Masters Program in Geospatial Technologies

Siting feasible water catchments for small irrigation projects in Western Honduras

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Siting feasible water catchments for small irrigation projects in Western Honduras

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis, and it has been written independently by me, solely based on the specified literature and resources which have been cited appropriately. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

The thesis has never been submitted for any other examination purposes. It is submitted exclusively to the Universities participating in the Erasmus Mundus Master program in Geospatial Technologies.

Castellón de la Plana, 26 February 2015

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ABSTRACT

In Western Honduras, most of people live in rural areas under extreme conditions of poverty. This area is part of the Centro American dry corridor which is affected by droughts and, therefore, water scarcity. Access to water is limited; which affects human welfare and agricultural production. As a plausible solution, this thesis work provides a tool to identify feasible water catchments for small irrigation projects in Western Honduras based on Geographic Information Systems (GIS) and surface features. This tool can support decision makers to address water catchments in the study area.

Two versions of this tool were developed. Both desktop and online versions allow the user to find potential sites to take water from streams through hosepipes. The suggested paths, over which these hosepipes can be installed, are modeled by using the Least-Cost Path (LCP) approach. We contrasted the results provided by the tool with two actual cases. The results showed the potential of this tool to find possible water intakes different from the current cases. In both cases, the tool was capable of finding water intakes very close to the current sites. This thesis proves that the use of GIS technologies in combination with decision rules and surface features can provide a novel solution to the real problem of water scarcity in Western Honduras.

KEYWORDS

Dry Corridor

Extreme Poverty

Geographic Information Systems

GIS Application

Irrigation Systems

Surface Features

Least-Cost Path

Water Catchments

Water Scarcity

ACRONYMS

ACF	Action Against Hunger
ASTER GDEM	Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Map
CIAT	International Center for Tropical Agriculture (Centro Internacional de Agricultura Tropical)
DEM	Digital Elevation Model
ENSO	El Niño-Southern Oscillation
ESRI	Environmental Systems Research Institute, Inc.
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic Information System
ICF	National Institute for Conservation and Forest Development, Protected Areas, and Wildlife
IFSAR	Interferometric Synthetic Aperture Radar
LCA	Least-Cost Analysis
LCP	Least-Cost Path
LULC	Land Use/Land Cover
METI	Ministry of Economy, Trade and Industry of Japan
NASA	National Aeronautics and Space Administration
NGA	National Geospatial-Intelligence Agency
SRTM	Shuttle Radar Topography Mission
UNDP	United Nations Development Programme

USAID	U.S. Agency for International Development
USD	U.S. Dollar
USGS	U.S. Geological Survey

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

The Government of Honduras, the U.S. Agency for International Development (USAID) and the International Center for Tropical Agriculture (CIAT) are working together to try to establish a solution to the water shortage in Western Honduras. This area is affected by extreme climatic conditions and cyclical droughts related to the phenomenon of El Niño-Southern Oscillation (ENSO) (FAO & ACF, 2012). The study area of this project is located in Western Honduras and is part of the Centro American “dry corridor” (corredor seco) which is formed by some areas of Guatemala, Honduras, El Salvador and Nicaragua (FAO & ACF, 2012).

Water scarcity and droughts occur especially in arid or semi-arid areas where the contrast weather impacts crops carrying them into low yields as well as affecting farmers who get low farm incomes (Pulver, Jaramillo, Moreira, & Zorrilla, 2012). This is what happens in the Honduran “dry corridor”, where people live in extreme poverty with incomes lower than $2 USD per person per day and most of farmers practice rainfed subsistence agriculture (The World Bank, 2015). In this context, water access plays an important role as the main source for human welfare and agricultural production. One of the ways to try to reduce agricultural loss for small farmers, who are the most affected by water access, is establishing irrigation systems and, therefore, providing water for agricultural production (Mwenge Kahinda, Rockström, Taigbenu, & Dimes, 2007). The most common water sources used for irrigation in the Western part of Honduras are catchment points from streams. The target population of this study is smallholders living in rural areas in the zone of influence; who conduct water to the farms through hosepipes by using gravity (Smits, Mejía, Rodríguez, & Suazo, 2010). The paths where the water is transported are not efficient in some cases, forcing them to install pumps in between to impulse water. Furthermore, the slope and vegetation are important characteristics which should be taken into account. This implies spending money and effort in installing hosepipes over certain paths which may not provide the needed water. In this case to spend money in installations that are not efficient generates a big impact on the farmers since, as said before, they live in extreme conditions of poverty.

Whether the water demand of crops is supplied and the water availability is improved, farmers can get incomes based on the yield of each parcel. Therefore, farmers will be less vulnerable to extreme climatic conditions and agricultural loss. Information to support decision making on addressing water catchments is not currently available in the study area. Given this, a Geographic Information System (GIS)-based solution can be implemented as has been used through the world by researchers for identifying sites where farmers can obtain water as supply for crop irrigation (Al-Adamat, Diabat, & Shatnawi, 2010; El-Awar, Makke, Zurayk, & Mohtar, 2000; Shatnawi, 2006).

The present study provides the methodology implemented and results obtained in order to develop a GIS-based tool to address water captures in Western Honduras. This tool can be used by decision makers to geographically determine sites for water management and agricultural investments. It combines decision rules and surface features such as slope, vegetation and some protected basins. Based on these, two versions of the tool were developed. Both desktop and online versions were created by using software developed by Environmental Systems Research Institute, Inc. (ESRI[1]). The desktop version is a toolset which was implemented in ArcGIS for Desktop[2] as a toolbox. On the other hand, the online web application was developed by using ArcGIS Online[3], Web AppBuilder for ArcGIS[4] and two geoprocessing services created through ArcGIS for Desktop and ArcGIS for Server[5].

1.1 Problem Statement

As water is the main source for human welfare and agricultural production, its access, therefore, is among others, one of the most important constraints to successfully achieve the latter. This dependency on water in conjunction with conditions of extreme poverty it is the current scenario of the Western part of Honduras. It is clear so the need for identifying new or better sites for water catchments in the region. This thesis work provides a tool which is based on GIS and surface features to address water captures for small irrigation projects in the study area. This can be achieved by

[1] http://www.esri.com/
[2] http://www.esri.com/software/arcgis/arcgis-for-desktop
[3] http://www.esri.com/software/arcgis/arcgisonline
[4] http://doc.arcgis.com/en/web-appbuilder/
[5] http://www.esri.com/software/arcgis/arcgisserver

providing paths with the least costs of crossing the surface, through which it is possible to install hosepipes to take water from surrounding streams. Also, by guarantying that the intake points are not located in protected areas and above the parcel location.

1.2 Objectives

Main objective: To identify feasible water catchments for small irrigation projects in Western Honduras based on GIS and surface features.

Specific objectives:

- To identify geographically the paths with the least costs of crossing the surface for better targeting of water capture investments.
- To create a GIS-based tool to identify water catchments in Western Honduras which is based on common decision rules and set of criterion layers.
- To validate the ability to identify water catchments of the tool developed in this thesis based on verification of previous/current experiences of water capture projects in the study area.

1.3 Thesis Structure

The present document is organized into seven chapters. The first one provides an overall introduction and the objectives of this research. The theoretical background and literature related to the topic of this research are provided in chapter two. In chapter three a description of the study area and its relevant characteristics regarding this research are given. The fourth chapter describes the datasets, software and tools used in this thesis. Chapter five explains the steps followed in the methodology implemented in this project. The results and corresponding discussions are presented in chapter six. Last but not least, is the seventh chapter where some conclusions and future work are provided.

2. LITERATURE REVIEW

The present review provides a brief description of what a Digital Elevation Model (DEM) is, the main processes to achieve a hydrologically conditioned DEM, the basis of modeling an overland path and how the process to extract hydrologic characteristics from a DEM is accomplished. Also, some related works are presented.

2.1 Digital Elevation Model (DEM)

The topographic surface of any place over the world can be represented with a DEM. This is the acronym for Digital Elevation Model. Many definitions of this term exist. According to the GIS Dictionary of ESRI[6], a DEM is “the representation of continuous elevation values over a topographic surface by a regular array of z-values, referenced to a common datum”. In a shorter way, the U.S. Geological Survey (1993) argues that a DEM “consists of a sampled array of elevations for a number of ground positions at regularly spaced intervals”. In accordance with the aforementioned definitions, it is possible to say that any raster (grid format) which represents the elevation of a portion of terrain can be considered as a DEM.

DEMs have been used worldwide for multiple kinds of applications such as hydrological modeling, flood modeling, orthorectification of aerial imagery, viewshed analyzes and many more (Hirt, Filmer, & Featherstone, 2010; W. Zhang & Montgomery, 1994). Among the wide variety of applications, in combination with GIS, these are fundamental to determine hydrologic parameters of watersheds such as catchment delimitation and its corresponding stream network (Choi, 2012; Li, 2014; Maune, 2007; H. Zhang, Huang, & Wang, 2013). Actually, they define how the water flows through the land surface (H. Zhang et al., 2013), which is essential for distributed water-based models (Colombo, Vogt, Soille, Paracchini, & de Jager, 2007; Li, 2014; H. Zhang et al., 2013).

[6] http://support.esri.com/en/knowledgebase/GISDictionary/term/DEM

W. Zhang and Montgomery (1994) mention two formats to store digital elevation data. On one hand is point elevation data, which in turn can be classified as a regular grid or Triangular Integrated Network (TIN) and; on the other hand, we have line contours. Both formats offer different advantages and disadvantages but as mentioned by W. Zhang and Montgomery (1994), grid format has been more widely used since availability of elevation data has increased with the need for environmental monitoring and management, land surface modeling, study of catchment dynamics and many more (Huang, 2003; Reuter, Nelson, & Jarvis, 2007; Wu, Li, & Huang, 2008; W. Zhang & Montgomery, 1994).

Among the most of the globally widespread DEMs at present are the Shuttle Radar Topography Mission (SRTM) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Map (GDEM). As described in Farr et al. (2007), the SRTM flew in February 2000 and was a cooperation between the National Aeronautics and Space Administration (NASA), the National Geospatial-Intelligence Agency (NGA), and the German and Italian Space Agencies. In this mission, it was collected data of about 80% of the Earth's land surface located between 60° north and 56° south latitude. In 2003, the SRTM data was released at 1 arc second of spatial resolution (approximately 30 m at the equator) for the United States and at 3 arc seconds (approximately 90 m at the equator) for the rest of the world (Jarvis, Reuter, Nelson, & Guevara, 2008). Years later, in 2014, it was globally released the SRTM data at 1 arc second[7]. The SRTM data can be downloaded from numerous websites but one of the most recognized is the USGS EarthExplorer which can be consulted at http://earthexplorer.usgs.gov/. On the other hand is the ASTER GDEM, and according to METI/NASA (2009) the data "was generated using stereo-pair images collected by the ASTER instrument onboard Terra". GDEM V2 is the latest version and adds 260,000 additional stereo-pairs to the version 1 whose coverage spans from 83° north latitude to 83° south (approximately 90% of the Earth's land surface). This data is freely available at 1 arc second of spatial resolution at https://asterweb.jpl.nasa.gov/gdem.asp.

[7] Further information at: http://www2.jpl.nasa.gov/srtm/index.html

Despite the advantages and diverse uses of the aforementioned DEMs, some studies provide evidence that the SRTM presents better quality of topographic data in comparison with ASTER (e.g. Hirt et al., 2010; Nikolakopoulos, Kamaratakis, & Chrysoulakis, 2006; Rajabu, 2005; Wong, Tsuyuki, Ioki, & Phua, 2014).

2.1.1 Hydrologically Conditioned DEM (Hydro DEM)

For many water resource applications concerning to the simulation of water flow over the land surface (Soille, 2004), it is indispensable to extract stream networks and to delimitate drainage areas. Before carrying out these processes, it is necessary to hydrologically correct the DEM (Reuter et al., 2007; Ulmen, 2000). This terminology is used for a sink-free DEM (i.e. depressionless) whose flow direction follows the expected flow over the land surface (Djokic, 2011; Ulmen, 2000; Wu et al., 2008).

A sink is a pixel which impedes the continuous downslope flow of water. It is located at the lowest point of a depression (a bunch of pixels) which does not have an outlet. It is possible that sinks are real in the landscape, natural depressions like karst areas, but they can also be resulting artifacts of pre-processing operations such as resampling processes (Wu et al., 2008). In order to obtain a stream network with flow paths reaching their corresponding outlets as well as ensuring the proper delineation of basins, spurious sinks have to be removed in advance (Soille, 2004).

The software ArcGIS contains the *Fill* tool for sink removal of a DEM. This tool works by filling each sink encountered in the DEM, to the height of the boundary cell with the lowest elevation of the contributing area of the sink (Jenson & Domingue, 1988; Wu et al., 2008). According to Jackson (2012), this tool could not be effective for hydrologically conditioning of DEMs due to the increment in the average elevation of the terrain and the creation of unnatural smooth areas. Instead of that, he proposes a new *Optimized Pit Removal V1.5.1* tool[8], which is an implementation of the methodology described by Soille (2004). In Figure 1 both conceptual depictions are compared.

[8] This tool is freely available at http://tools.crwr.utexas.edu/OptimizedPitRemoval/Optimized-Pit-Removal-V1.5.1.zip

Figure 1. Comparison between Fill (left) and Optimized Pit Removal (right) tools (Jackson, 2012)

The Optimized Pit Removal tool attempts to minimally affect the landscape by a combination of cut and fill, in order to eliminate sinks encountered in the DEM. In flat areas, where the definition of streams is erratic and it is infeasible to acquire vector data of known drainage lines, this tool enables the delineation of detailed flow paths (Figure 2).

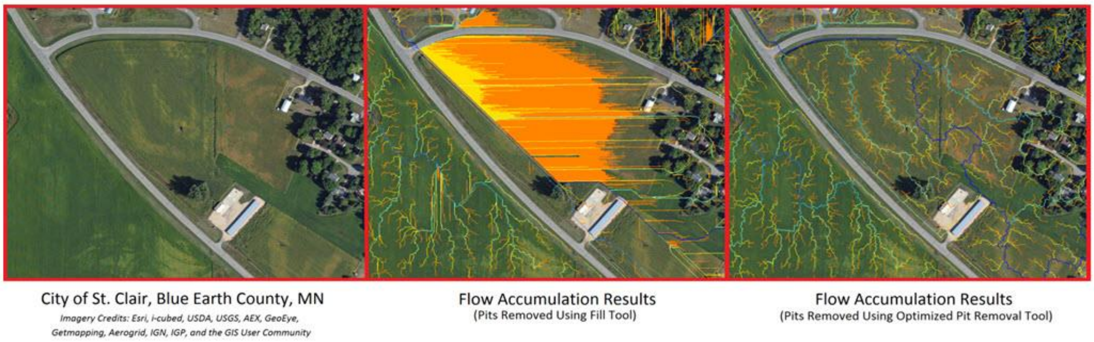

Figure 2. Delineation of drainage lines in flat areas with Fill (middle) and Optimized Pit Removal tools (right) (Jackson, 2012)

ArcGIS also contains the *Topo to Raster* tool that attempts to create a hydrologically correct DEM. This is an interpolation method which is also known as TopoGrid in ArcInfo and is based on the ANU approach (Hutchinson & Dowling, 1991; Hutchinson, 1988, 1989). It allows the user to input either spot points or contours as elevation sources. Furthermore, streams (for drainage enforcement process), known sinks, lakes, cliffs and coastal areas are also allowed as inputs. Despite this, Melles, Jones, Schmidt and Rayfield (2011) argue that after this method is applied, some sinks remain in the DEM.

In any case, the most important aspect of this process is the flow pattern (Djokic, 2011). Knowledge obtained from field work and about the weather of the study area is very useful to hydrologically condition a DEM. Additionally, alternate sources of topography and hydrologic data will allow to better carry out this process. If supplemental data is not provided, this process can be iterative until the flow direction suits the assumptions made on the flow pattern (Djokic, 2011).

2.1.2 Extraction of Hydrologic Characteristics from a DEM

DEMs have been used worldwide for the extraction of hydrologic characteristics such as stream networks and drainage areas (Choi, 2012; Li, 2014). However, as mentioned in section 2.1.1, it is fundamental to hydrologically condition the DEM beforehand. Topographic attributes such as slope gradient and slope aspect are also possible to be extracted from a DEM (Jenson & Domingue, 1988; Wu et al., 2008).

Multiple studies have been carried out to automatically extract hydrologic characteristics from a DEM (Choi, 2012; Soille, 2004; H. Zhang et al., 2013). Although many applications exist to obtain theses DEM derivatives, most of them use the D8 algorithm (i.e. deterministic 8) to calculate the flow direction (Melles et al., 2011). This is a single flow direction algorithm developed by O'Callaghan and Mark (1984) which uses neighborhood information from the eight nearest cells to direct the flow from each cell in the grid. This direction is the direction from the analyzed cell to the steepest downslope neighbor (O'Callaghan & Mark, 1984; Soille, 2004). In Tarboton (1997), however, are discussed other algorithms that implement multiple flow directions by applying on each cell weights from its neighbors.

The flow accumulation is then possible to be calculated based on the flow direction. Each cell in the generated surface contains the number of pixels that drain into it (Jenson & Domingue, 1988). Therefore, the value of one cell is the accumulated flow draining downslope to the cell. According to this, cells which have a flow accumulation value of zero, where no cells drain to it, are those normally located on the outline border of the basin (Jenson & Domingue, 1988).

Stream networks and drainage areas are based on the calculation of the flow direction and the flow accumulation (Choi, 2012; Jenson & Domingue, 1988; Metz, Mitasova, & Harmon, 2011; Wu et al., 2008). In order to determine the stream network of a basin, a stream threshold value has to be subjectively defined by the user (Li, 2014; Melles et al., 2011; H. Zhang et al., 2013). A cell belongs to the stream network if its accumulated flow value exceeds this threshold (Jenson & Domingue, 1988; Soille, 2004). This latter indicates, in turn, the upstream contributing area draining to that cell (Soille, 2004; H. Zhang et al., 2013). Although this value should be mostly based on geomorphological and weather characteristics (Soille, 2004; H. Zhang et al., 2013), most of times is arbitrarily assigned (H. Zhang et al., 2013). The greater the threshold value, the less dense the stream network (Jenson & Domingue, 1988). This value is vital and influences the definition of the stream network and consequently of the drainage area. To define this latter, it is necessary to delineate the area that drains surface water to a specific point located downslope (Choi, 2012; Soille, 2004). The surface water converges to this point which is the exit of the basin also called outlet.

The aforementioned processes can be carried out by using GIS-based software such as SAGA GIS[9], QGIS[10], gvSIG[11] or ArcGIS. This latter, as the GIS software chosen for this thesis work, provides the “Hydrology” toolset which contains tools to create a stream network or delineate watersheds. ESRI (2011) also provides Arc Hydro, which is an ArcGIS-based system aimed to support applications related to water resources (Djokic, Ye, & Dartiguenave, 2011). It has two main components which are Arc Hydro Data Model and Arc Hydro Tools. By using Arc Hydro and following the workflows suggested by ESRI (2013), it is possible to perform analysis often related to the water resources area. Based on the SRTM DEM and using Arc Hydro tools, the stream network and catchment areas will be modeled for the study area of this thesis.

2.2 Overland Path Modeling

Modeling an overland path falls on the subject of Least-Cost Analysis (LCA). This latter is a distance analysis tool enabled by GIS technology that allows finding the Least-Cost Path (LCP) between two locations. By using LCP method, it is possible to

[9] http://www.saga-gis.org/
[10] www.qgis.org
[11] www.gvsig.com

model movement across the surface while minimizing the cumulative cost along it (Melles et al., 2011; Mitchell, 2012; Rivera, 2014). This modeling is based on the idea that any movement across the surface implies a cost (Mitchell, 2012). Given this, the cost can be optimized in order to obtain the most cost-effective route between origin and destination. LCP is a raster-based method which relies on a resistance/friction surface (Theobald, 2005)—also known as cost surface as shown in Figure 3. This surface is a raster dataset commonly generated by making a weighted overlay of variables that influence the movement of the phenomenon to be modeled. The cost of each cell, in the cost surface raster, represents the cost of crossing it. This cost can be time, distance, money or any other variable defined by the modeler (Mitchell, 2012).

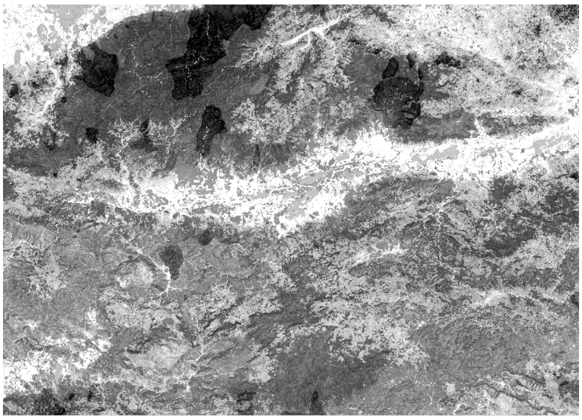

Figure 3. Example of a cost surface (dark areas represent higher resistance)

Many factors can influence the movement or its direction. For example, slope as being anisotropic (Herzog, 2013), can increase or decrease the real distance of the movement. In the case of water through a pipeline/hosepipe, the slope can speed up the movement while moving downhill or decelerate it in uphill direction (Mitchell, 2012). Other factors such as vegetation, lake, rivers, fences or roads play an important role as impedance surface factors (Mitchell, 2012; Rivera, 2014). Additionally, protected areas should be mostly avoided by LCP and they can also be included as a factor to derive the cost surface.

As movement is affected by multiple factors, the distance used for modeling the LCP cannot be a Euclidean distance. Instead of that, LCP uses a cell-to-cell distance to calculate a cumulative distance across the surface (Figure 4). This approach is achieved by using a cost distance surface which reflects the cumulative distance from the pixel containing the origin to each of the other pixels (Mitchell, 2012).

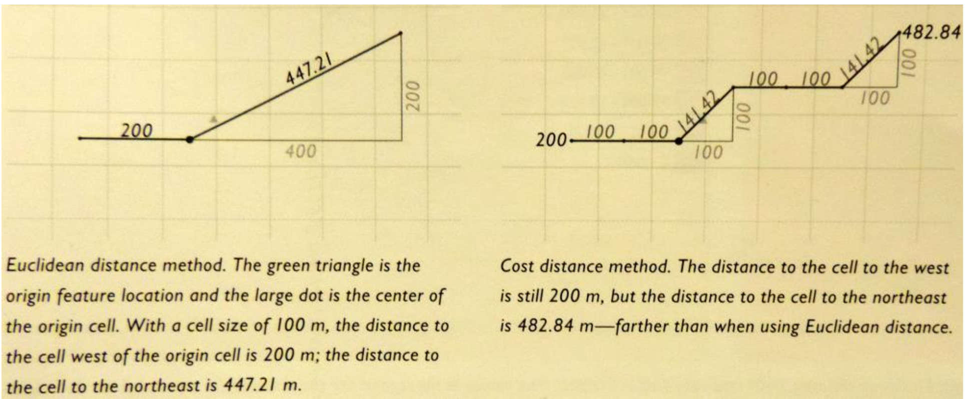

Figure 4. Comparison between Euclidean (left) and cell-to-cell (right) distances (Mitchell, 2012, p. 219)

The steps to model an overland path can be encapsulated in three main phases as described by Rivera (2014): Preparation, analysis and output. These steps can be executed in ArcGIS which provides tools to achieve the modeling of an LCP.

Preparation

Firstly, any source layer has to be clipped by using the boundary of the study area. The source layers (e.g. slope, vegetation and protected areas) should be rasterized if they are in vector or another format. Then, a reclassification process has to be carried out in order to classify the rasterized source layers into a ratio scale[12] (Mitchell, 2012). Categorical and continuous layers, such as vegetation and slope, need to be converted in values into the defined scale. The higher the cost value, the more difficult to cross over. Therefore, steeper slopes can be represented by higher values and flat areas by lower values. It works similarly for vegetation. Zones with forests or riparian covers are represented by higher values because it is more difficult to cross these areas than, for example, grasslands. The movement over some areas, such as protected areas, has to be restricted and, therefore, the highest value into the scale should be assigned.

[12] As defined by Stevens (1946), one characteristic of a ratio scale is that it entails an absolute zero as is the case of a slope layer, where a value of zero means a smooth area.

Analysis

This is the main phase of the entire process. It is composed of the creation of both the cost surface and the cost distance surface; and the modeling of the best path (LCP). As mentioned before, LCP is based on a resistance/friction surface which is in turn based on impedance factors. These factors are criterion layers defined for the model. For instance, in the modeling of a wildfire, factors such as vegetation and slope influence the ease/difficulty of the movement (Mitchell, 2012). The combination of them allows creating an overall surface (e.g. Figure 3). The cost surface is the result of a weighted overlay process taking as inputs these criterion layers. For each of these layers, a weight is assigned which represents its importance into the model. The sum of the weights has to be equal to 100%. If for example, vegetation, slope and protected areas are used as inputs for the model, then weights of 40%, 40% and 20% can be respectively assigned.

The cost surface and the location of the origin are the inputs for the cost distance model. In this step, the cost distance surface (Figure 5) and the cost direction layer (Figure 6) are created. While the former provides the cumulative cost of travel outward from the origin, the latter defines the direction of travel from each cell to the next neighboring cell along the LCP (Mitchell, 2012). The values in this layer are ranged from 0 to 8, where 0 is the value assigned to the cell that represents the origin location (Figure 6).

Figure 5. Cost distance surface (left) and cost direction layer (right) (ESRI, 2015)

Figure 6. Cost direction layer. Direction coding (left) and directionality (right) (ESRI, 2015)

Finally, after the required inputs for the cost path model are created, then it is possible to find the best path (LCP), which is a point-to-point path between the origin and the provided destination (Mitchell, 2012). In the case of a pipeline, for example, the origin and destination are connected by the most cost-effective route. The LCP depends so, on the criterion layers used as impedance surface factors, the defined scale, the classification of the layers and the weights assigned to them.

Results

The resulting LCP will be only one cell wide (Theobald, 2005), which can be later converted to a vector format if desired. For the last aforementioned case, only one destination is provided. However, it is possible to model different paths from the same origin to multiple destinations as shown in Figure 7 (Mitchell, 2012). This is the case when more than one possible destination is provided in order to compare among the different resulting LCPs. Through the demonstration of concept of this thesis, multiple catchment points from streams will be evaluated for a provided origin, which in this particular case is the farm location.

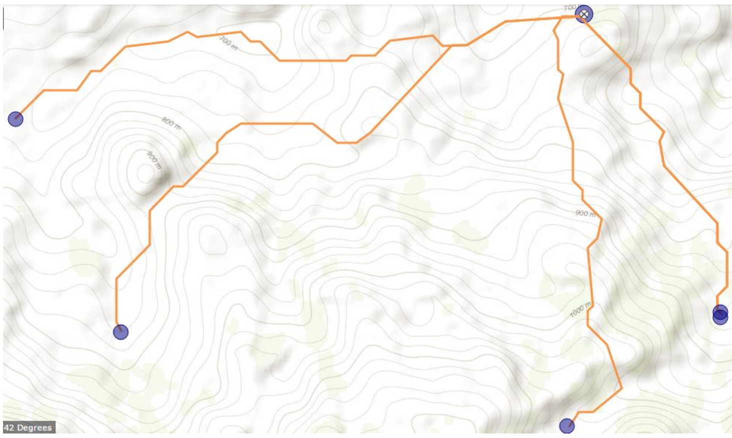

Figure 7. Example of an LCP between an origin and multiple destinations

LCA has been used for multiple GIS applications. Mitchell (2012) mentions two examples where LCA can be used. They are a wildfire and insect infection. In both cases, it is possible to analyze which areas would be reached by either the fire or the insect, and how they spread outward from their origins. In his book, Mitchell (2012) also provides other examples such as the use of LCP for a pipeline between two locations, and the identification of potential paths for a wildlife corridor between two protected areas.

In particular, Herzog (2014) provides a revision of 15 recent archeological studies (dated between 2012-2013) where LCA has been used to calculate site catchments, LCPs or accessibility. In another case, Melles et al. (2011) used an LCP approach to the delineation of streams using lakes as patches and a DEM as a cost surface.

In a recent paper, Rivera (2014) presents a novel approach of using LCP. In this study, LCP is used to predict a possible route that an illegal immigrant would take from a location surrounding the international border between U.S. and Mexico, and a set location inside the U.S. territory. Rivera (2014) also mentions in his study, the possibility of using LCP for recreational use such as the development of a hiking route in order to save energy and conserve time and distance.

Other applications such as the installation of transmission lines or the design of a canal are also possible to be carried out by using the LCP model. Many more GIS applications could be mentioned. The diverse and multiple uses of this approach demonstrate its potential. For this thesis work, the LCP approach will be used in combination with decision rules and surface features. The latter will be used as criterion layers which determine the impedance surface factors of the model.

2.3 Related Work

Climate change—which produces severe and recurrent droughts as well as floods—, population growth and contamination of water sources, are problems which globally affect water supplies and generate a common water crisis consequently. This situation has urged people to start looking for other water provisions through the implementation of solutions among which are water harvesting and installation of pipelines to bring water from external sources. In England, for example, eight possible solutions were examined in order to supply water for the current deficiency (Barford & Everitt, 2012). Among the solutions they have come up with are the construction of reservoirs, and the idea of bringing water by gravity from the Scottish borders to the South East of England. In Australia, many solutions have been also studied in order to battle droughts in their regions (Australian Government, 2010). The main idea is transporting water from northern to southern Australia via long pipelines, but they have also evaluated other solutions such as transport water by trucking, shipping or open channels, though.

In other areas of the world such as Northern Jordan, a GIS-based water harvesting solution has been implemented to identify ponds in order to collect water for domestic, agricultural and livestock usages (Al-Adamat et al., 2010). As Jordan is a water-shortage country, many water harvesting projects have been implemented for centuries (Al-Adamat et al., 2010). Al-Adamat et al. (2010) propose to use GIS in combination with Weighted Linear Combination[13] and Boolean techniques for the selection of suitable areas for water harvesting ponds in arid or semi-arid regions. This selection is based on socio-economic and physical characteristics of the study area; in the case of Northern Jordan were rainfall, slope, distance to Wadis, soils, and distances to urban centers and roads. The results of this study showed that 25% of the study area had potential to implement water harvesting ponds.

Water harvesting can also provide irrigation water for rainfed agriculture. Mwenge Kahinda et al. (2007) analyze the functions of water harvesting on agrological and hydrological basis as well as its impacts on crop yield. These analyzes were done in six districts of the semi-arid Zimbabwe. According to Mwenge Kahinda et al. (2007), supplemental irrigation provided by water harvesting technologies reduces the risks of crops to fail; converting them to more stable high productive irrigated crops. In Latin America, Pulver et al. (2012) established 12 reservoirs in Nicaragua and four in Mexico as a solution to provide surplus irrigation water for rainfed crops. This project focused on small crops with relatively low requirement of irrigation water. Rice and some irrigated crops as well as cattle, fish and dairy were taken into consideration. They introduced the concept of water harvesting in those areas and promoted its use by capturing and storing rainwater which can be used later as irrigation water. The implementation carried out in Pulver et al. (2012), resulted in increasing of crop productivity and farmer incomes.

Not going too far, in North Carolina, a novel tool for siting potential reservoirs was developed by Walsh, Page, McKnight, Yao and Morrissey (2015). The North Carolina

[13] For further information refer to Malczewski (2000).

Reservoir Siting Tool ("NC-RES", see Figure 8) is a GIS tool based on the web which allows non-specialist users to assess possible sites for reservoirs. This tool has been recently developed as an attempt to provide water supplies for the alarming low levels of water in drought periods. It is based on terrain data derived from North Carolina's LiDAR[14]. In addition, geospatial layers are used to assess the possible impacts of creating a reservoir in a desired location.

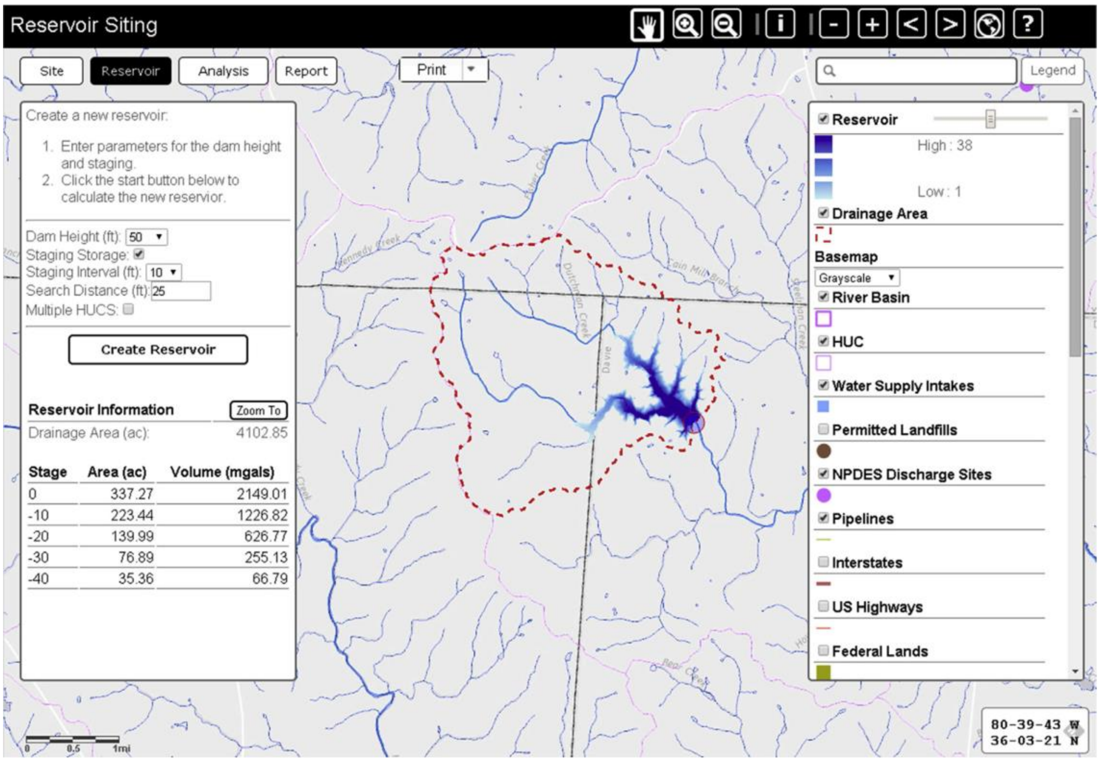

Figure 8. The NC-RES tool (Walsh et al., 2015)

NC-RES tool also allows users to perform spatial analysis such as reservoir inundation and drainage areas based on LiDAR derivatives. For the development of this tool, they used ArcGIS Server, ESRI map services and three geoprocessing services. ESRI JavaScript API was used to develop the interface of the tool.

All the aforementioned works were examined in this chapter because they have implemented approaches related in one way or another to the main objective of this thesis. In any case, these approaches will be taken into consideration for the implementation of the solution proposed in this thesis work for the current problem of water scarcity in the Western part of Honduras. It is important to mention that none of

[14] In order to know what LiDAR is refer to National Oceantic and Atmospheric Administration (NOAA) (2015).

these works were carried out in that area, only that work accomplished by Pulver et al. (2012) was implemented in near countries such as Nicaragua and Mexico; where in contrast to this thesis work, a manually in-field work at a larger scale was applied. Another important aspect to highlight is that there are not studies which have already implemented solutions strictly aimed to alleviate the alarming water shortage in Honduras. This thesis will focus on providing a novel solution to this problem by integrating GIS technologies, decision rules and surface features. The combination of these elements provides a different approach in comparison to the aforementioned works as it is the first time that LCPs will be used to address water catchments for small irrigation projects in areas affected by constant droughts. Furthermore, this thesis work will also attempt to provide a final tool to be used on computers (without Internet) as well as on mobile devices through Internet access; unlike the case of Walsh et al. (2015) in which only an online application was developed. The latter was the single case found in the search of related works in which an online tool was implemented as a final solution.

3. DESCRIPTION OF THE STUDY AREA

In this chapter are described the most important aspects of the study area related to this research.

3.1 Location

The study area is located in the Western part of Honduras in Central America and approximately covers the portion of the dry corridor that lies in the country (Figure 9). This area is surrounded by Guatemala in the West, El Salvador in the South, Nicaragua in the South East, the interior of the country in the East, and the Caribbean Sea in the North. The area compromises about 52,503 Km^2 and spans from 15.900°N to 12.982°N latitude and from 89.353°W to 86.053°W longitude. It completely covers the departments of Choluteca, Comayagua, Copán, Cortés, Francisco Morazán, Intibucá, La Paz, Lempira, Ocotepeque, Santa Bárbara and Valle, and partially El Paraíso and Yoro.

Figure 9. Location of study area

3.2 Topography

The region is characterized by slopes ranging from 0° (coastal zones) to 74° (steep hills). The North and South of this area are lowlands while the interior is mountainous. The elevation ranges from 0 to 2,851 m.a.s.l. The study area contains mountains with the highest peaks of the entire Honduras. The Honduras' mountains are merged to Guatemala's mountains in the West and to Nicaragua's mountains in the South East.

3.3 Climate

For the period 1992-2011, Honduras was one of the most vulnerable countries in the world due to extreme weather events (Gourdji, Craig, Shirley, & Ponce de Leon Barido, 2014; UNDP, 2011). As mentioned in chapter 1, the study area is affected by cyclical droughts related to ENSO (FAO & ACF, 2012). The area is characterized by a rainy season from May to November, leaving the rest of year as the dry season. The precipitation has a bimodal behavior that is interrupted by a dry period from mid-July to mid-August; which is called "canícula". The rainy periods before and after "canícula" are called "primera" and "postrera" respectively (FAO & ACF, 2012). These latter ones define the two agricultural seasons in the area. The annual precipitation ranges from 800 mm up to 2,000 mm while the mean temperature varies from 6°C to 30°C (FAO & ACF, 2012).

3.4 Agriculture

In general, the agriculture in the study area is carried out in hillside lands by small-scale farmers who mostly plant corn during the Primera and beans during the Postrera. In some cases, a combination of both is also implemented. These crops are used primarily for their subsistence needs. In areas with steep slopes, they also plant coffee. As these crops are cultivated in hillside lands, are vulnerable to soil erosion and degradation, and consequently to a decrease in productivity (Paniagua, 1999; Wollni & Andersson, 2014).

The agriculture practiced in this region is mostly rainfed agriculture. Unfortunately, periods of water scarcity affect the productivity of this agriculture generating a threat for food production. Irregular precipitation, droughts as well as a lack of irrigation systems, entail that small-scale farmers can only produce two crops in a year.

3.5 Socioecomical Aspects

Honduras remains as one of the poorest countries in Latin America (Paniagua, 1999; The World Bank, 2015) with a population of 7.9 million inhabitants. More than half of Honduran population live with incomes under the national poverty line while 46% of them live in extreme poverty (The World Bank, 2015). 70% of all poverty live in rural lands, which are mostly located in the Western and Southern areas of the country (The World Bank, 2015). In the Honduran dry corridor, people live in extreme poverty with incomes lower than $2 USD per person per day and most of farmers practice rainfed subsistence agriculture (The World Bank, 2015). Despite the high rate of employment in agriculture and its importance as the main source of income, Honduras is still dependent on imports because of the low agricultural productivity and vulnerability to market prices (The World Bank, 2015).

4. RESOURCES USED

This chapter provides a description of the datasets, software, hardware and tools used in this thesis work.

4.1 Description of Data Used

The datasets used for the purpose of this research come from either public sources or courtesy of some institutions.

4.1.1 Digital Elevation Model (DEM)

The SRTM DEM at 1 arc second of spatial resolution was used as elevation surface. The product "SRTM 1 Arc-Second Global" was downloaded from the USGS EarthExplorer web portal[15] which offers worldwide coverage of void filled data. In Figure 10, it is possible to see the tiles downloaded for this DEM. Each square represents a 1 by 1 degree tile. 11 tiles were downloaded in GeoTIFF format which cover the total extension of the study area.

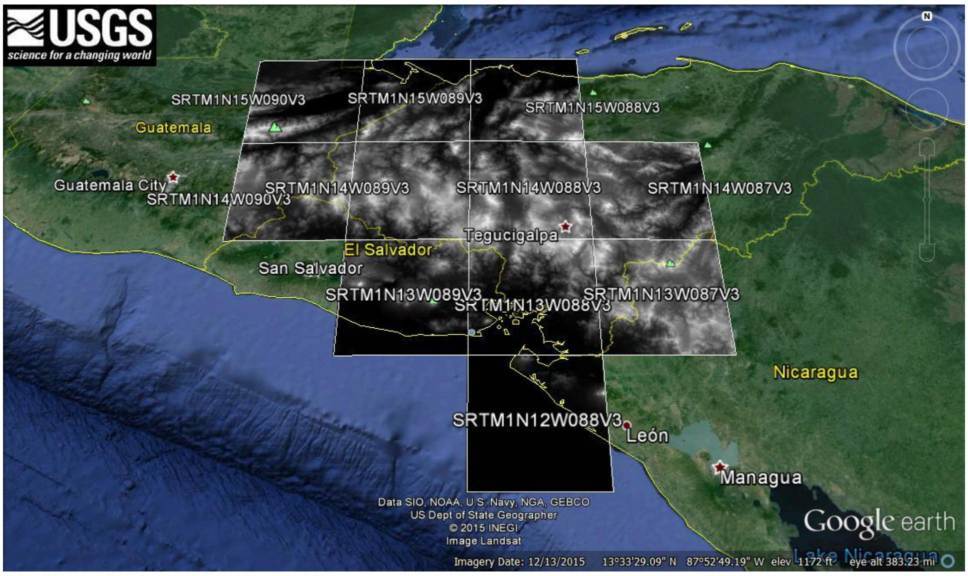

Figure 10. Tiles downloaded of the SRTM at 1 arc second.

[15] It can be accessed at http://earthexplorer.usgs.gov/

4.1.2 Land Use/Land Cover

In this study it was used the Land use/Land cover (LULC) map which was elaborated at a minimum scale of 1:25,000 with Corine Land Cover classification for whole Honduras (Figure 11). It was generated from RapidEye imagery of 2012 and 2013 at 5 m of spatial resolution (Duarte et al., 2014). This dataset was provided in ESRI Shapefile format as a courtesy of the National Institute for Conservation and Forest Development, Protected Areas, and Wildlife (ICF).

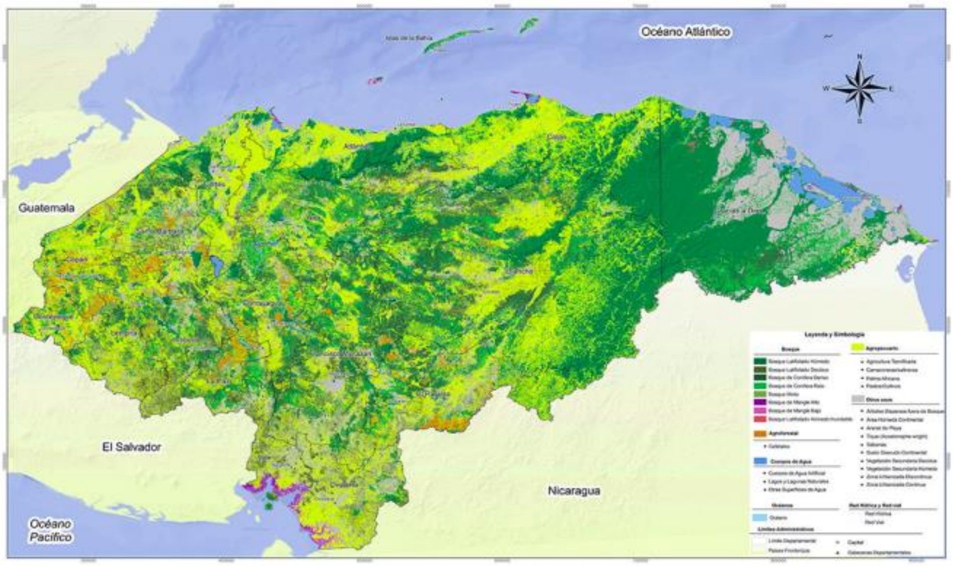

Figure 11. Land use/Land cover (LULC) map (Duarte *et al.*, 2014)

This map consists of 26 categories, eight (8) of which are forests and 16 non-forests. These categories can be clustered in five macro-categories: Forests (48%), agriculture and livestock (30%), other categories (18%), agroforest areas (2%) and water bodies (2%) (Duarte et al., 2014). The percentages represent the area of the Honduran territory (112,492 Km^2) covered by each macro-category.

4.1.3 Protected Basins

In Honduras, most of the drinking water comes from forest lands, 7% of which are declared as protected areas (Cardona, 2010). These areas are distributed in 575 basins and compromise about 392,018 ha. In order to provide drinking water mainly to the rural population, these basins were declared protected areas since 1987 (Cardona, 2010). This dataset was also provided in ESRI Shapefile format by the ICF. In the following figure it is possible to see the distribution of the aforementioned basins:

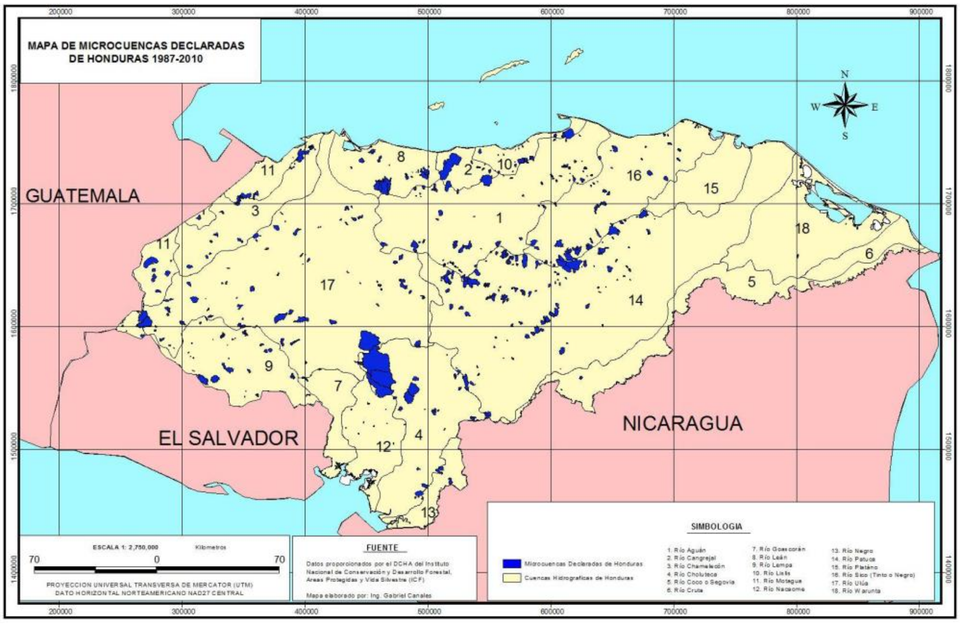

Figure 12. Protected basins in Honduras (Cardona, 2010)

4.1.4 Validation Data

Some track points of current hosepipe paths as well as farm locations and their respective water intake points were provided by USAID. These datasets were taken with GPS in the field in collaboration with technicians of Fintrac Inc. These datasets were compared with the results provided by the tool implemented in this thesis as will be discussed later in sections 5.6 and 6.3.

4.2 Description of Software and Hardware Used

The software and hardware used for this research can be divided into two stages:

Development

The work was carried out using the GIS software ArcGIS 10.2.2 for Desktop in combination with Python 2.7, ArcPy and GPSBabel[16]. Complete features and specifications of the computer used are detailed in Table 1.

[16] Freely available at http://www.gpsbabel.org/

Table 1. Computer specifications

Operating System	Windows 10 Home Single Language
Processor	Intel(R) Core(TM) i7-3630QM 2.4 GHz
Number of processors	4
RAM	8 GB
Hard Drive	1 TB

Implementation

ArcGIS 10.2.2 for Desktop allowed the creation of two geoprocessing services which are used by the online web application. The latter was created by using Web AppBuilder for ArcGIS and stored on an organizational account of ArcGIS Online. ArcGIS 10.1 for Server houses the two geoprocessing services and is hosted on a server with the following specifications:

Table 2. Server specifications

Operating System	Windows Server 2008 R2 Standard
Processor	Intel(R) Xeon(R) E5450 3.00 GHz
Number of processors	8
RAM	32 GB
Hard Drive	10 TB
Web Server	Internet Information Services (IIS)

5. METHODOLOGY

This chapter provides the methodological steps carried out to achieve the objectives of this thesis work. In Figure 13 is shown a flowchart of the methodology which provides an overall idea of the major steps, datasets and results of this thesis.

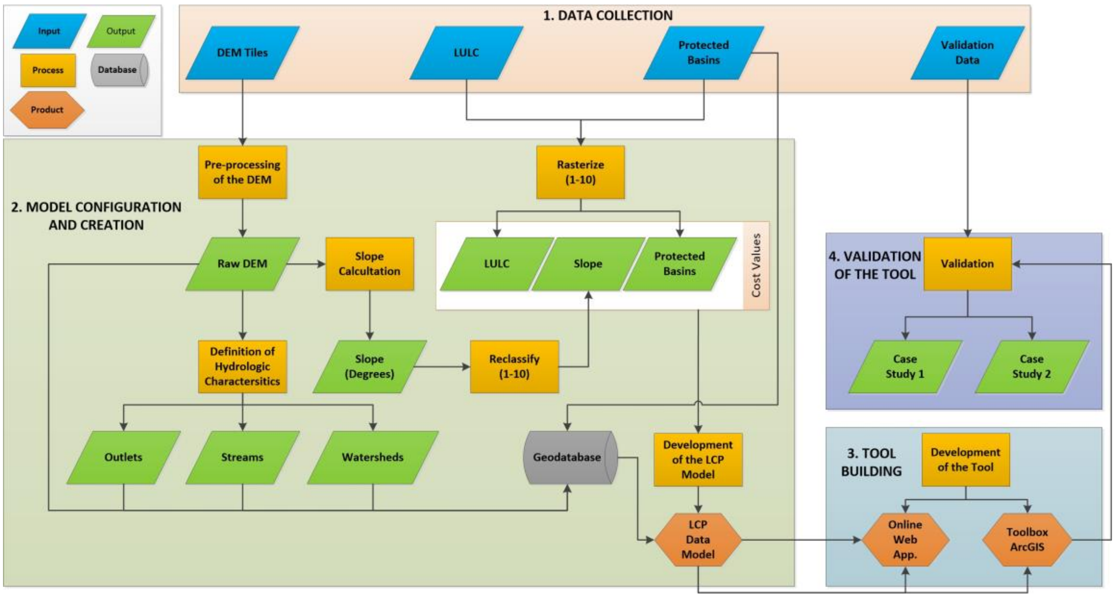

Figure 13. Flowchart of the methodology

It is very important to highlight that all the spatial information used in this work was projected to the spatial reference system "WGS84 UTM Zone 16 N" with datum WGS 1984. This process was carried out to avoid mismatches among the different layers used. Furthermore, it is indispensable to work with projected information for processes involving calculations such as linear distances, areas and slopes.

5.1 Pre-processing of the DEM

The tiles downloaded of the SRTM DEM 1 arc second (Figure 10) were merged into a new raster dataset with the tool "Mosaic to New Raster" in ArcGIS for Desktop. The resulting dataset of this process is shown in Figure 14.

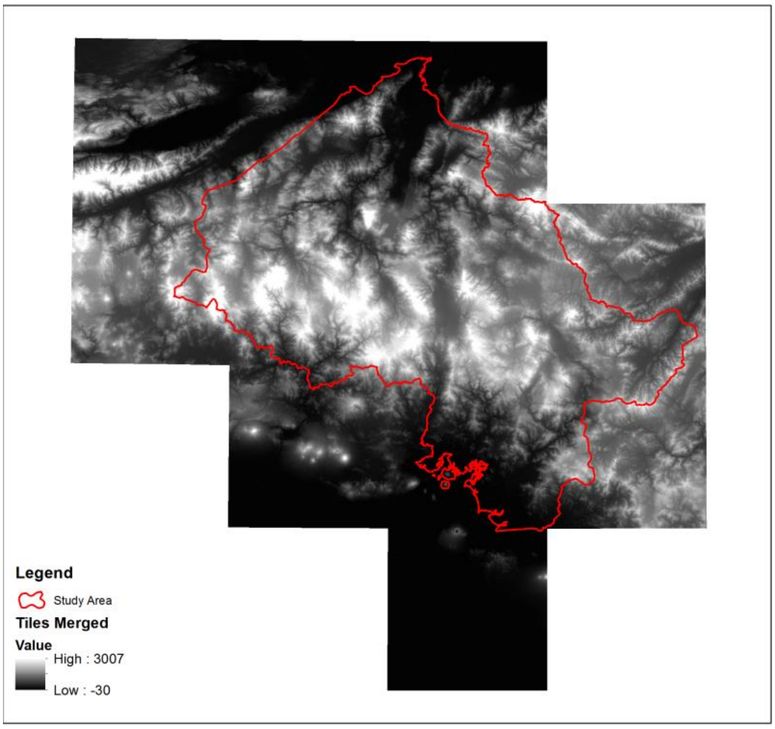

Figure 14. Tiles merged of the study area

The dataset in Figure 14 was then clipped with the boundary of the study area in order to obtain the raw DEM. This DEM is shown in the following figure:

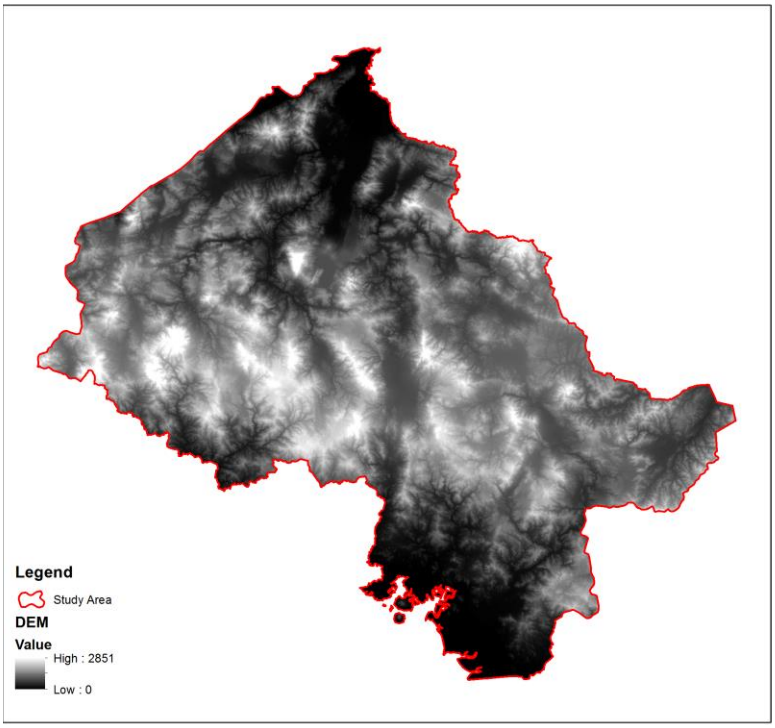

Figure 15. DEM of the study area

After the dataset was clipped, it was possible to obtain the raw DEM of the study area with the corresponding range of elevations which goes from sea level till 2,851 m.a.s.l. It was not necessary to implement any void-filling algorithm or interpolation as the product downloaded "SRTM 1 Arc-Second Global" provides void filled data.

5.2 Definition of Hydrologic Characteristics

In order to obtain a hydrologically conditioned DEM (hydro DEM) for generating the streams and watershed delineations of the entire study area; the data model in Figure 16 was developed in ArcGIS for Desktop by using its application Model Builder. This data model was made based on Arc Hydro tools (ESRI, 2011) and following the workflows suggested by ESRI (2013). In addition, the Fill sinks process was implemented using the Optimized Pit Removal V1.5.1 tool developed by Jackson (2012).

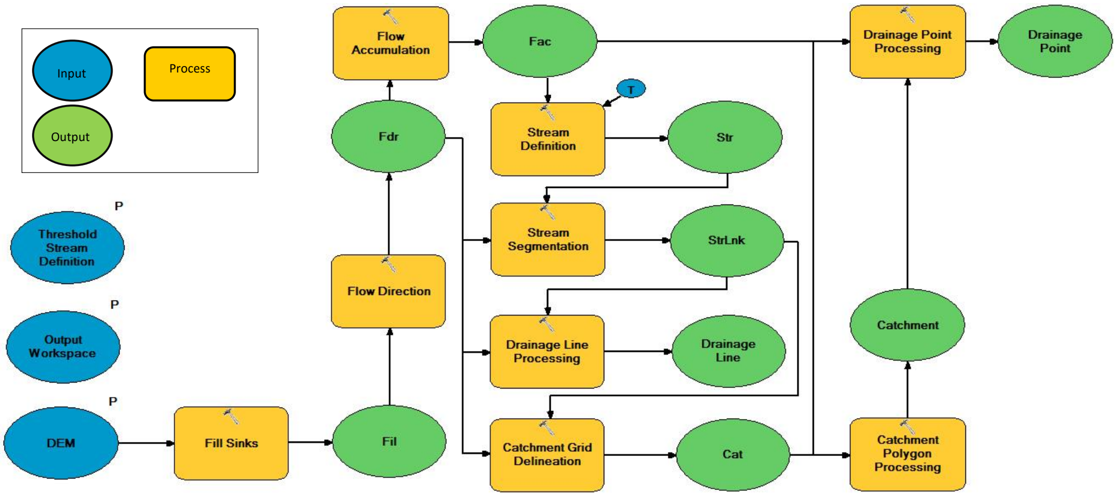

Figure 16. Data model for definition of hydrologic characteristics

The input parameters for the data model in Figure 16 (blue ovals on the left) are the raw DEM of the study area (Figure 15), the workspace path and the threshold value for the definition of the stream network. As mentioned in Soille (2004) and H. Zhang et al. (2013), this latter should be defined based on geomorphological and weather characteristics, but most of the time is arbitrarily defined (H. Zhang et al., 2013). Given this, multiple iterations were carried out until this threshold value was finally set as 500. Therefore, any pixel with a flow accumulation value greater or equal to this threshold is part of the stream network. This value ensures a very well detailed stream network for the study area.

In general, the model removes all the local depressions (sinks) in order to generate continuous flows. Then it calculates the flow direction and flow accumulation based on the sink-free DEM. Some intermediate layers are later created. Finally, it defines all the outlets (drainage points), streams (drainage lines) and watersheds (catchment areas) of the study area. One possible step of creating a hydro DEM is to enforce drainages with stream features. It is possible to do so by rasterizing provided stream features and burning them into the DEM. The resulting surface will have deep channels that work well for routing flow and follow the real patterns. In this case, however, it was not possible to obtain supplemental data of streams for the drainage enforcement process. Therefore, the stream network was generated based on the sink-free DEM.

5.3 Least-Cost Path (LCP)

Before starting the implementation of the LCP method, it is necessary to condition the criterion layers used as impedance surface factors. For the specific case study of this thesis work, the criterion layers used were vegetation (LULC), slope and protected basins. The two first determine the difficulty of the movement whereas the latter mostly restricts the path over its areas. The objective of this process is to determine the best path from the farm location to an intake point (outlet) located in a surrounding stream. Over this path, then it is possible to install a hosepipe to capture water from the stream.

The first surface generated was the slope surface. It was calculated in degrees using as input the raw DEM and executing the tool "Slope" in ArcGIS for Desktop. In this case, the raw DEM (Figure 15) was used because as Djokic (2011) argues, the hydro DEM must be only used for routing flow and not for surface characterization. As the resulting surface is a continuous surface, it was reclassified into a scale of 1 to 10. This was the scale selected to represent the cost values in each criterion layer. This scale represents the ease/difficulty of travel over such a surface. In order to obtain a final slope surface classified into the defined scale, it was used the classification method “Natural Breaks (Jenks)” described in Jenks and Caspall (1971). The slope intervals defined in ArcGIS for Desktop with their corresponding cost values and areas are shown in Table 3.

Table 3. Cost values assigned to slope intervals using the classification method “Natural Breaks (Jenks)”

Interval	Lower Limit (%)	Upper Limit (%)	Cost Value	Area (Km^2)
1	0.00	4.64	1	9,719
2	4.64	9.57	2	8,305
3	9.57	14.21	3	8,747
4	14.21	18.56	4	8,200
5	18.56	22.62	5	6,526
6	22.62	26.68	6	4,844
7	26.68	31.03	7	3,227
8	31.03	35.96	8	1,848
9	35.96	42.91	9	874
10	42.91	73.94	10	212
				52,503

The LULC layer was also clipped with the boundary of the study area. The resulting LULC layer contains 23 of the 26 categories for all Honduras. Since the original categories were in Spanish, they were all translated into English. Furthermore, a cost value into the defined scale was assigned to each of these categories. These values were assigned similar as in the case of slope: the higher the cost value, the more difficult to cross over. Taking into consideration the case study of this thesis work and according to Mitchell (2012), the higher values were assigned to categories that are difficult but not impossible to traverse, such as forests or discontinuous urban fabric. On the other hand, the lower values were assigned to categories that do not impede the travel over or are easy to traverse, such as pastures, crops and secondary vegetation. Additionally, for categories such as wetlands or continuous urban fabric, where is impossible to install a hosepipe over the surface, we assigned a value of “RESTRICTED”. In the latter case, those categories were assigned as “NoData” when rasterizing the LULC layer based on the cost values. In Table 4 are shown the resulting categories in both Spanish (original) and English, the cost values and their corresponding areas.

Table 4. Cost values assigned to LULC categories

LULC Spanish	LULC English	Cost Value	Area (Km^2)
Pastos y/o Cultivos	Pastures and/or crops	1	17,079
Suelos Desnudos Continentales	Inland bare soils	1	203
Vegetación Secundaria Seca	Dry secondary vegetation	2	4,984
Vegetación Secundaria Húmeda	Moist secondary vegetation	3	3,534
Árboles Dispersos	Scattered trees	4	1,008
Café	Coffee	4	2,334
Pino Ralo	Sparse pine	5	3,703
Agricultura Tecnificada	Technified agriculture	6	866
Palma Africana	African oil palm	7	255
Bosque Mixto	Mixed forest	8	1,863
Pino Denso	Dense pine	8	7,534
Bosque Latifoliado Seco	Broad-leaved dry forest	9	4,175
Bosque Latifoliado Húmedo	Broad-leaved moist forest	10	3,210
Zonas Urbanizadas Discontinuas	Discontinuous urban fabric	10	301
Áreas Húmedas Continentales	Inland wetlands	RESTRICTED	151
Arenales de Playa	Beaches, dunes, sands	RESTRICTED	2
Camaroneras y Salineras	Shrimp farms and salt evaporation ponds	RESTRICTED	177
Cuerpo de Agua Artificial	Artificial water bodies	RESTRICTED	87
Lagos y Lagunas Naturales	Natural lakes and lagoons	RESTRICTED	91
Mangle Alto	Tall mangrove	RESTRICTED	177
Mangle Bajo	Low-height mangrove	RESTRICTED	160
Otros Cuerpos de Agua	Other water bodies	RESTRICTED	238
Zonas Urbanizadas Continuas	Continuous urban fabric	RESTRICTED	373
			52,503

The third layer used as impedance surface factor was the layer of protected basins. They compromise about 2,198 Km^2 of the study area and were declared protected areas because they provide drinking water mainly to rural population (Cardona, 2010). In this specific case, a cost value of 10 was assigned to all of them. This cost value mostly restricts the installation of hosepipes over those areas but does not make it impossible. Indeed, it allows the model to avoid at most it is possible the path over such areas but in the extreme case where there is not a path with a less cost, the LCP method will provide a path traversing those areas.

In Western Honduras, permanent water sources are scarce. Therefore, farmers need to take water from streams through hosepipes/pipelines to their crops. These water catchments are either distant or do not supply the water needed for irrigation. Indeed, the paths through which they install the hosepipes are not totally efficient because require much effort due to they do not always take into account impedance surface factors. Based on this need, it was implemented the design of a data model (Figure 17) to determine the best path with the least cost of crossing the surface from the farm location to each potential water intake point. The data model in Figure 17 was implemented following the guidelines suggested by Mitchell (2012). The inputs of this model are the slope, LULC and protected areas which were previously classified into the defined scale. In addition, the farm location (origin) and the intake points (destinations) are also used as main inputs.

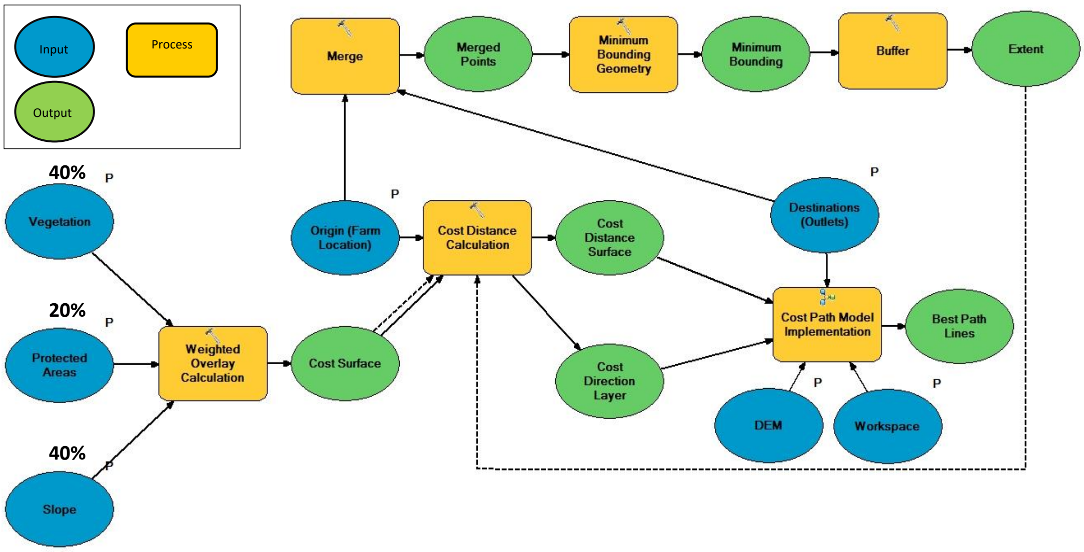

Figure 17. Data model for finding the best path between the parcel location and water intakes/outlets

The development of the data model in Figure 17 is based on the idea that any movement across the surface implies a cost (Mitchell, 2012). This cost can be optimized in order to get the least-cost path (LCP) of traveling from the origin to the destination(s). Therefore, it is necessary to have a cost surface which determines the ease/difficulty of traversing it. This cost surface was created by making a weighted overlay of the three impedance surface factors used for the study area. These factors were LULC, slope and protected areas. For each of these factors, a weight was assigned which represents its importance into the model. Since the sum of all the weights has to be equal to 100%, we assigned a weight of 40% for both LULC and slope, and of 20% for protected areas.

Firstly, the model creates the resistance/friction surface (cost surface) based on the three impedance surface factors. This is the part of the model that can be considered static as the cost surface is created only once. This surface can be changed if desired, but in our case, it was calculated based on the aforementioned cost values and weights. The middle and right parts of the model depend on both origin and destination(s), so in each modeling the cost distance and cost path processes have to be run. In order to establish an analysis area, it is created a buffer area of the merge of both the origin and the destination(s). Then, this area is set as the analysis extent of the cost distance process.

The drainage points/outlets obtained in the extraction of hydrologic characteristics (section 5.2), were used as potential locations where farmers could take water from streams. These captures allow farmers to use supplemental irrigation water for rainfed crops due to most of them practice rainfed subsistence agriculture in the Western part of Honduras. In Figure 17, these outlets—also called as intake points—are provided as destinations for the data model.

By using the data model shown in Figure 17, it is possible to model different paths from the same origin to multiple destinations. Therefore, multiple intake points from streams are evaluated for a provided origin, which in this particular case is the farm location. The multiple calculations are carried out in the cost path model by iterating among the different destinations as shown in Figure 18. This latter is a submodel of the model in Figure 17 and allows modeling more than one LCP from the same origin. Furthermore, it adds valuable surface information such as maximum, mean and minimum slopes, and surface distance. This surface information is calculated based on the raw DEM. The surface distance is a very important characteristic of the LCP because determines how long the hosepipe will be. This implies the length of the path and, therefore, the money that farmers need to invest in buying the hosepipe. Another important aspect is the slope because provides an overall description of the topography over which the hosepipe will be installed.

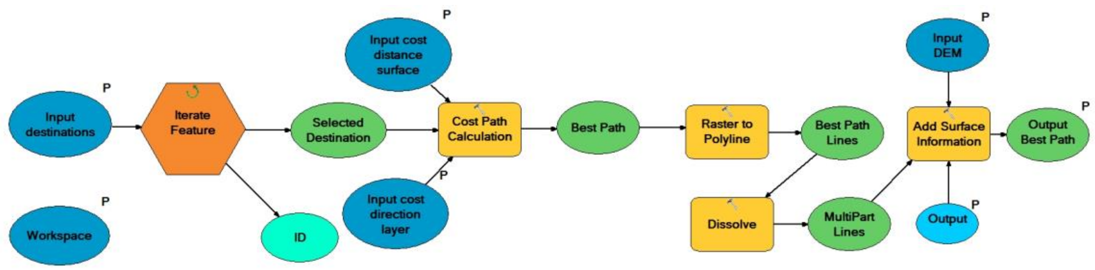

Figure 18. Cost path model for multiple destinations

With the two previous data models, then it is possible to automate routines in order to find the best paths from a desired farm location (origin) to multiple water intake points (destinations). The automation processes for both desktop and online versions are explained in the following sections.

5.4 Requirement Analysis

In order to develop a tool to identify feasible water catchments for small irrigation projects in Western Honduras, we first had an approach with population of the study area. This approach was carried out through a meeting with around 20 participants in which were integrated some farmers and people from different institutions such as USAID, Fintrac and CIAT. While the former are the target population of this study, the latter are the possible users of the tool. Furthermore, we also had a field trip in the department of Intibucá to understand and realize the serious conditions of both poverty and water scarcity.

The first approach was very important and fundamental for the development of this thesis work. On one hand, because we could hear and understand the current problems in the study area by means of informal interviews with stakeholders. On the other hand, they explained us through in-field observations, how the current water catchments work and what the procedures to install them are. The most important remarks we received from farmers as well as from technicians can be summarized in the following bullets:

- Farmers take water from streams through hosepipes/pipelines trying to avoid the installation of pumps in between of the water intake and the farm location. This is done in order to reduce investments. As a solution, they mostly take water from upper areas using gravity to impulse it until the farm location.
- It is very important the length of the path, so they look for possible water intakes in streams not so far from their farms.
- It is restricted to install water intakes in the basins declared as protected areas.
- Technicians are the people who help farmers to carry out this process. They normally use handheld GPS devices to navigate in the territory looking for new or better water intakes. Given this, it is very important for them to manage files or information that is readable by these devices. The file formats which they usually work with are KML, GDB or GPX.

Based on these remarks, we established the decision rules to find feasible water intakes for a farm. The solutions proposed to solve/deal them were:

- The tool has to look for water intakes located above the farm location. Therefore, it is necessary to obtain the elevations of both farm location and each water intake and then to filter the water intakes that are at least 10m above the farm location.
- The tool has to allow the user to search water intakes within a linear radius from the farm location.
- Any water intake located within the protected basins has to be discarded.
- It is necessary to allow the user to convert from GDB and GPX files to a format established as input for the tool. Also, the results should be exported to a file format readable by handheld GPS devices (i.e. KML).

Water intakes that go through the first three of the previous conditions are considered potential sites for a farm. If more than five sites are found by the tool, they are restricted to only five. These sites are provided in ascending order based on their surface distances to the farm location. In any case, this amount of potential sites is sufficient to find the most feasible one for the farm. The final sites, where is possible to take water from streams, are provided as destinations to the model in Figure 17.

5.5 Development of the Tool

The remarks provided by the stakeholders allowed us to develop the tools presented in this thesis. These tools were developed to be used by either technicians or decision makers who can address the process and help farmers to solve their problems related to water supply. In the following sections are explained the two versions developed in this thesis work.

5.5.1 Desktop Version

The desktop version implemented in this thesis work was a toolset which consists of the data models shown in Figures 17 and 18, and five tools that are based on Python scripts. This toolset was developed as a toolbox in ArcGIS for Desktop. Each of these tools works similar to any default tool in ArcGIS. They require the definition of input and output parameters and contain their corresponding metadata. The tools stored on this toolset were the following:

1. GDB To Shapefile / GPX To Shapefile
2. Best Paths
3. Generate Watersheds
4. Results To KML

The numbers in the names of the tools indicate the possible sequence to be followed in order to have a successful and complete run. This depends, of course, on what the user wants to do. The two tools, whose names are preceded by the number "1", can be both firstly executed based on the need of converting from either GDB or GPX format to Shapefile. The essential tools of this toolset are "2. Best Paths" and "3. Generate Watersheds". While the former determines the best paths (LCPs) from a farm location to potential water intakes, the latter defines the drainage areas of these sites. Most of these tools need basic information to carry out their processes. In consequence, this information was stored on a geodatabase which consists of the raw DEM, the hydrologic characteristics (i.e. outlets, stream network and catchment areas), the protected basins and the cost surface.

This desktop version was developed to be mainly used in office but it is also possible to use it in the field with a laptop. It is necessary to have ArcGIS for Desktop and Python installed on the computer. The latter, however, is automatically installed with ArcGIS for Desktop. In addition, the software GPSBabel is also required since it is used by the tool "1. GDB To Shapefile" to convert from GDB (MapSource) to GPX (GPS eXchange) format.

5.5.2 Online Version

In order to allow the user to run on any device—not only on desktop computers or laptops—the main tools developed in thesis work, it was created an online web application with the use of platforms and software based on GIS. The main tools used were "2. Best Paths" and "3. Generate Watersheds". Therefore, these tools were published as geoprocessing services using ArcGIS for Desktop and hosted on a server with ArcGIS for Server installed. It is important to mention that in the creation of the geoprocessing services with ArcGIS for Desktop and ArcGIS for Server, it was necessary to make some relevant changes in the toolbox, input formats and scripts in order to avoid future problems which could take long time to solve them.

By using Web AppBuilder for ArcGIS, the online web application was finally built and stored on an organizational account of ArcGIS Online. The online web application uses the two geoprocessing services as well as ready-to-use widgets. As a result, the final version of the online web application eliminates the user's dependency of using a computer to run the main tools, because it can be run on a mobile device. On the other hand, the online web application has the drawback of requiring Internet access.

5.6 Validation of the Tool

The information supplied by USAID consisted of track points of two current hosepipe paths with their respective water intakes and farm locations. They were captured in 2015 in the municipality of Yamaranguila, department of Intibucá. The two following figures show in perspective the paths of the two current hosepipes.

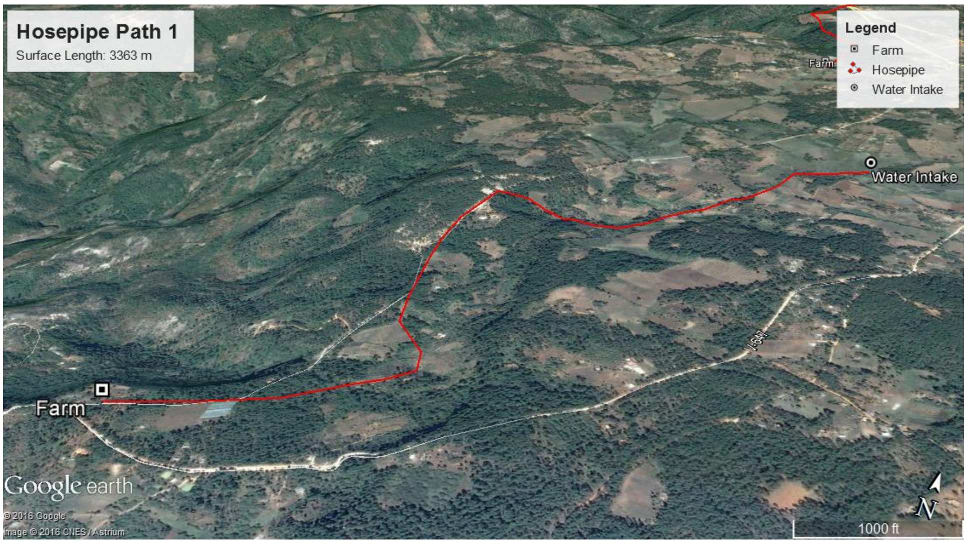

Figure 19. Hosepipe path 1 (surface length 3,363 m)

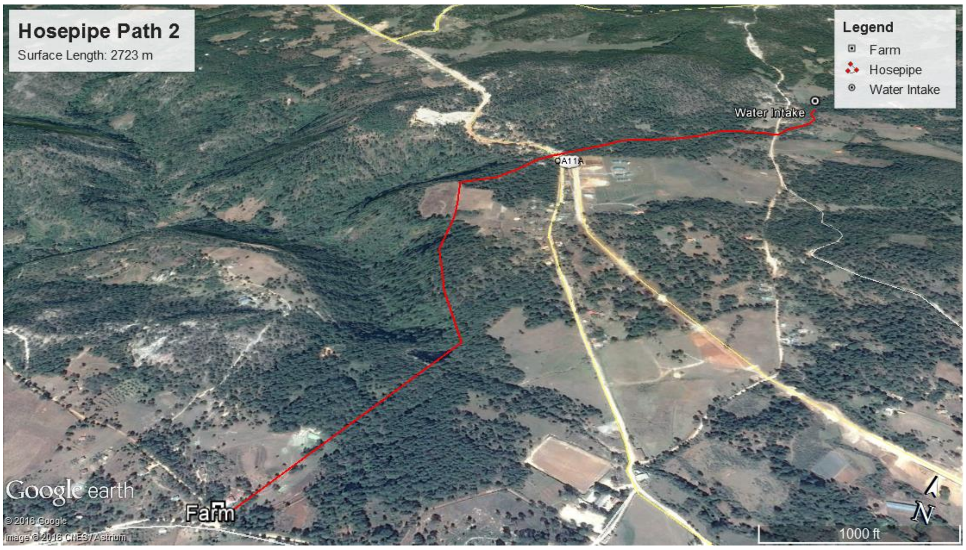

Figure 20. Hosepipe path 2 (surface length 2,723 m)

These datasets were converted to Shapefile format and compared with the results provided by the tools “2. Best Paths” and “3. Generate Watersheds”. For running the former, it was set a search radius of 10 Km from the farm location. Additionally, the elevation difference between the potential water intakes and the farm location was set as 10 m. The latter is the minimum elevation difference allowed by the application in order to bring water by using gravity. In this process, we calculated the surface distances, the costs of both current and modeled paths and determine the drainage area of each site.

It is important to mention that we did not validate the correctness of the tool “2. Best Paths”. Instead of that, we compared two current cases with the results provided by this tool. This comparison was carried out in order to identify if possible improvements in water intake - parcel location can be achieved. In other words, if it is possible to find supplemental or new water intakes, maybe closer to the farm location than the current one, with paths less difficult to traverse.

6. RESULTS AND DISCUSSION

The results achieved through the demonstration of concept of this thesis, their respective analyzes as well as some discussions are presented in this chapter.

6.1 Hydrologic Characteristics

The hydrologic characteristics obtained from the hydro DEM were the outlets (drainage points), streams (drainage lines) and watersheds (catchment areas). As a result, 59,172 watersheds were delimited and consequently the same amount of outlets was defined. Since all of these results were defined at a very detailed scale, it is impossible to appreciate their features at a general view, therefore, some of them are shown in Figure 21 for a small window of the study area.

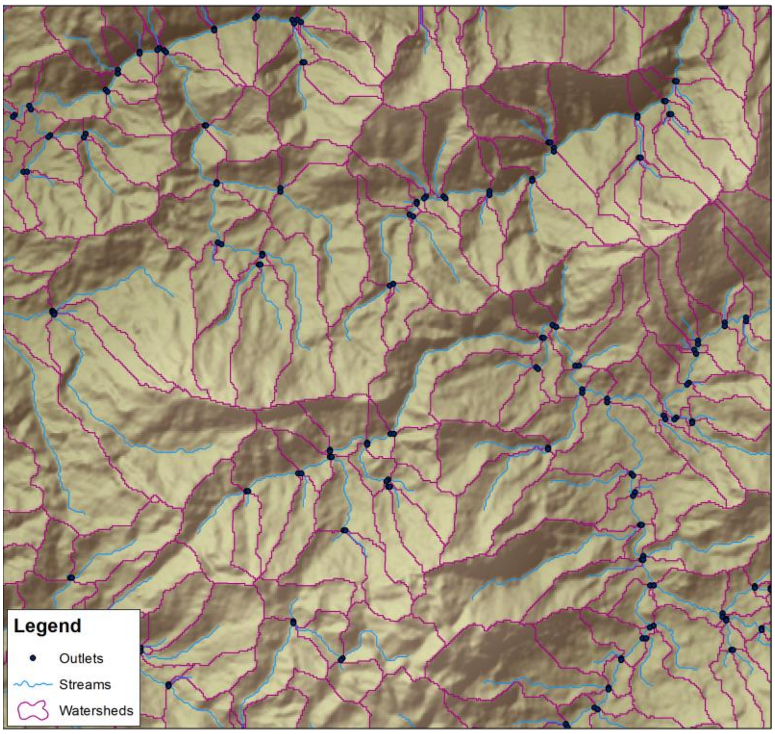

Figure 21. Hydrologic characteristics for a small window of the study area

These results define the hydrologic conditions of the study area at a very detailed scale. However, they depend on factors such as the spatial resolution of the DEM and the threshold value for the definition of the stream network. A DEM with a better spatial resolution enables the definition of more accurate hydrologic characteristics but at the same time it is also necessary more processing and storage capacity. Local elevation datasets—such as contours or elevation points—and alternate sources of hydrologic data could help to improve the detail and accuracy of the results. Unfortunately, we could not obtain supplemental information to better carry out this process. Another important factor is the threshold value for the delimitation of the stream network and consequently of the watersheds. As discussed before, this is considered a vital factor and should be based on geomorphological and weather characteristics. Nevertheless, in our case, it was defined after multiple iterations changing its value. Anyway, for the purpose of this thesis work, the detail worked was good enough to accomplish the successful results obtained.

It is important to mention the usage of each of these results. Therefore, the drainage points/outlets were used as potential locations where farmers could take water from streams. They are also called as intake points and the resulting ones that go through the decision rules explained before (section 5.4), are provided as destinations for the data model in Figure 17. Subsequently, the streams provide an idea of how water flows in the channels of the study area. Based on the streams, the outlets and watersheds were defined. Finally, the latter were used to give an idea of the areas that drain surface water to potential water intake points. In consequence, the three hydrologic characteristics are used by both the desktop and the online versions of the implemented tools.

6.2 Tool to address water captures in Western Honduras

The cost surface is fundamental to the process of finding the LCP. This surface was generated from three impedance surface factors, i.e., slope, vegetation (LULC) and protected basins. These factors were classified into a scale of 1 to 10 which represents the ease/difficulty of traversing the surface. At last, the cost surface was accomplished by making a weighted overlay of the aforementioned impedance factors. The resulting surfaces are shown in Figure 22.

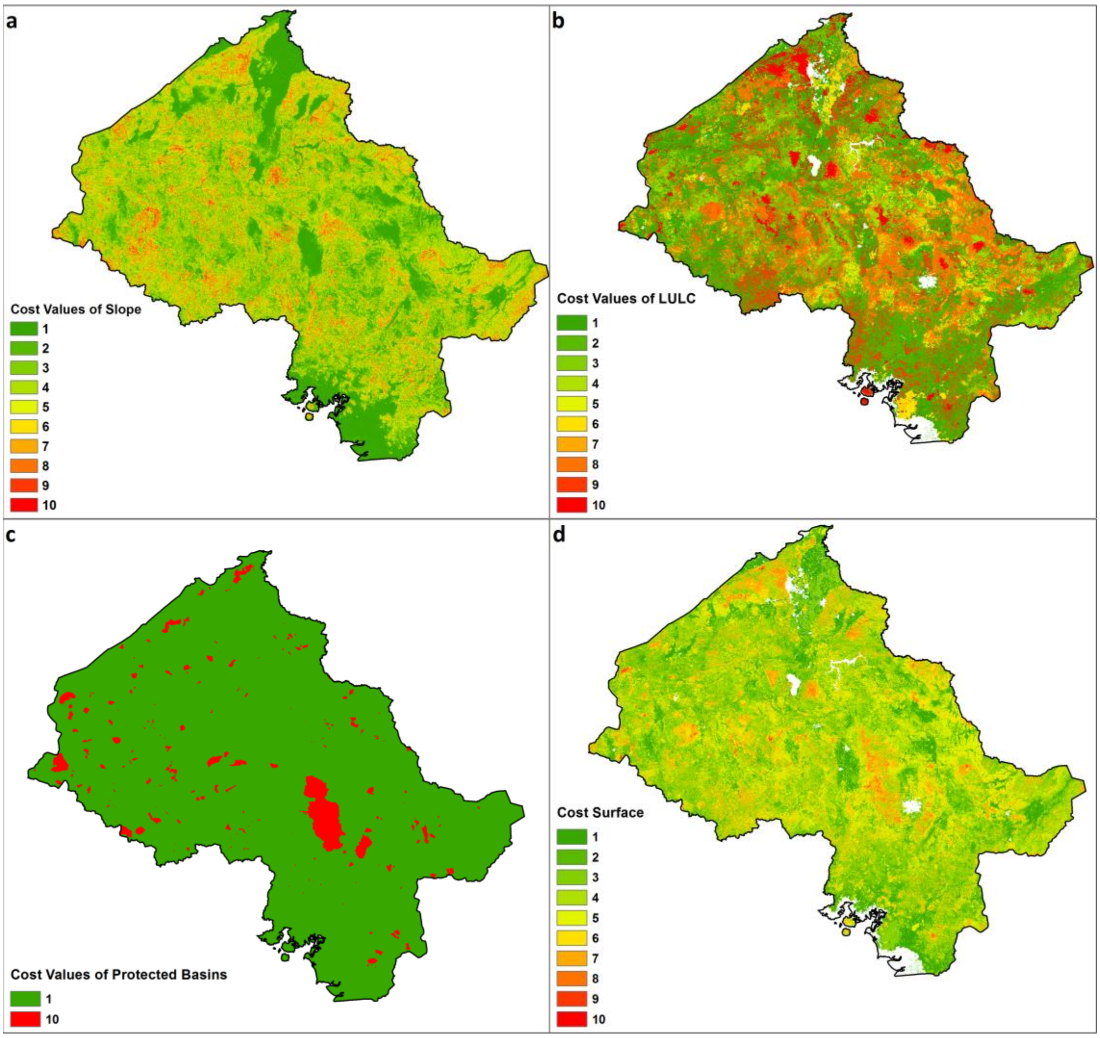

Figure 22. Cost values of slope (a), LULC (b), protected basins (c) and cost surface (d)

The final cost surface contains voids because of the LULC layer. The latter consisted of categories which were assigned as “NoData” when rasterizing it based on its cost values. These are the categories classified as “RESTRICTED” in Table 4. The cost values were assigned based on the idea that both slope and LULC determine the difficulty of the movement whereas the protected areas mostly restrict the path over their areas. Therefore, these cost values are meaningful and realistic attempts to represent the ease/difficulty of traversing the surface to install a hosepipe. Anyway, it would have been a great idea to contrast these cost values with personal opinions of farmers, and thus define them based on the real effort that they make to traverse any of the LULC categories.

Each of these impedance surface factors was multiplied by the corresponding weight which represents its importance into the model. In our case, LULC and slope were taken as two times more important than the protected areas. However, for other applications, a different set of weights can be applied based on different criteria. Even it is possible to integrate different impedance surface factors, and then design scenarios to be contrasted in order to define the final cost surface that better represent the phenomenon to be studied. In the latter case, it would be necessary then to validate the correctness of the results with the real conditions of the movement over such a surface.

Cost values and weights play the most important roles when defining the LCP. As it is hard to quantify these values in order to represent the reality, it is necessary to contrast the results with knowledge from either experts or people who know about the study area. Even in some cases, including additional layers in the modeling provide more realistic conditions of the area. Therefore, it is notable that LCP depends on factors such as the criterion layers used as impedance surface factors, which in turn depend on the scale at which they were created, the classification of the layers and the weights assigned to them.

The cost surface, the hydrologic characteristics, the raw DEM and the protected areas were stored on a geodatabase to be used by the tools packaged as a toolset in ArcGIS for Desktop (Figure 23). Two of them (tools enclosed by yellow rectangles in Figure 23) were published as geoprocessing services which are in turn used by the online web application.

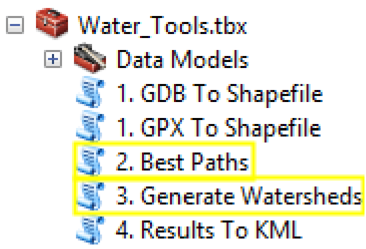

Figure 23. Tools packaged as a toolbox in ArcGIS for Desktop. In yellow rectangles, the tools published as geoprocessing services.

In Table 5 are described all the tools shown in Figure 23 and it is provided their use per version of the application.

Table 5. Overview of tools developed

Tool Name	Description	Version	
		Toolbox ArcGIS	**Online Web App.**
1. GDB To Shapefile	It converts waypoints stored in a GDB file (MapSource format) to Shapefile format (.shp). To run it, it is necessary to have installed the GPSBabel software. It also extracts the elevation from the DEM for each of the waypoints.	X	
1. GPX To Shapefile	It converts waypoints stored in a GPX file (GPS eXchange format) to Shapefile format (.shp). It also extracts the elevation from the DEM for each of the waypoints.	X	
2. Best Paths	It determines which the best paths from the outlets to the parcel location in a specified search radius are. All the processes are based on the Cost Surface previously calculated by running a weighted overlay using as inputs the vegetation, slope and protected areas.	X	X
3. Generate Watersheds	It creates polygons of drainage areas given the final outlets which should have been created by executing the tool "2. Best Paths".	X	X
4. Results To KML	This tool converts the resulting Feature Dataset obtained by running the tools "2. Best Paths" and "3. Generate Watersheds", to KML. This file is compressed using ZIP compression, has a .kmz extension.	X	

These tools enable the user to carry out a complete process, from converting to Shapefile the farm coordinates taken with a handled GPS in the field, until obtaining in KML format the potential water intakes for that farm, the best paths to reach them and the areas that drain to them. If the user decides to use the online web application, he/she does not need any computer, just a mobile device with Internet and consequently he/she is able to run the main tools but analyzing in real time the results provided by it. Besides, it permits to export the results as a CSV file, Feature Collection or GeoJSON. The online web application can be seen by clicking on the following link:

http://csi.maps.arcgis.com/apps/webappviewer/index.html?id=713cf0cf71c44bdda3d1213768ffb1be.

Figure 24 shows the interface of the online web application which was called "WatCat" as an acronym of Water Catchments.

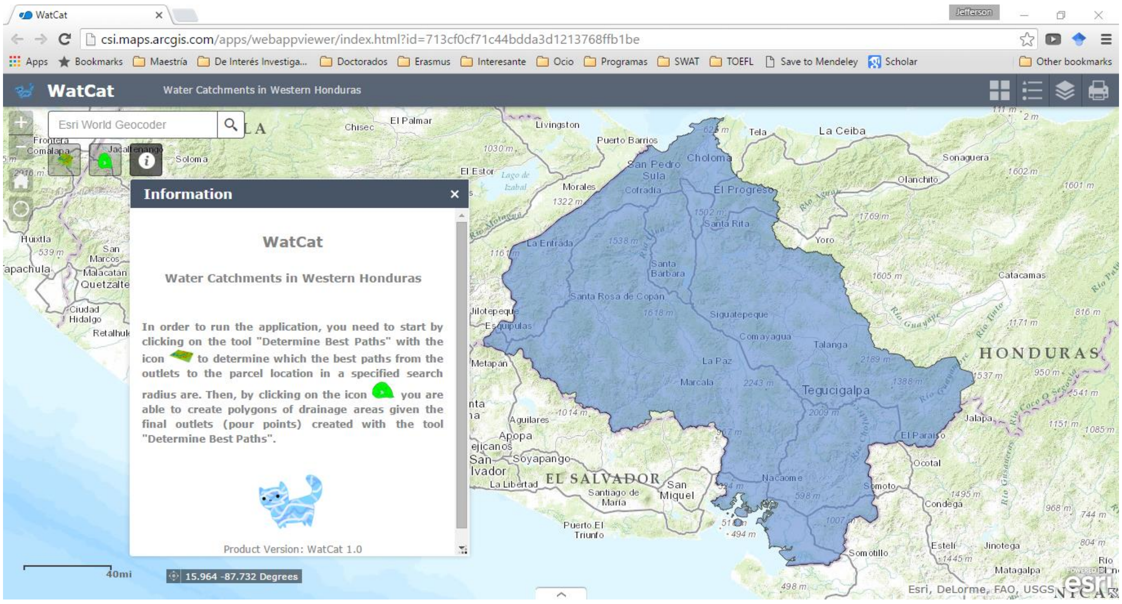

Figure 24. Online web application

When opening it, the user sees an information window with explanations about how to run the two geoprocessing services included into the application. In addition, it allows the user to change the basemap and print the map with the current view. Also, it is possible to use the ESRI World Geocoder to search for a place in the world. Moreover, the legend and the layer list are ready to use on the right side. By using the latter, it is possible to see the attribute tables of the resulting layers and, therefore, make filters and sort any field of a layer. Figure 25 shows how the application looks like after a complete run for a specified position of a farm (parcel).

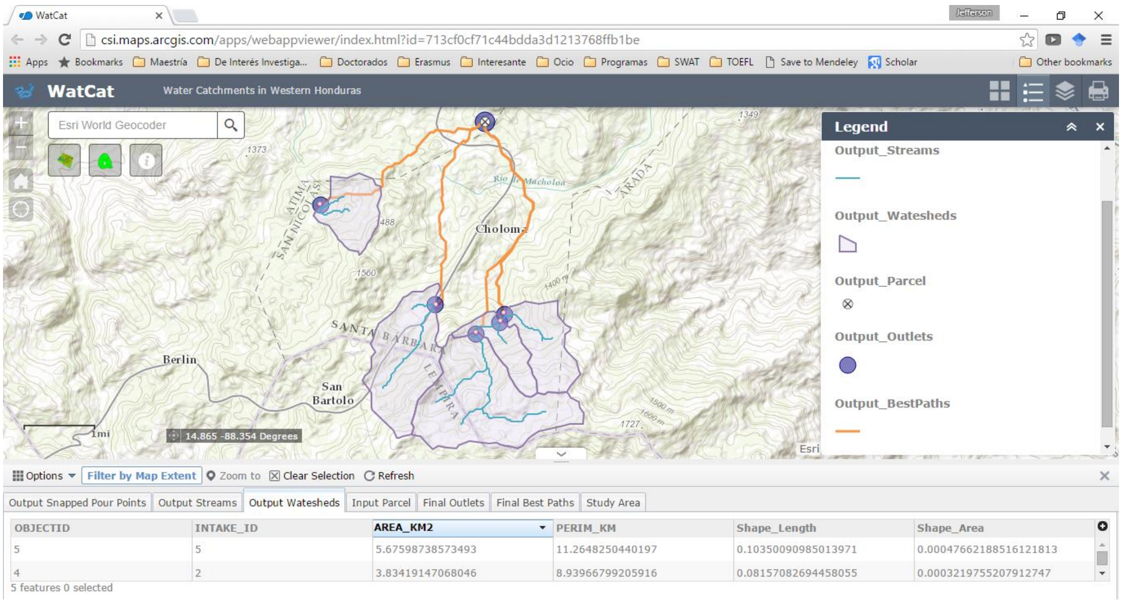

Figure 25. Results of a run in the online web application

6.3 Validation of the Tool

For each of the current hosepipe paths used to validate the tool developed in this thesis work, we modeled five other different potential paths that connect the farm to sites different—close in some cases—to the current water intakes. The sites provided by the tool are a subset of the outlets obtained in the definition of hydrologic characteristic. These are located exactly on the conjunction of streams as an attempt to find sites with enough water to supply the subsistence needs of farmers. On the other hand, the paths modeled by the tool are least-cost paths (LCPs), i.e., paths optimized to obtain the most cost-effective routes between the farm and feasible water intakes. Figure 26 provides an overall outlook of the current paths and the results obtained by the tool.

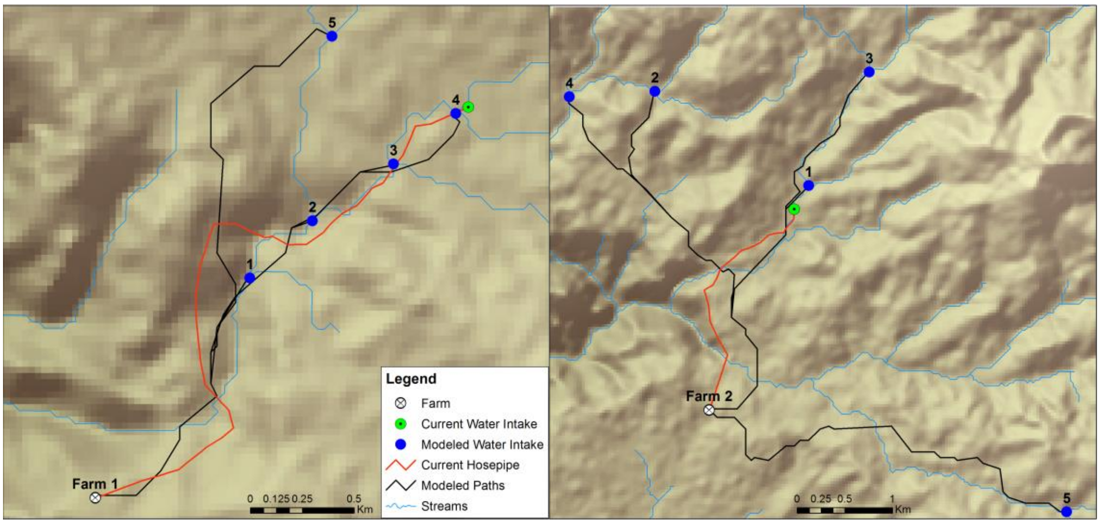

Figure 26. Comparison between the current hosepipe paths and the paths modeled by the tool

The numbers over the modeled water intakes (blue dots) were ordered according to the closeness to the farm. In both cases, one of the five options provided by the tool was very close to the current water intake. Table 6 shows the summarized results obtained after running the tool for each farm location and compared with the characteristics of the current hosepipe paths.

Table 6. Main characteristics of the current hosepipe paths and the paths modeled for each actual case

Farm	Path	Surface Length (m)	Water Intake Elevation (m)	Elevation Delta (m)	Cost Path	Cost Path Difference (%)	Drainage Area (ha)
1 Elevation: 1639 m	Current	3363	1703	64	4975.8	-	75.8
	1	1485	1650	11	2406.6	-51.6	676.9
	2	1910	1670	31	3661.2	-26.4	581.3
	3	2401	1699	60	4381.4	-11.9	323.4
	4	2879	1703	64	4885.8	-1.8	214.4
	5	3089	1702	63	4902.5	-1.5	165.5
2 Elevation: 1732 m	Current	2723	1744	12	3759.3	-	695.5
	1	3157	1752	20	4189.8	11.5	671.5
	2	4521	1767	35	7625.8	102.8	318.6
	3	4652	1809	77	7023.2	86.8	445.9
	4	4657	1750	18	6593.8	75.4	585.0
	5	4783	1827	95	7676.2	104.2	147.7

As shown in Table 6, the results achieved for the farm 1 (left side in Figure 26) were successful. All the paths are shorter and with less costs than the current path. Furthermore, the areas that drain to each of the modeled water intakes are also bigger than the area that drains to the current one. Although the size of the area draining an outlet does not imply the streamflow in the channel, it is expected that outlets with bigger drainage areas could receive higher streamflows, following and depending on the hydrology of the area.

The tool was capable of finding sites very close to the current water intakes. This was the case of the site 4 for the farm 1, which is even at the same elevation but with a path 484 m shorter and whose cost is 1.8% less than that of the current one. Another important aspect of the site 4 is that is located on the conjunction downstream of the current water intake. This possibly allows capturing more water but with less cost and a shorter path than the current hosepipe. It is important to mention that the costs in Table 6 represent the criteria taken into consideration for the model. Therefore, the units of the costs are relative allowing making comparisons based on percentage calculations. For instance, it is possible to say that the cost of one path is less than the cost of another; like in the case of the farm 1 when comparing all the options with the current hosepipe path.

All the aforementioned characteristics are related to the various options provided by the tool for the farm 1. These options are paths different from the current one but with less costs, shorter lengths and bigger drainage areas. Furthermore, all the options are also located above the farm location as a condition to use gravity in the transporting of water through hosepipes. In this case, the results provided plenty options which could be considered by the farmer in order to reduce effort, save money and maybe capture more water.

For the farm 2 (right side in Figure 26), the tool found paths longer than the current one. In addition, the costs of the modeled paths ranged from about 12% to 104% more than that of the actual path. The option 1 provided the closest water intake to the current one but with a path 434 m longer. In contrast to the option 4 for the farm 1, the option 1, in this case, is located on the conjunction upstream of the current water intake. This situation could be a limitation of the model since the tool was developed to find outlets only on stream conjunctions. We established this condition because it is very difficult to provide multiple sites along streams as they are continuous water flows. Something really important, but unknown in our case, is the amount of water that farmers are currently capturing from the sites. It would be very interesting to know the current water taken from those sites as well as the water available in the water intakes provided by the tool. This would allow making comparisons and determine which the most feasible site would be according to the real conditions of the farmer. In the first approach that we had with population of the study area, they told us about some actual cases where the sites defined to capture water do not provide the water needed for their subsistence. In this case, therefore, the tool would offer distinct options where would be possible to take water to alleviate the problem of water scarcity in the study area.

Another important aspect is the restriction of crossing/traversing some areas owned by large-scale landlords. In this specific case, it would be necessary to count on another layer to be included in the model. Thereupon, this layer would be a new impedance surface factor which would restrict the installation of any hosepipe over its areas.

In any case, an additional step would be needed in order to validate the correctness of this tool. This could be carried out by an expert or person who knows very well the area and can assess manually in the field the paths and sites provided by the tool developed in this thesis work.

7. CONCLUSIONS AND FUTURE WORK

Farmers in the Western part of Honduras have been suffering water scarcity during the last years. Due to their alarming conditions of poverty as well as the need for water for their subsistence based mostly on rainfed agricultural, a GIS-based tool has been implemented in this thesis as an attempt to help them in finding supplemental or new sources of water. This thesis demonstrated that the use of GIS technologies in combination with decision rules and surface features can provide a plausible solution to the real problem of water scarcity in Western Honduras.

This tool involves the integration of impedance surface factors such as vegetation, slope and protected areas. Furthermore, it is also based on hydrologic characteristics, i.e., outlets, streams and watersheds which were extracted from a hydrologically conditioned DEM. We addressed the feasibility of taking water from some potential sites located in streams surrounding a farm, by using the LCP method. This method allows finding the most cost-effective routes between the farm and those sites (water intakes). The LCP method is based on a resistance/friction surface which determines the ease/difficulty of traversing it. In this regard, we used a weighted overlay process involving the three impedance surface factors, their corresponding cost values and the weights assigned to them. We established the decision rules to find feasible water intakes for a farm, based on remarks provided by the farmers themselves.

The purpose of this tool is to identify feasible water catchments for small irrigation projects in Western Honduras. As a result, two versions of this tool were developed. The desktop version is a toolset which consists in turn of five tools and can be used in ArcGIS for Desktop. On the other hand, the online web application was developed to facilitate the implementation of the main tools on Internet. The latter eliminates the user's dependency of using a computer to execute the tools implemented in this thesis work. In general, this tool can support technicians or decision makers to address water catchments which are essential for alleviating the problems of farmers related to water supply.

We contrasted the results provided by the tool with two actual cases. The results showed the potential of this tool to find possible water intakes different from the current cases. In both cases, the tool was capable of finding water intakes very close to the current sites. The results for the first case were successful as all the resulting options involved less costs, shorter paths and bigger drainage areas. For the second case, the tool provided sites with longer paths, more costs to reach them and smaller drainage areas. This last case is specifically related to the restriction of the model to take into consideration outlets in between of stream conjunctions. Anyway, the tool offered distinct options where could be also possible to install hosepipes in order to take water from other sites, possibly with higher water availability than the current case. This last case showed up the weakness of the tool to make comparisons between different sites based on water availability.

Despite the strengths and potentiality of this tool, some improvements can be carried out. The integration of water balance could finally determine if a site is more feasible than another. This can be taken as a future addition to the model to better accomplish the entire process. Supplemental hydrologic features could be used to enforce drainages into the DEM allowing obtaining a hydrologically conditioned DEM whose flows follow the real patterns. Additionally, the inclusion of a layer with restrictive areas owned by large-scale landlords would improve the results provided by the tool. Validation of the correctness of the tool should be accomplished as a future work. This will be necessary to finally demonstrate the potential of the developed tool.

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