand the background of the study are. Accordingly, the same pattern might be applied for the analysis process itself. Namely, it is a methodology (description of used approaches), well-described list of criteria, alternatives of solutions, sufficient discussion on achieved results, or additional supportive statistics (Vassoney et al. 2017). Following these guidelines might improve not only the study itself but the interpretation of results too.

2.2 AHP

The analytic hierarchy process (AHP) is the most used method regarding environmental studies. Huang et al. (2011) claimed in their bibliometric study that almost half of MCDA-based studies used the AHP approach for weights. It is a mathematical-based method in which the complex decision is being analysed and organised to be more balanced (Saaty 1980). It has three hierarchical phases with one-way relationships among them. In the first one is the objective of evaluation, in the second one are the criteria of evaluation, and in the third one are the alternatives of choices see *Figure 3*. The definition of AHP in a mathematical way is based on the matrix of pairwise comparisons among criteria. More generally is a matrix of one-to-one criteria relations.

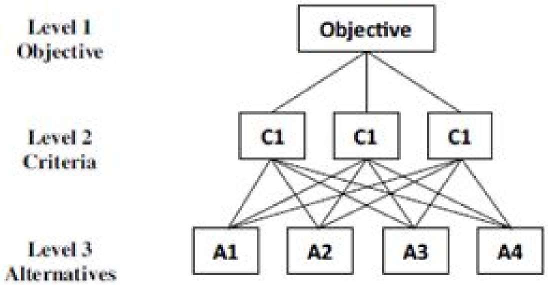


Figure 3: Schema of AHP hierarchy, Source: Fuentes-Bargues & Ferrer-Gisbert (2015)

2.3 Rank order

In this study two different weighting methods were used, the Rank Order (RO) method and AHP. The RO method is the most basic method for deriving at weights and according to the Sureeyatanapas, (2016) this method should only be used to get a first approximation of suitable areas. For more precise results the AHP method is recommended. Important to note that both of these methods have a degree of subjectivity within them. In ranked order method the factors are ranked in regard to their importance. The most important factor is assigned 1 and the second most important factor are assigned 2, this process continues until every factor has been assigned a value. In order to get the weights this mathematical expression is used:

((amount of factors) +1 -(the rank order of a factor)) / sum of all factor values

If this procedure is repeated for each factor, all factors will have weights. The weights represent how many percents that factor will impact the final result. The sum of all the weight should always be 1. As stated before, weights derived from this method should not be used as a final result due to the basic structure of the method. The weights could be used as a preliminary indication of results to come from the AHP.

Table 1. Weights obtained from AHP and RO

Factor	Rank order	AHP
Undulation	0.28571	0.35426
Close to city	0.23810	0.23005
Hydro. head	0.19048	0.18684
Water discharge	0.14286	0.11986
Forest	0.09524	0.06364
Roads	0.04762	0.04535

3 Data processing

The very first step was to gain knowledge about the study area which was done through an extensive literature study. Based on the literature study was possible to figure out what criteria should be a part of spatial MCDA. Forest conservation is regarded highly in this region, thus it was chosen as a criterion. According to Baban and Wan-Yosof (2003), the most important criteria for locating dams and reservoirs are 1. Urban areas, 2. Topography, 3.Geology, and 4. Agricultural land classification. All of the mentioned criteria can be obtained from a DEM, Satellite images, or geological maps. Through the literature study it was concluded that the study area is prone to landslides, which should have been taken into account in this study but due to lack of a geological map, the criteria was not included. Urban areas can be viewed both as a factor and a constraint. The construction of a new dam should have not been at a location that would flood already existing urban areas, thus it was used as a constraint. At the same time, it is more efficient to build it close to urban areas due to a lower cost of laying cables, i.e. the closer to a city the dam is built, the less work is needed to bring the electricity to where it is needed. The increased interest in forest conservation leads to another factor and constraint. The dam should not be built in the virgin forest, which is a forest that has not been touched by humans. Thus, the distance of potential dam sites to the virgin forest is also important. The farther away it is, the better.

In order to produce electricity from a new dam, there are some conditions that need to be met. The water discharge or the flow of the water must be over $5m^3/s$, otherwise, the energy production will not be sufficient. The amount of $5m^3/s$ is only a minimum value needed, the higher water flow, the better, and the more efficient it the energy production. The undulation within the surrounding areas of the river should be formed in such a way that it can hold the water. By using the existing terrain, more water can be stored within a smaller dam. There is no need to build a high dam if the terrain can hold the water anyway. The higher the undulation is, the better, and the lower demands on construction are. Another important criterion that affects the water discharge is the hydrological head, i.e. the steepness of the slope that the water runs along. In table 2., all the factors and the constraints within this study are listed.

Table 2. Constraints and Factors

Constraint	Description	Factor	Description
Virgin forest	Dam can not be built in virgin forests,	Roads	Close to roads are good, economical reasons
	virgin forest = 0, every thing else = 1	Urban areas	Close is good, economical reasons
Urban areas	Dam can not be built on urban areas,	Undulation	The more undulation the better, more energy
	urban areas = 0, every thing else = 1	Hydrological head	The bigger slope the better, more energy
Existing dams	Dam can not be built on existing dams,	Forest	The further away the better, conservation
	dams = 0, everything else = 1	Water flow	The more the better, more energy

After the factors and criteria were decided, they had to be created. The data processing workflow has been split into five parts. First one was the procedure of getting factor and constraint maps for urban areas and virgin forests. The methodologies of gathering urban area and virgin forest layers were relatively similar, thus they have been described together. Similarly, the second one was the methodology used to get the land use and runoff layer. The third one was about getting the water discharge layer. The fourth part was focused on the hydrological head and undulation. Finally, the fifth part was dedicated to the Roads and existing dams. The whole workflow is visualized in

Appendix A. Resolution of all the data was 30m x 30m according to the “thousand-million” rule (American Society of Civil Engineers 1999).

3.1 Urban Areas and Virgin Forest

From the Object-Based Image Analysis (OBIA) in the eCognition software, the urban areas and virgin forests could be classified in a satisfactory way based on Landsat 7 imagery and the DEM. The process of classification in OBIA can be split into two different categories. The first part is to create objects, which is done through multiresolution segmentation of the images. Urban areas were segmented, from bands 2, 4, and 7. Classification of urban areas was made in regard to “brightness”, “standard deviation” and “Max. Difference”. Segmentation for the virgin forests was done in a similar way, only based on bands 2, 3, and 4. The classification of virgin forest was based on Normalized difference vegetation index (NDVI), and height above 1400 m.a.s.l. The results of OBIA analysis were exported as vector data for further processing. Then they were converted into rasters and reclassified according to the boolean constraint maps schema, i.e. 0 for urban areas and virgin forest and everything else were assigned to value 1. This resulted in two constraint maps, one for urban areas and one for virgin forests (se figure 4. a) and b)). The third constraint map of existing dams is based on OpenStreetMap (OSM) data.

Table 3. Landsat 7 bands and their wavelength

Landsat 7 (ETM+ sensor)	Wavelength (micrometers)	Resolution (meters)
Band 1-blue	0.45 - 0.515	30
Band 2-green	0.525 - 0.605	30
Band 3-red	0.63 - 0.69	30
Band 4-NIR	0.75 - 0.90	30
Band 5-SWIR	1.55 - 1.75	30
Band 6-Termal	10.40 - 12.5	60
Band 7-SWIR2	2.09 - 2.35	30
Band 8-Pan Band	.52 - .90	15

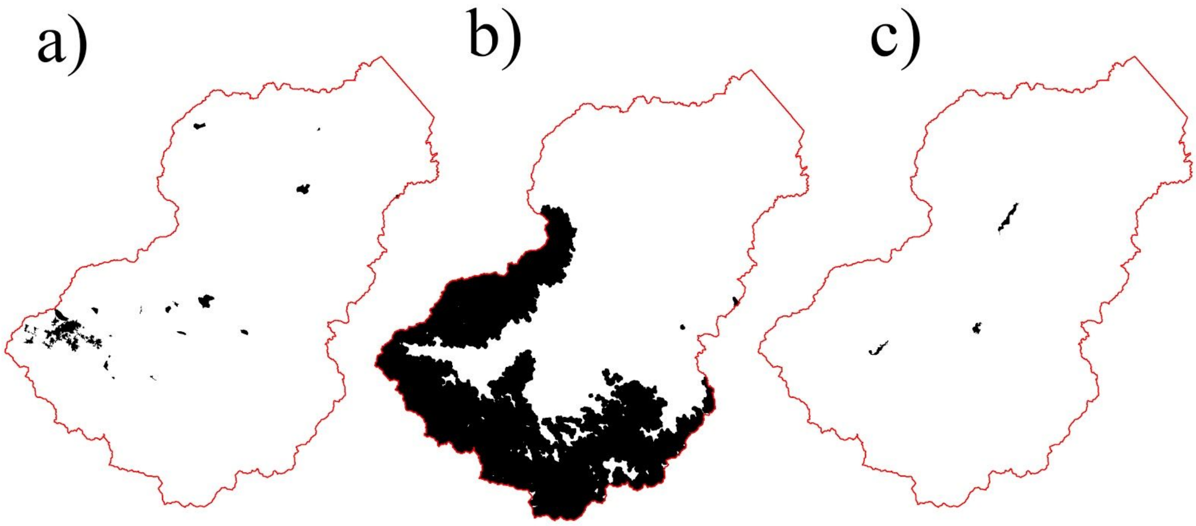


Figure 4. The constraint maps used in this study. The non-suitable areas are represented by black and the value of those areas are equal to 0. The white areas represent suitable areas, (=1). a) Urban Areas, b) Virgin forest, and c) Existing dams.

3.2 Land use and runoff

In order to create a factor map for water discharge, a land use map needed to be produced. This map was made in the TerrSet software by supervised classification. The supervised classification was based on 6 classes: 1. Water, 2. Urban Areas, 3. Forest, 4. Clouds and noise, 5. Pasture, and 6. Agriculture. Training sites for each class were identified and used in order to produce the land use/land cover map.

“Runoff” is a measurement of how much water stays in the ground and how much water runs off into the rivers, according to Miller (1994) the runoff is mostly based on land use and on the degree of steepness in an area. Therefore a “runoff” coefficient was given to each land use class. The coefficient for clouds and noise class was given the same coefficient value as the forests because most of the cloud coverage occurred on top of the forests. Coefficients were based on Miller’s (1994) calculations. The coefficients can be seen in Table XX. The coefficients can be interpreted as, for example in forests, that 80% of water runoff and contribute to the rivers, while 20% is absorbed in the ground. The value also changes with the different level of slope. The steeper the slope the more water runoff into the rivers.

Based on the DEM a slope map was made. This slope map was reclassified into the four classes (table 3) and assigned the slope-runoff coefficient. The land use map and the slope map were then multiplied with each other in order to get a map of the total runoff percentage.

Table 4. Runoff Coefficients for land use and slope

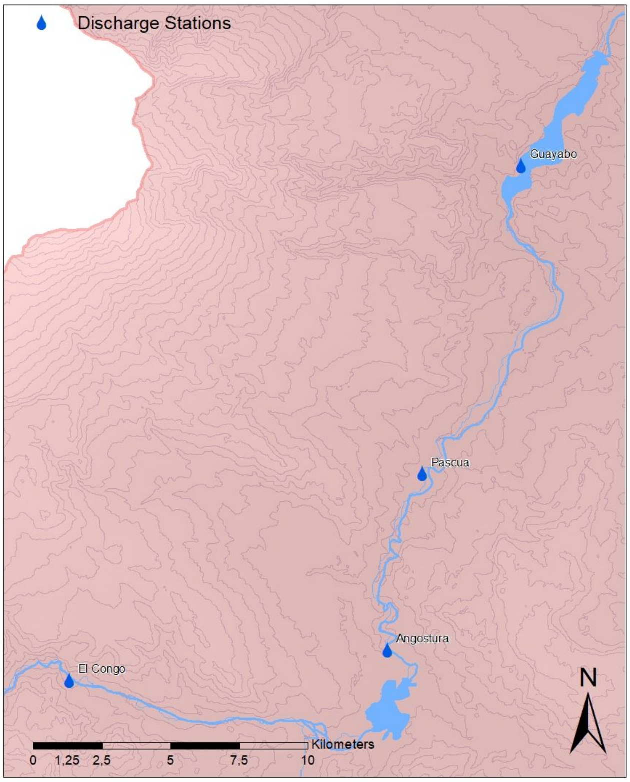
Landuse	Slope %
Urban areas 0.95	Extremely steep slope (>20) = 1
Water 1	Hilly/steep slope (>12) = 0.95
Forest 0.8	Medium slope (>5) = 0.90
Cloud 0.8	Gentle slope (>0) = 0.80
Pasture 0.7	
Agriculture 0.6	

3.3 Water Discharge

Based on the precipitation data, a continuous raster was made by Thiessen polygon interpolation. According to Brandt (1999), the monthly evapotranspiration in this region is estimated to be around 100 mm/month. In order to take the evapotranspiration into account, the rainfall raster was subtracted with 1200 mm/year. (12*evapotranspiration per month). The values were at this point still in millimetres so it had to be transformed into m^3/s, which was made with the following expression:

$$m^3/s = (\text{Weighted runoff grid [mm]} * 0.001 * \text{cell area [m2]}) / (60*60*24*365 \text{ [s]})$$

The rainfall raster was then multiplied with the runoff raster. This resulted in a new raster in which precipitation, the runoff for slope and land use, and evapotranspiration had been accounted for. This step was required in order to perform a weighted flow accumulation. The weighted flow accumulation resulted in a raster of rivers with the accumulated water discharge for each pixel. This water discharge image was filtered so that only pixels with more than $5m^3/s$ were left. This water discharge map was used both as a factor and as a way to calculate the hydrological head and the undulation. For the use of the discharge map as a factor, the values were normalized by stretching to a scale of 0-255 (see figure XX).



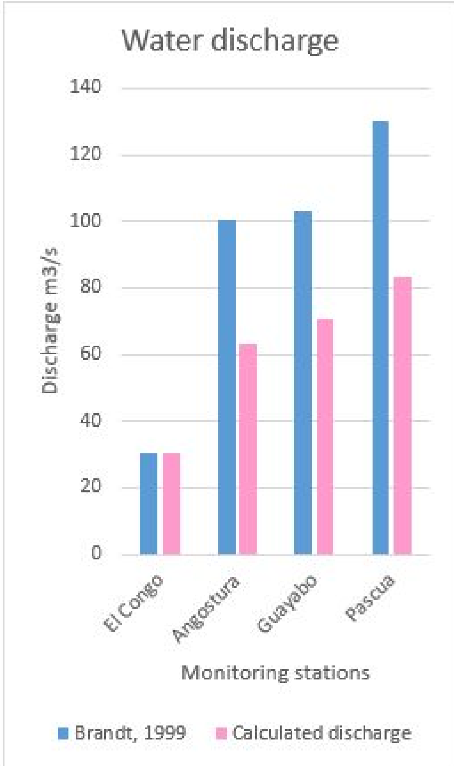


Figure 5. Four points along the Reventazón river (left), and their water discharge (right)

3.4 Hydrological head and Undulation

Based on the water discharge and the DEM, the hydrological head could be calculated with the tool "focal statistics" in ArcScene software. For the hydrological head, the minimum value within a circle with a radius of 1000 meters was chosen regarding the rivers with DEM heights. For undulation, the maximum value of a circle with 500 meters was chosen regarding the DEM itself. Focal statistics assigns the minimum/maximum value within a chosen range to a cell. The undulation and hydrological head were then normalized to the same scale as water flow i.e. 0-255 so they could be used as factor maps (see figure 6. a) and c)).

3.5 Roads and existing dams

Data downloaded from OpenStreetMap contained roads and existing water bodies in the area. The water bodies for the existing dams were identified and turned into a constraint map by rasterizing the vector. The Euclidean distance was applied to the roads and then the values were stretched in order to produce a factor map for the distance to roads.

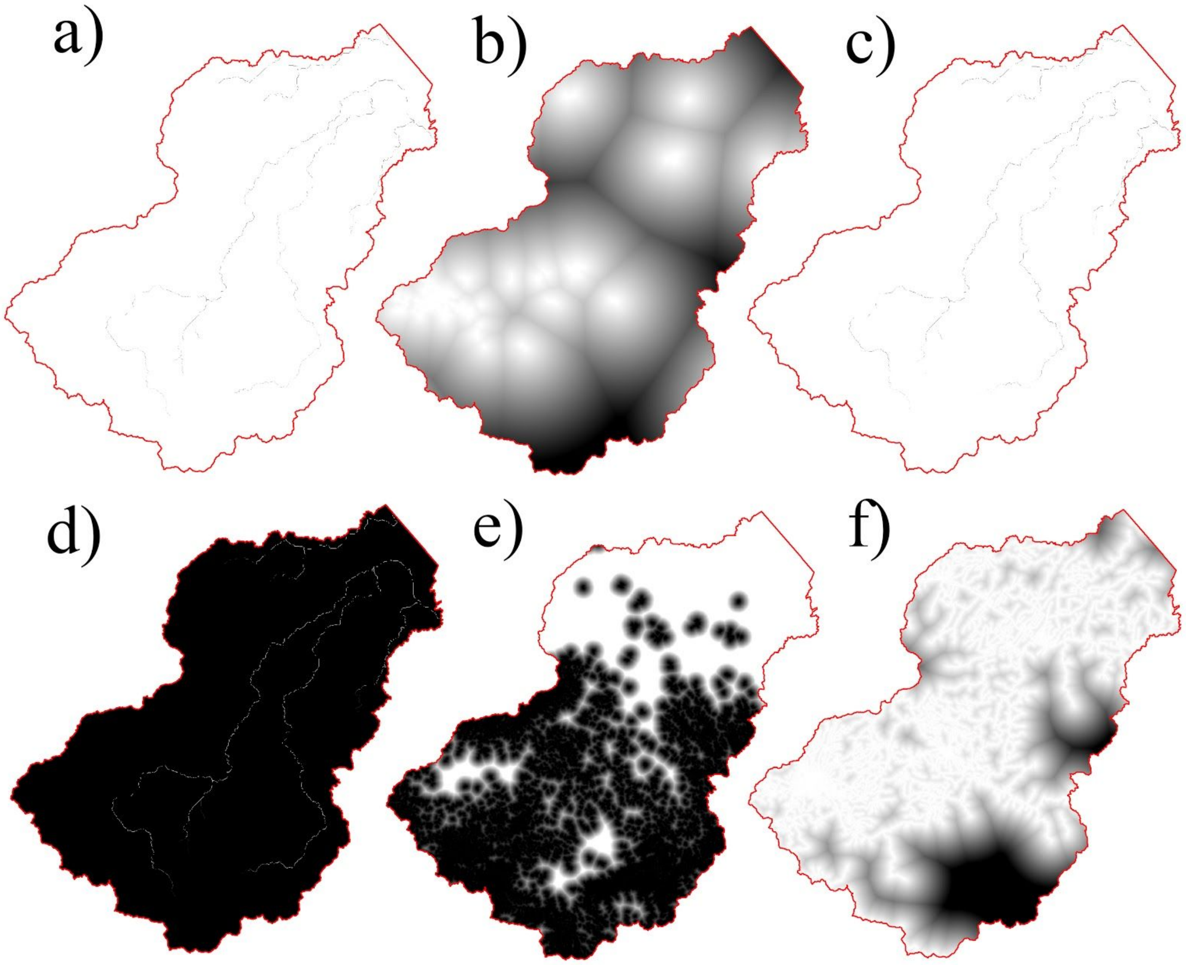


Figure 6. Factor maps used in this study. All factor maps have been stretched to the scale of 0-255. Black represents a lower value and white represent a higher value. a) Undulation, b) Cities, c) Hydrological head, d) Discharge, e) Forest, and f) Roads

4 Results

The use of AHP, as well as the RO method, resulted in two different suitability maps. The highlighted areas indicate suitable areas for development of new hydroelectric power plants. Both methods achieved relatively similar results, except for a few differences which are further discussed in section 4.1 and 4.2. After the visual classification was done, the highest values were considered as potentially suitable. The research of these location has been done to verify its suitability, explore its surrounding, examine its factors, and discuss consequences of different scenarios. Thus some of the potential sites were omitted straight after the MCDA phase. After the research, only three out of five possible sites were evaluated as a suitable and for each site were derived technical specifications, such as area, volume, potential energy and so forth (Table XX. tech spec). Different alternatives of dams were proposed in light of the size and potential energy production to derive at a more versatile portfolio for the final construction scenario.

4.1 Rank-order-based MCDA

RO method of MCDA has produced four probably suitable areas. Two out of these areas were located in between existing dams on the Reventazón river. The third of them was located on the Pacuare river in the lower elevation in the north direction, and the fourth in the more southern mountainous area on the Marta river (Figure 7). Even though the four alternatives were suitable according to the RO MCDA results, after examining the factor values and its potential energy production was omitted. The energy potential and its location were way weaker than in other alternatives.

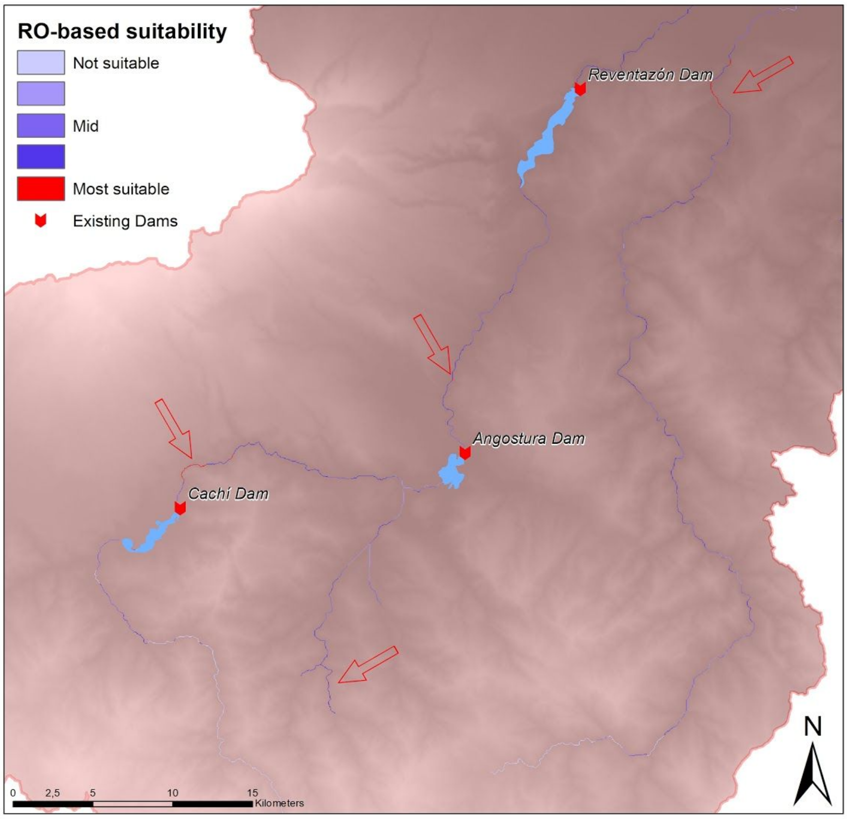


Figure 7. Most suitable locations based on the RO method

4.2 Analytic-hierarchy-process-based MCDA

Based on weights obtained from AHP, five potential sites were located (Figure 8). Four of them correlate with the results from RO MCDA, which improves their credibility. The alternative located in the more southern mountainous area on the Marta river was omitted for from the same reasons as in the RO MCDA. The new area, which appeared in the AHP results is located southern more on the Pacuare river. After considering the potential energy production and its location, this alternative was omitted as well. Thus only the three most suitable alternatives were selected out of five different options.

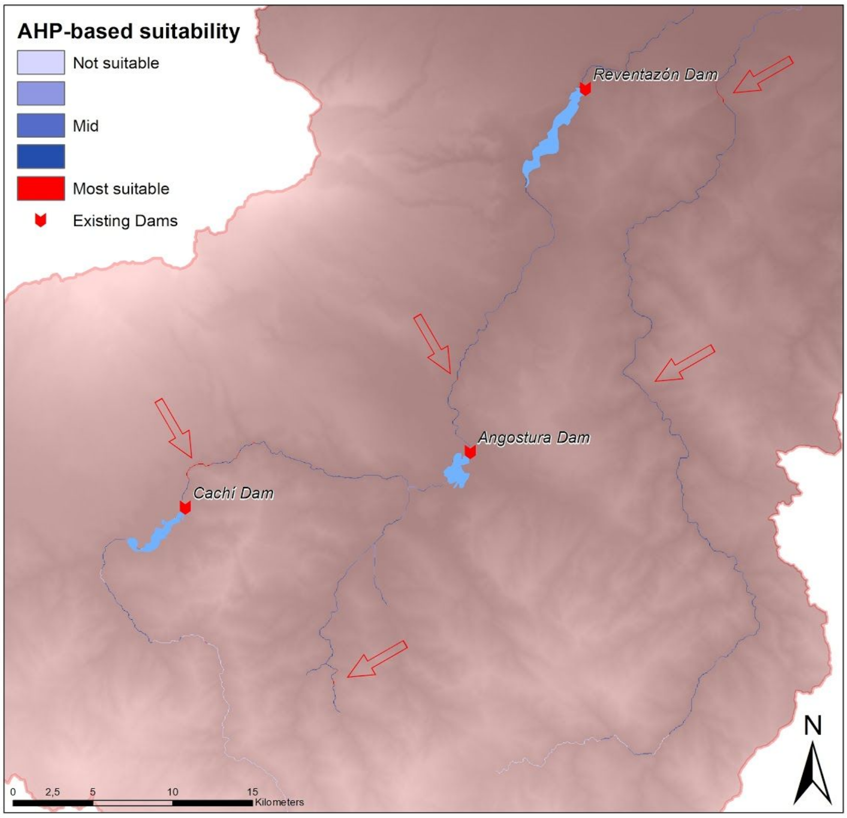


Figure 8. Most suitable locations based on AHP

4.3 Proposed alternatives

Both MCDA methods were selected out of different options. The decisions were based on the AHP method as of more legible and complex method (Vassoney et al., 2017). Nevertheless, both methods of performed MCDA resulted in the same three most suitable sites. Considering the values from factor maps, these three options were formulated by seven technological specifications based on their surroundings (Table 5.). The flooded area was visually represented in Figure 9. as well as calculated in the form of area and volume of the water bodies (Table 5). The technical specifications of alternatives were designed considering all the factors and taking different hydropower demands into account. Therefore, the more specified hydropower production demands are, the easier it is to decide optimal alternative. The same pattern of decision can be applied to the conservation of the environment. The dam with smaller flooded area and volume can be considered as less harmful for the environment.

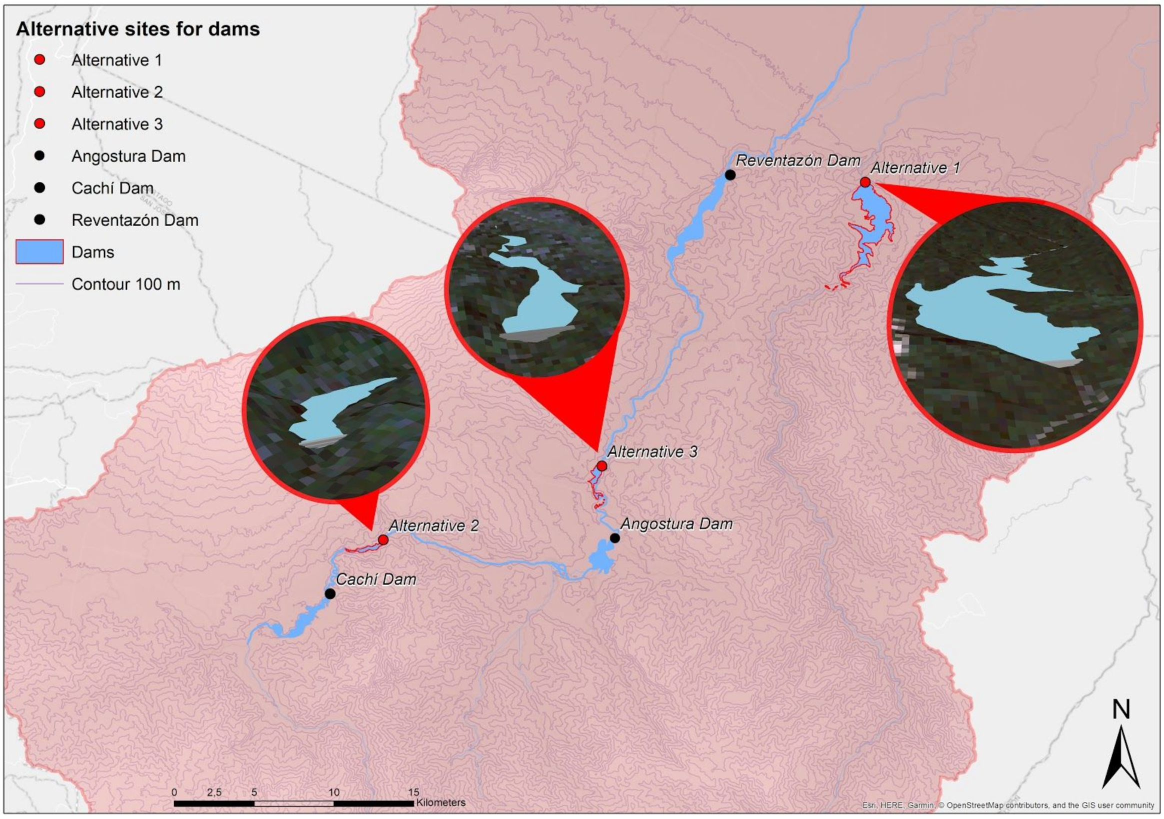


Figure 9. Three alternatives proposed for the hydropower plant construction

Table 5. Technical specifications for the three alternatives of hydropower plant construction

	Alternative 1	Alternative 2	Alternative 3
Potential energy [kW/h]	190541353	97525474	149517169
Distance to nearest power plant [km]	8,5	4,7	4,6
Width of dam body [m]	390	180	420
Flooded Area [m2]	711619	514960	6769831
Volume (water capacity) [m3]	14656019	11860053	287839706
Height of hydro head [m]	68	45	30
Water discharge [m3/s]	38,4	29,7	68,3

4.4 Consequences of the alternatives

The research of alternative's surroundings was done to see the effects on the settlements close to the proposed areas. In this phase, the areas that might be potentially flooded were examined whether there are some buildings or facilities or where are the nearest settlements and how many inhabitants are there. Alternative 1 is located on the Pacuare river and close to the Siquirres city with approximately 30,000 inhabitants (INEC, 2011). The are no houses or facilities that would be flooded. Compared to the other alternatives this one is the biggest and it is flooding the biggest area. On the other hand, it has the highest potential energy production. Thus, it might be suitable for Siquirres city as the main source of energy. Alternative 2 has a way smaller flooded area compared to the Alternative 1, thus might be less harmful to the environment. Choosing this alternative would mean to flood some of the houses next to the river. Other than that there is no other settlement in danger. Alternative 3 is located in the area around which is close to a lot of cities and villages, thus both of these has a suitable location considering closeness to the city. Both alternative 2 and 3 are on the Reventazón river as well. Alternative 3 would not flood settlements, neither facilities (Figure 10. and 11.).

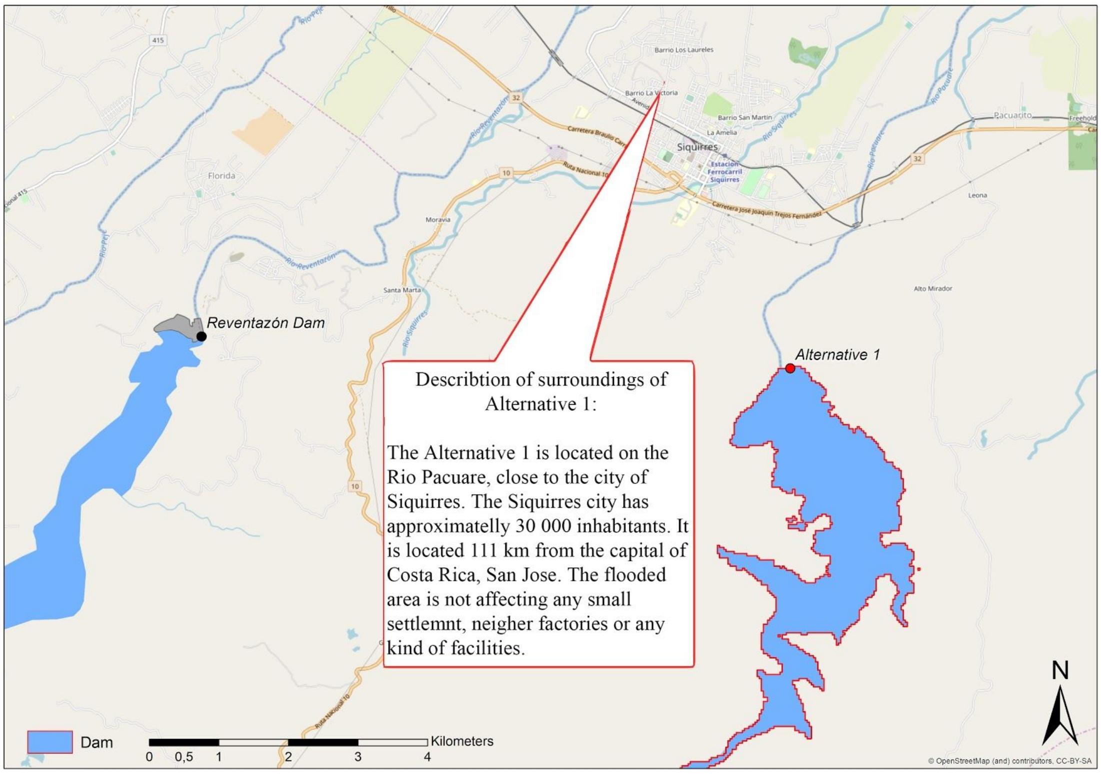


Figure 10. Study of the effects of Alternative 1

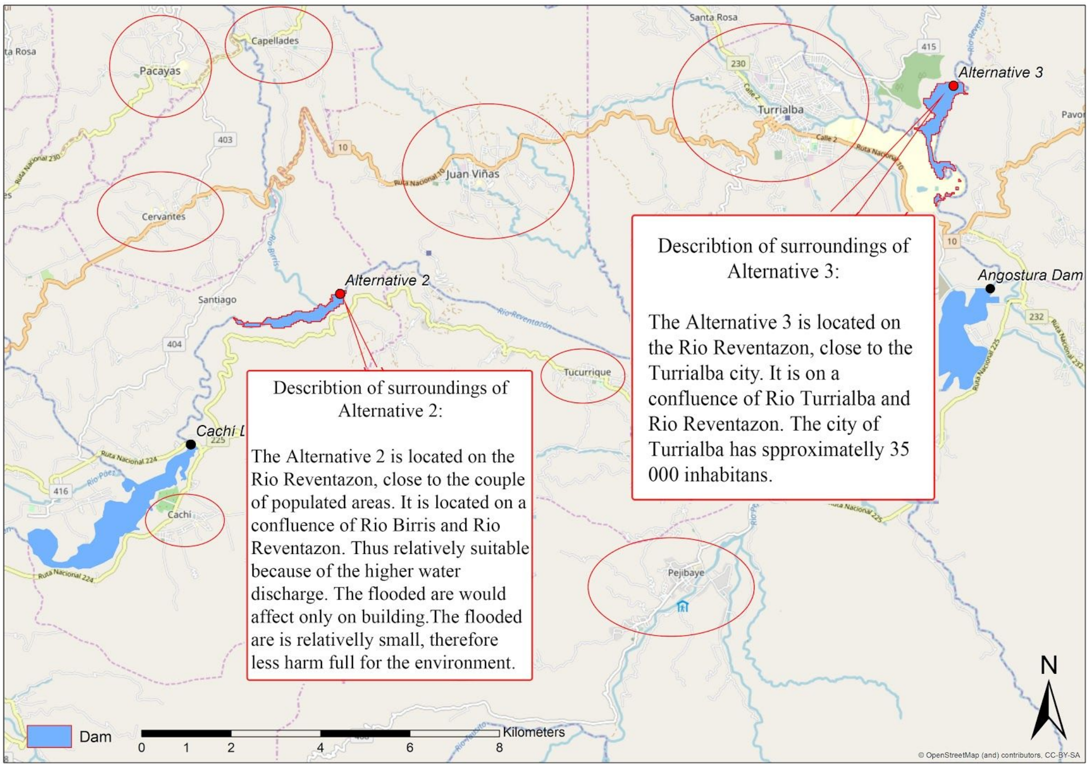


Figure 11. Study of the effects of Alternative 2 and Alternative 3

4.5 Sensitivity analysis and evaluation

Since the CR index, **0.0282** is lower than 0.1, the assigned weights of AHP are being considered as a robust and well-balanced. (Saaty 1980). The robustness of AHP weights was also tested by changing the importance of undulation factor towards other factors (*Table 6*). In the first step, the factor was lowered by 10% of its importance in the pairwise comparison towards each criterion. In the second step, the difference was increased to 30%. A new set of weights was compared to the original one by subtraction. The changes in each weight are visualised by either positive and negative change. The observed changes were within the same direction and relatively small Thus, assigned weights might be considered as robust (Triantaphyllou and Sánchez 1997).

Table 6. Sensitivity analysis of the AHP. Delta shows the change in weights after undulation was lowered in the pairwise comparison by 10%, and then by 30%.

Rank	Factor	Used weights	10% change	30% change	Delta 10%	Delta 30%
1	Undulation	0,35426486	0,3307246	0,2779927	**-0,0235403**	**-0,07627**
2	Cities	0,23005078	0,2383665	0,2569775	**0,0083158**	**0,02693**
3	Hydro. head	0,18683537	0,1937359	0,2092183	**0,0069005**	**0,02238**
4	Discharge	0,11985656	0,1241389	0,1337082	**0,0042823**	**0,01385**
5	Forest	0,06364016	0,0659838	0,0712386	**0,0023437**	**0,0076**
6	Roads	0,04535227	0,0470503	0,0508647	**0,0016980**	**0,00551**

5 Discussion and Conclusion

In both AHP and in the RO method there is a degree of subjectivity. In the RO method, the criteria were ranked, as well as in AHP the weight coefficients were assigned, based on the author's judgement. By conducting interviews with experts and letting them express their opinion about which criteria are more important could have minimized the degree of subjectivity. Important to note is that both AHP and RO always contain some degree of subjectivity, there is never an absolute truth to what criteria is most important, and some people might value the importance of different criteria completely different which in some cases makes it hard to assign weights.

In some instances within this project, the need for specific constraint maps was reduced by the fact that the constraint already had been incorporated by a factor map. For example, both the undulation and hydrological head factor map only contained rivers that exceeded a flow of 5 m^3/s and a factor map of flow had also been created so there was no need for a constraint map with the same information. This is why water discharge is not listed in table 2 as a constraint.

In this paper, suitable sites for further development of hydroelectricity have been identified and potential effects on social, ecological and economical factors have been accounted for. This paper could lay the foundation for selecting one final site. Which could be done in the future by creating a new MCDA but for the three sites depending on the criteria that the developer deems most important. This was left undone in this study in order for future stakeholders to have their say as well. Therefore we have proposed three different sites suitable for various demands on electricity production, environmental conservation and the construction costs.

Further research may include a study regarding the geological nature of the Reventazón basin. According to Brandt (1999), the geological constitution has a high impact on the sediments transported in the river. The new reservoir might also affect the geomorphology in the Reventazón basin. Most importantly, there would be a need for a study on the effects that the proposed dams could have on the existing dams.

References

American Society of Civil Engineers (1999). GIS Modules and Distributed Models of the Watershed: Task Committee on GIS Modules and Distributed Models of the Watershed, ISBN: 9780784404430

Baban, S. M., & Wan-Yusof, K. (2003). Modelling optimum sites for locating reservoirs in tropical environments. *Water Resources Management*, 17(1), 1-17. doi:10.1023/A:102306670

Brandt, S. A. (1999). Reservoir desiltation by means of hydraulic flushing: Sedimentological and geomorphological effects in reservoirs and downstream reaches as illustrated by the cachí reservoir and the reventazón river, Costa Rica. Institute of Geography, University of Copenhagen.

Calvo-Alvarado, J., McLennan, B., Sánchez-Azofeifa, A., & Garvin, T. (2009). Deforestation and forest restoration in guanacaste, costa rica: Putting conservation policies in context. *Forest Ecology and Management, 258(6). 931-940.* doi:10.1016/j.foreco.2008.10.035

Huang, I. B., Keisler, J., & Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. *Science of the Total Environment*. doi:10.1016/j.scitotenv.2011.06.022

Instituto Nacional de Estadística y Censos (INEC) (2011). Censo 2011. Distribución porcentual de las personas por número de carencias críticas, según cantón.

International Hydropower Association (IHA) (2017). Costa Rica Angostura, retrived from www.hydropower.org/case-studies/costa-rica-angostura, 2019-03-19.

Kordi, M., & Brandt, S. A. (2012). Effects of increasing fuzziness on analytic hierarchy process for spatial multicriteria decision analysis. *Computers Environment and Urban Systems,* 36(1). 43-53. doi:10.1016/j.compenvurbsys.2011.07.004

León J. (1948). Land utilization in Costa Rica. *Geographical Review,* 37(3). 444-456. doi:10.2307/210905

Lutz, E., & Daly, H. (1991). Incentives, regulations, and sustainable land use in Costa Rica. *Environmental and Resource Economics,* 1(179). 179-194. doi:10.1007/BF00310017

Macoun, P., & Prabhu, R. (1999). Guidelines for applying multi-criteria analysis to the assessment of criteria and indicators. CIFOR: Jakarta, Indonesia. doi:10.17528/cifor/000769

Miller, S. (1994). Handbook for agrohydrology. Natural Resources Institute, University of Wisconsin

Nandwani, S. S. (2006). Uses of solar energy in Costa Rica. *Renewable Energy,* 31(5). 689-701. doi:10.1016/j.renene.2005.08.008

Saaty, R. W. (1980). The Analytic Hierarchy Process. *Decision Analysis.*

Sanchez-Azofeifa, G.A. and Harriss, R.C. (1994). Remote sensing of watershed characteristics in Costa Rica, *Water Resources Development*, 10(2), 117-130 doi:/10.1080/07900629408722617

Sureeyatanapas, P. (2016). Comparison of rank-based weighting methods for multi-criteria decision making. *KKU Engineering Journal*. 43(). 376-379. doi:10.14456/kkuenj.2016.134.

Triantaphyllou, E., & Sánchez, A. (2007). A Sensitivity Analysis Approach for Some Deterministic Multi-Criteria Decision-Making Methods. *Decision Sciences*. doi:10.1111/j.1540-5915.1997.tb01306.x

Vahrson, W.G. (1992). Tropische Starkregen und ihre Verteilung - das Beispiel des Einzugsgebietes des Río Reventazón, Costa Rica (Spatial distribution of heavy rainfalls in the tropics - the example of the Río Reventazón catchment, Costa Rica). *Die Erde,* 123 (1), 1-15 (in German).

Vassoney, E., Mammoliti Mochet, A., & Comoglio, C. (2017). Use of multicriteria analysis (MCA) for sustainable hydropower planning and management. *Journal of Environmental Management.* doi:/10.1016/j.jenvman.2017.02.067

Waylen, P. R., Caviedes, C. N., & Quesada, M. E. (1996). Interannual variability of monthly precipitation in Costa Rica. *Journal of Climate,* 9(10). 2606-2613. doi:10.1175/1520-0442(1996)009<2606:IVOMPI>2.0.CO;2

Figure sources

Fuentes-Bargues, J. L., & Ferrer-Gisbert, P. S. (2015). Selecting a small run-of-river hydropower plant by the analytic hierarchy process (AHP): A case study of Miño-Sil river basin, Spain. *Ecological Engineering*. doi:10.1016/j.ecoleng.2015.10.020

Appendix

Workflow