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# A GIS-based methodological framework to identify superficial water sources and their corresponding conduction paths for gravity-driven irrigation systems in developing countries

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ABSTRACT

The limited availability of fresh water is a major constraint to agricultural productivity and livelihood security in many developing countries. Within the coming decades, smallholder farmers in drought-prone areas are expected to be increasingly confronted with local water scarcity problems, but their access to technological knowledge and financial resources to cope with these problems is often limited. In this article, we present a methodological framework that allows for identifying, in a short period of time, suitable and superficial water sources, and cost-effective water transportation routes for the provisioning of gravity-driven irrigation systems. As an implementation of the framework, we present the automated and extensible geospatial toolset named "AGRI", and elaborate a case study in Western Honduras, where the methodology and toolset were applied to provide assistance to field technicians in the process of identifying water intake sites and transportation routes. The case study results show that 28 % of the water intake sites previously identified by technicians (without the support of AGRI) were found to be not feasible for gravity-driven irrigation. On the other hand, for the feasible water intake sites, AGRI was able to provide viable and shorter water transportation routes to farms in 70 % of the cases. Furthermore, AGRI was able to provide alternative feasible water intake sites for all considered farms, with correspondingly viable water transportation routes for 74 % of them. These results demonstrate AGRI's potential to reduce time, costs and risk of failure associated with the development of low-cost irrigation systems, which becomes increasingly needed to support the livelihoods of some of the world's most vulnerable populations.

## 1. Introduction

With a steadily growing world population and associated food demands, the paramount significance of water availability and accessibility for agriculture is increasing (De Fraiture and Wichelns, 2010). The stress on water requirements for agriculture is sharpened by several factors, such as the increased competition of industrial and urban water use (De Fraiture and Wichelns, 2010) and the upstream presence of hydraulic infrastructure, such as dams and reservoirs, that may change timing of water availability (Schewe et al., 2014). Another important factor is climate change (Haddeland et al., 2014), with resulting extreme weather phenomena such as severe droughts (Thornton et al., 2011). Consequently, water scarcity is increasing, and in turn the availability and access to fresh water sources becomes more important for sustained agricultural practices. Particularly vulnerable are smallholders in developing countries (Giordano et al., 2019), who are strongly dependent on agriculture (Dile et al., 2013) and typically rely on low-cost water supply systems. Furthermore, they normally have limited access to relevant technical knowledge, hydro-climatic information or methodological frameworks to mitigate the vulnerability to changes in short and long-term weather projections and the reduction of water provisions due to multiple uses (Esham and Garforth, 2013; Mapfumo et al., 2013).

In this article, we present a methodological framework for the development of low-cost gravity-based irrigation systems for small-scale agricultural practices in developing countries. Specifically, the

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framework allows for identifying suitable and inexpensive water intake sources, and cost-effective water transportation routes to farm locations. We hereby focus on Central and South America, with Western Honduras as a case study, but our work is applicable to other regions with similar geographical conditions.

Honduras is one of the poorest countries in Latin America with a rural population of about 50 % (The World Bank, 2015). Simultaneously, it is recognized as one of the countries most affected by extreme climatic events in Central America (Gourdji et al., 2014). The Western part of Honduras belongs to the Central American "dry corridor" (in Spanish known as the "corredor seco"), an area affected by severe water scarcity (Bouroncle et al., 2017). This area covers zones of Guatemala, Honduras, El Salvador and Nicaragua. In Honduras' dry corridor, people live under extreme poverty conditions, with incomes below the $2 USD per person per day poverty line, and consequently their livelihoods greatly depend on rainfed subsistence agriculture (The World Bank, 2015). Hence, water access plays an important role, as it is one of the main constraints for enhancing human welfare and agricultural production.

One of the actions undertaken to reduce agricultural losses in small-scale farms, which are commonly affected by the lack of water access, includes the establishment of irrigation infrastructure to enable sustainable water provisioning (Kahinda et al., 2007). Most of the poor farmers in Western Honduras inhabit steep lands where permanent water sources tend to be scarce. In consequence, they rely on low-cost solutions, and transfer water to their farms through hosepipes using gravity (Smits et al., 2010). In some cases, the hosepipes are installed along routes where gravity is not enough to pull the water to crop areas, forcing farmers to install pumps in between source and outflow to improve water flow. Although many governments, NGOs, and international agencies' efforts are currently directed to assist farmers in improving their access to water for crop production (Bitterman et al., 2016; Murugani and Thamaga-Chitja, 2018), field technicians are dispensed limited information to guide them during the process of identifying potential water intakes and their corresponding conduction paths. As a result, the establishment of gravity-driven water supply systems to irrigate croplands is often a long and challenging operation, and involves high costs related to field assessments and trial and error pipeline installation (in-field communications with implementers of the Alliance for the Dry Corridor - ACS). Furthermore, in most cases, this process is inefficient, as the installed hosepipes end up re-conducting water from distant sites or do not provide the water volume needed for irrigation.

Based on the above-mentioned conditions, we developed a GIS-based methodological framework to identify water intakes in streams for supplemental irrigation in small-scale farms, and define the most cost-effective routes for gravity-driven water transportation, taking into account topography, land cover and environmental restrictions such as the presence of protected areas. This may lead to saving time and money and reduces the risk of failure during water deviation investment projects. The framework integrates GIS technologies, decision rules and surface features, and uses the Least-Cost Path (LCP) approach to optimize the transfer of captured water to farm locations. As an implementation of the framework, we present the automated and extensible tool named AGRI ("AGua para RIego" - Water for Irrigation, in Spanish), and elaborate a case study in Western Honduras, where the methodology and the tool were applied to identify water intake sites and cost-effective conduction paths for local smallholder farmers. Based on the case study, we evaluated the effectiveness of AGRI to identify viable water conduction paths, and compared its results to expert-provided paths. Finally, we discuss the use of AGRI in practice, both in agriculture and other scenarios.

## 2. Materials and methods

### 2.1. Study area

The study area includes the Western part of Honduras and approximately covers the portion of the dry corridor that lies in the country (see Fig. 1). This area comprises 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 contains the departments of Choluteca, Comayagua, Copán, Cortés, Francisco Morazán, Intibucá, La Paz, Lempira, Ocotepeque, Santa Bárbara and Valle, and partially El Paraíso and Yoro. This area is characterized by slopes ranging from 0° (coastal zones) to 73° (steep hills) with altitudes that range between 0–2,850 m.a.s.l. The annual precipitation ranges from 800 mm up to 2000 mm while the mean temperature varies from 6 °C to 30 °C FAO, 2012). The rainy season lasts from May to November, 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, 2012). In general, the agriculture in the study area is carried out in hillside lands by small-scale farmers who mostly produce corn during the "primera" and beans during the "postrera" period. In areas with steep slopes, coffee is produced as well.

### 2.2. Problem identification

To understand the needs of organizations investing in water solutions for agriculture in the study area, we conducted group meetings and one-on-one interviews with experts in the field and key stakeholders. These stakeholders included representatives from different institutions dealing with agricultural policies and education as well as aid and development in Western Honduras, such as the U.S. Agency for International Development (USAID), Agricultural Finance (Fintrac), Honduras Strategic Investment (INVEST-H), Ministry of Agriculture and Livestock (SAG) and the Panamerican Agriculture University Zamorano, and local farmers as well. With these activities we aimed to better understand how the process of identifying suitable sites for water intake for small-scale agriculture is currently taking place and what are the main limitations to identify these sites in a cheaper, more effective and rapid manner. The interviews were accompanied by field visits in the departments of Intibucá, Lempira and Santa Bárbara to recognize terrain conditions and current strategies of farmers to obtain water for agriculture. This resulted in the following observations:

(O1) Low-cost solutions are essential to reach the target users, as local farmers do not have the financial means to invest in costly or moderately costly solutions. Also, the purchase of water pumps may pose a financial challenge.

(O2) As farmers currently take water from streams through hosepipes/pipelines, they try to avoid the installation of pumps in between the water intake and the farm location. Hence, they mostly take water from upper areas, using gravity to pull it to the farm location.

(O3) The length of the path is decisive in order to reduce hosepipe/pipeline costs and installation efforts, vulnerabilities, and point-to-point pressure loss. Consequently, farmers look for possible water intakes in streams close to their farms.

(O4) In certain areas it is prohibited to install water intakes, e.g. in basins in protected natural parks or other protected areas, such as indigenous recognized lands.

(O5) Technicians provide assistance to farmers in the process of site identification. They normally go to the field without any previous geographical information that guides them in terms of selecting areas with high potential for water intakes. This site identification process

**Fig. 1.** Location of study area.

could take several months and involves many field visits and tests of pipeline installation to confirm effective water transportation. Technicians are equipped with handheld GPS devices to take coordinates of candidate sites with potential for installing water intakes. As a technical note, the file formats which they usually work with are KML, GDB or GPX.

Based on these observations, we established the main requirements for a tool to accelerate and improve the effectiveness of the process for finding feasible water intakes for a farm. These are:

(R1) Water intake sites should be at an altitude of at least 10 m above the farm location to avoid installing water pumps (due to O1, O2).

(R2) The user must be able to search for water intake sites within a linear radius from the farm location (due to O3).

(R3) Any potential water intake sites located within protected areas (basins) have to be discarded (due to O4).

(R4) On a more technical/practical level, any new tools supporting water intake site identification should work well with and/or complement existing processes and tools. For example, they should support/complement technicians currently providing assistance to farmers, and therefore allow exporting results to a file format readable by handheld GPS devices (e.g. KML) (due to O5).

While the first three requirements are fundamental for water intakes to be considered potential sites for water sourcing for a farm, the fourth requirement is more practical. Closer sites to the farm location are considered better, in other words, the distance between the water intake site and the farm location establishes a metric according to which suitable sites can be ordered.

### 2.3. *Methodological framework*

A methodological framework was developed to identify water intake sites and their corresponding conduction paths under the given conditions, and the resources required to instantiate it, see Fig. 2. In essence, the methodology identifies suitable water sources and ranks them based on their closeness (closer is better) to a farm, in terms of pipeline surface length. The framework is based on two main components: 1) A hydrological component that defines hydrological features, and that is used to identify sites within streams where the likelihood of sufficient water volume is high; and 2) a water transportation route component based on a Least-Cost Path (LCP) approach. To generate these components, the framework requires a Digital Elevation Model (DEM), Land Use and Land Cover (LULC), and the Protected Basins of the targeted area (indicated in blue in Fig. 2). The outputs consist of the Water Intakes and Best Paths (indicated in purple in Fig. 2) for the farm.

In the text which follows, we capitalize words when they correspond to input, calculated or output models as denoted in Fig. 2.

#### 2.3.1. *Hydrological component*

The hydrological component corresponds to the lower left part of the methodological framework in Fig. 2. This component defines the hydrological features (Outlets, Streams and Watersheds) by calculating the water flow direction and accumulation, based on topographic properties of the landscape (see Wu et al., 2008; Metz et al., 2011; Choi, 2012). To perform these calculations, a hydrologically-corrected (Hydro) DEM is required, which refers to the raw DEM from which the sinks (i.e. areas of undefined flow directions) have been eliminated (Jarihani et al., 2015; Lindsay, 2016).

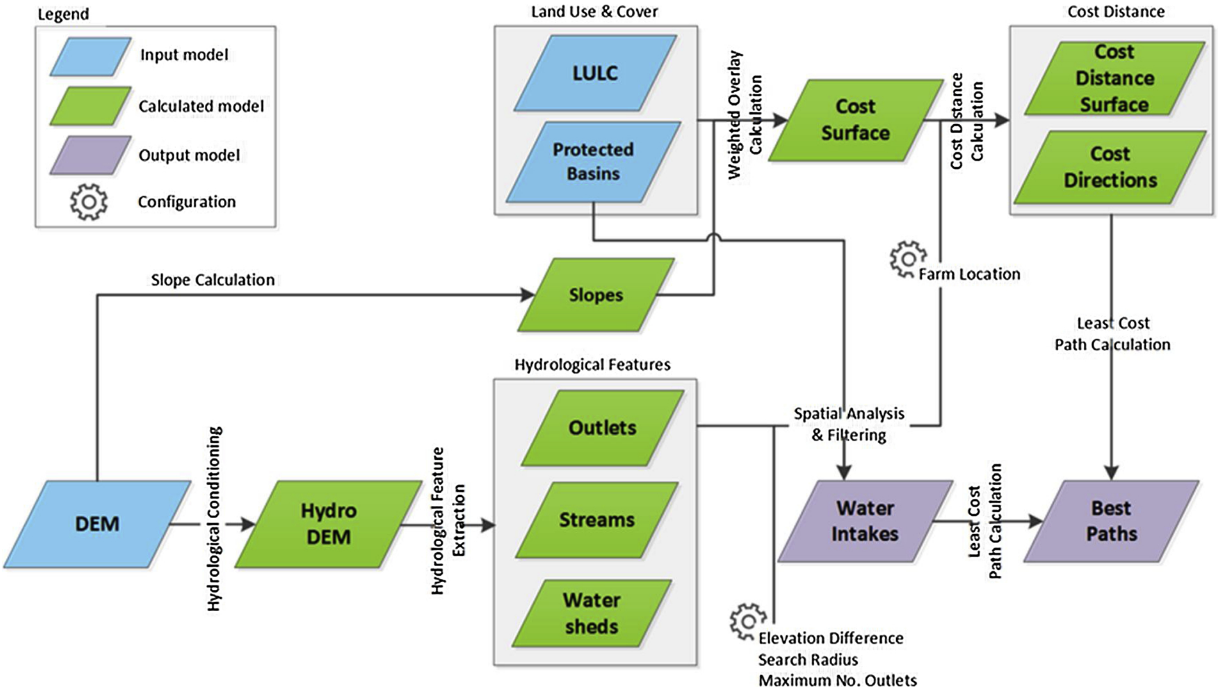

**Fig. 2.** Methodological framework.

A sink is a pixel (or a bunch of pixels) with equal or lower altitudinal values compared to its neighboring pixels, which interrupts a continuous downslope water flow direction. Although it is possible that sinks are real properties of the landscape such as natural depressions like karst areas, in many cases they are artefacts resulting from preprocessing operations such as resampling processes (Wu et al., 2008). Removing these sinks allows for the definition of a stream network with flow paths reaching their corresponding outlets and enables the proper delineation of basins (Soille, 2004).

### 2.3.2. Water transportation route component

The water transportation route component corresponds to the right part of the methodological framework in Fig. 2. This component uses the Least-Cost Path approach, which is a distance-based analysis tool provided by GIS technologies that allows for the modeling of the most efficient route between a source and destination location (Melles et al., 2011). This is based on the idea that any movement across the surface involves a cost, which can be expressed as time, distance, money or any other variable defined by the modeler (Collischonn and Pilar, 2000). In our case it represents the impediments imposed by land surface characteristics for the installation of hosepipes that transfer water from an intake site to a farm location. The LCP approach relies on a resistance/friction surface (Theobald, 2005) —also known as cost surface—which is used to calculate the most cost-effective route between origin and destination.

The framework employs the raw DEM to generate the Slopes. Then, based on the latter along with LULC and Protected Basins, it uses a weighted overlay calculation to generate the Cost Surface. The Slope and LULC impose restrictions to water movement, whereas the Protected Basins impose restrictions to the potential location of water intake sites and paths across the landscape. The resulting Cost Surface is used to identify the best path to install a hosepipe for the transportation of water from an intake site to the farm location, taking into account these restrictions. Based on the Cost Surface along with the location of the farm, the cost distance is calculated resulting in a Cost Distance Surface and Cost Directions layer.

Finally, two outputs are generated: (i) the Water Intakes, derived using spatial analysis and filtering from the Outlets, Protected Basins and some user configuration parameters (minimum elevation difference between the water intakes and the farm, search radius within which to identify water intakes and the maximum number of water intakes to be provided); and (ii) the Best Paths, using the LCP approach with the Water Intakes along with the Cost Distance Surface and the Cost Directions. The implementation of the methodological framework in the form of the AGRI tool is described in the following sections.

## 2.4. AGRI development

The methodological framework was implemented in an automated tool named AGRI, which is an extensible geospatial toolset that can be applied in any developing country where farmers are affected by water scarcity. It was developed as a toolbox, consisting of six tools, for ArcGIS for desktop, utilizing its modeling and spatial data processing capabilities, combined with Python for scripting and automation (Fig. 3 and Fig. 4). It consists of the following tools: 1) Convert to Shapefile; 2) Calculate Best Paths; 3) Calculate Final Path; 4) Generate Watersheds; 5) Export Results to KML; and 6) Convert KML to GPX. The numbers indicate a possible sequence to be followed for a successful and complete implementation of the AGRI tool. This depends, of course, on what the user wants to do. Most of these tools use a geodatabase which consists of the raw DEM, the hydrological features (i.e. outlets, stream network and catchment areas) and the cost surface, generated in turn from the criterion layers (i.e. slope, vegetation and protected basins). The essential tools of AGRI are “Calculate Best Paths” and “Calculate Final Path”. The former determines the best paths (LCPs) from a farm location to a number of potential water intakes. In contrast, the latter tool is used to determine the best path from a farm to a predefined water intake site. Also, the tool “Generate Watersheds” defines the drainage areas of the potential water intakes, while the other tools (1, 5 and 6) allow the user to convert between the input and output formats.

### 2.4.1. Data collection and preprocessing

The following datasets were used for the development of the tool: 1) the SRTM (Shuttle Radar Topography Mission) DEM (Digital Elevation

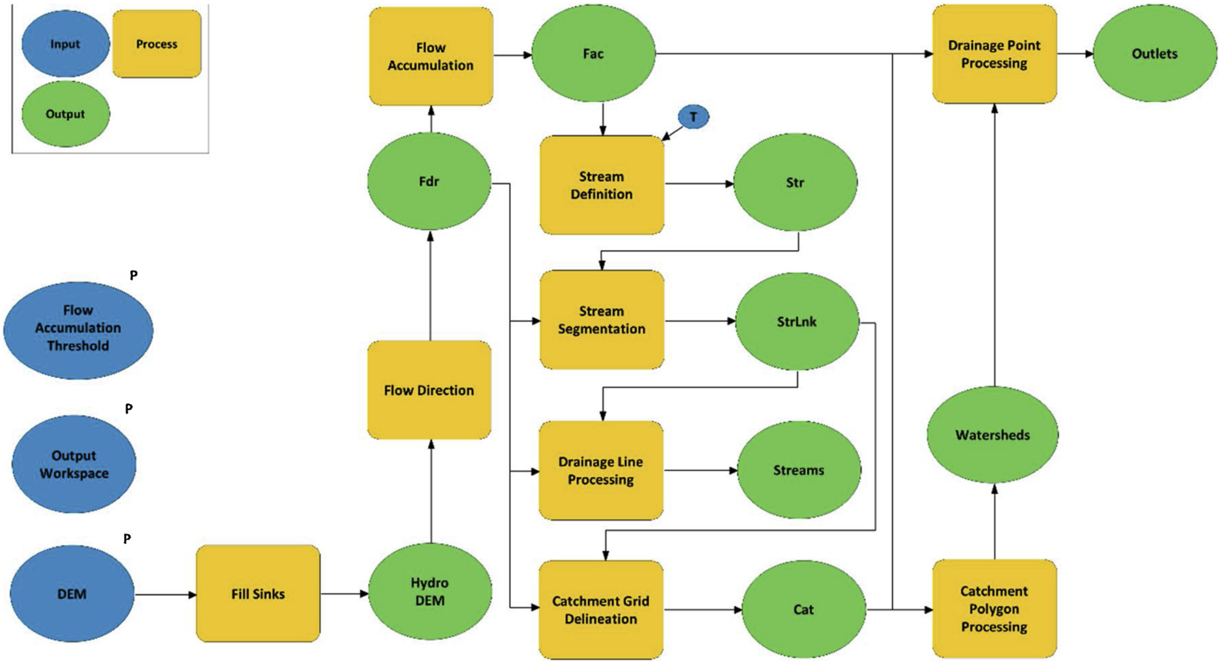

**Fig. 3.** Model for definition of hydrological features. Output raster or feature class layers are abbreviated: Fdr = Flow Direction, Fac = Flow Accumulation, Str = Stream, StrLnk = Stream Link and Cat = Catchment.

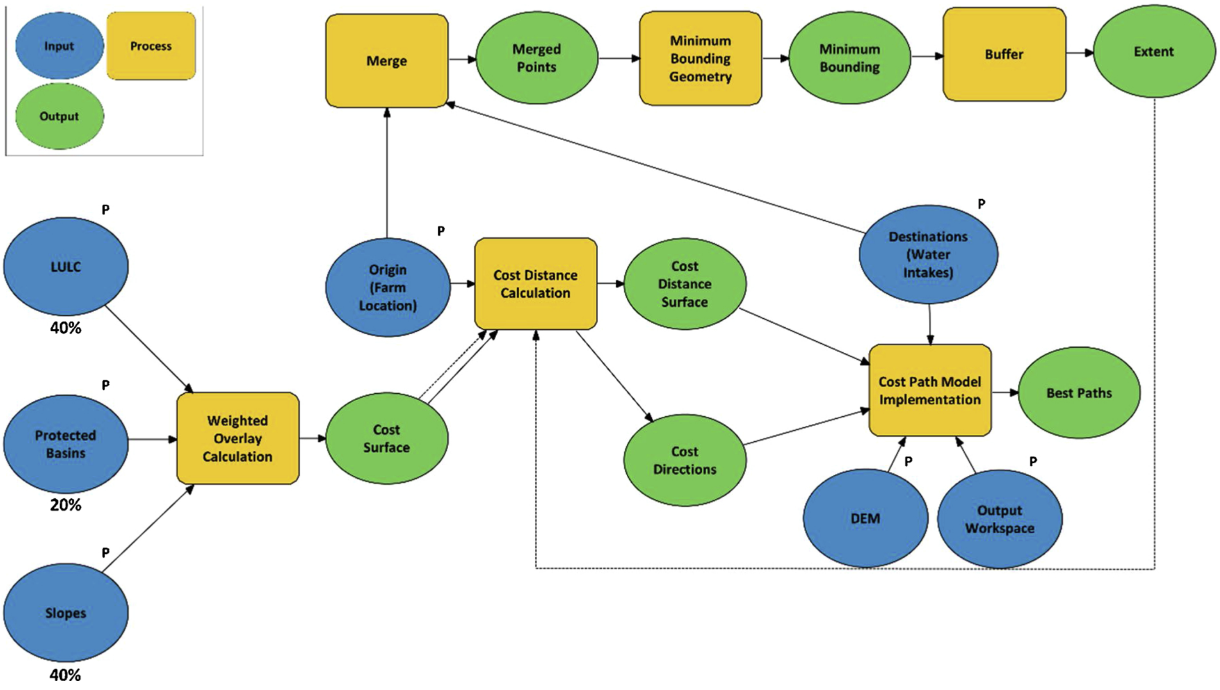

**Fig. 4.** Model for finding the best paths between the farm location and water intakes.

Model) with void filled data at 1 arc second spatial resolution (equivalent to about 30 m at the equator) to define the topography of the study area (NASA JPL, 2013); 2) a Land Use/Land Cover (LULC) map of Honduras, which was elaborated at a minimum scale of 1:25,000 using the Corine Land Cover classification system (Duarte et al., 2014); and 3) a layer of declared protected basins since 1987, where water infrastructures to facilitate uses other than for human drinking water are prohibited (Cardona, 2010). These datasets were freely accessible.

Eleven tiles (1 by 1 °) of the SRTM DEM were downloaded from the USGS (U.S. Geological Survey) EarthExplorer web portal[1] in GeoTIFF format to cover the total extension of the study area. Using ArcGIS for Desktop 10.2, we merged the tiles into a new raster dataset. The resulting raster was clipped with the boundary layer of Western Honduras to obtain a DEM for the study area. The same was done for the LULC and protected basins layers. As we planned to develop a raster-based model, we converted the latter two layers to raster format with the

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

same spatial resolution as the DEM. All spatial information used in this study was projected to the "WGS84 UTM Zone 16 N" coordinate system.

In addition, to compare potential solutions provided by the tool developed in this study, and potential water intake sites and paths as identified by technicians, we obtained a database with 87 farm locations, for which 89 potential water intake sites and corresponding water conduction paths had been identified by technicians (for one farm there were three potential sites and paths). The database contains the coordinates and elevation values of the farms and potential water intake sites, as well as surface length information of their corresponding water conduction paths.

### 2.4.2. *Definition of hydrological features*

The models shown in Figs. 3 and 4 were developed in ArcGIS for Desktop using the Model Builder application. The model in Fig. 3 corresponds to the hydrological component as implemented in the methodological framework (see Section 2.3) for defining the hydrological features. Its main input parameters include the raw DEM and the Flow Accumulation Threshold, while its outputs consist of raster or feature class layers. The end products generated by the model include feature class layers of the streams, watersheds and outlets, which are stored in the Output Workspace.

The model employs the raw DEM to generate the Hydro DEM. Although the ArcGIS software contains the "Fill" tool for the hydrologically conditioning of DEMs, this tool may not be accurate, as it increments the average elevation of the terrain and creates unnatural smooth areas (Jackson, 2012). Hence, we alternatively used the Optimized Pit Removal V1.5.1 tool proposed by Jackson (2012) that attempts to minimally affect the landscape by filling the pit area to a certain elevation, after which a path is carved from that elevation to an outlet.

The calculation of flow direction and accumulation for the definition of hydrological features was performed following procedures described in ESRI (2013), and by using the Arc Hydro tools (Maidment, 2002), which provides a modelling framework and tools to support water resource analyses in an ArcGIS environment.

The Flow Accumulation Threshold is used to define the stream network. In this sense, any pixel with a value greater than this threshold is considered part of the network. The conditional input parameter "T" in Fig. 3 assigns a value of 1 to all pixels with a flow accumulation greater than the specified threshold, resulting in a mask layer (raster with values of either 1 or NoData) of the stream network.

While it is argued that the Flow Accumulation Threshold value should be defined based on geomorphological and weather characteristics (Soille, 2004; Zhang et al., 2013), in most cases an arbitrary value is chosen (Zhang et al., 2013). Given this, we examined the effect of the threshold value on the stream network by performing model iterations using different values, until the threshold value was finally set to 500. We contrasted the resulting stream distribution with satellite imagery available on Google Earth, which affirmed that the chosen threshold value leads to a detailed and accurate stream network with high probability of containing water in its channels, as will be discussed later in Section 3.1.

### 2.4.3. *Least-cost path approach*

The model in Fig. 4 corresponds to the water transportation route component as defined in the methodological framework (see Section 2.3). For the purpose of the Honduras case study, we conditioned three criterion layers to generate the cost surface. The first criterion layer generated was the slope surface. It was calculated in degrees using the "Slope" tool in ArcGIS with the raw DEM as input data. As the slope layer is a continuous surface, it was reclassified into a scale of 1–10 (see Table S1, supplementary material) using the "Natural Breaks (Jenks)" classification method described in (Jenks and Caspall, 1971). This was the scale chosen to represent the cost values in all criterion layers, as to ensure an adequate representation of the values' variability in each layer. It represents the suitability of the land surface for the installation of a hosepipe, with higher values indicating worse suitability.

The second criterion layer was the clipped LULC layer, containing 23 of the 26 land cover classes for all Honduras. Each land cover class was assigned a cost value from 1–10 indicating high and low suitability for hosepipe installation, respectively. The resulting categories in both Spanish (original) and English, the cost values and their corresponding areas are displayed in Table S2 (supplementary material).

The third criterion layer used was the layer of protected basins. They comprise about 2198 $km^2$ (~4 %) of the study area and were assigned a cost value of 10. This value restricts the installation of hosepipes within areas where infrastructure building is prohibited.

Based on the above-mentioned criterion layers and using a number of potential water intake sites and a farm location as input parameters, the most cost-effective paths for water transportation can be identified (Fig. 4). Cost paths are calculated in the opposite direction of the water flow due to model parameterization, starting from the farm location (origin) to the candidate water intake sites (destinations).

Fig. 4 shows that for each independent model run, the middle and right parts of the model change as they depend on both origin and destination(s). On the other hand, the cost surface is generated only once by performing a weighted overlay of the three criterion layers (left part of the model). Finally, within each run, buffer areas around the origin and destination locations are generated to delineate the area for which to calculate the cost paths and distances.

To put emphasis on the restrictions imposed to water movement in finding the best paths, a weight of 40 % was given to both vegetation and slope, while a weight of 20 % was given to protected basins. These weights represent the relative importance of the variables in the model. In this specific case study, we considered vegetation and slope to be equally important, while protected basins have a lower impact in the model. This weighting gives the highest values to areas with dense vegetation and steep slopes, while lower values are assigned to flatter and less densely covered areas. Therefore, the weights assigned to the criterion layers facilitate the hydraulic design of pipelines, take into account protected areas, and in turn allow for the protection of forests. The weights are configurable, and can thus be changed depending on the conditions of the case study at hand, which may have a significant impact on the calculation of the best paths.

## 3. AGRI evaluation

The AGRI tool, and its underlying methodological framework, were extensively tested and applied in practice, to verify: (i) the correct identification of potential water intake sites, (ii) the use of AGRI to detect wrongly identified water intake sites by technicians (iii) the ability of AGRI to identify (better) alternative conductions paths as compared to technician-identified paths.

### 3.1. *Testing and validation*

We assessed the ability of AGRI to identify potential water intake sites in streams where the likelihood of water availability is high, in three dry watersheds within the departments of Intibucá, Lempira and Ocotepeque, and one wet watershed in Santa Bárbara (Honduras). These watersheds were selected because development agencies and governmental institutions prioritized these areas for small irrigation projects that use water diverted from nearby streams. To validate the AGRI tool, it was used to identify 27 potential water intake sites within these watersheds. Then, we verified water availability in the identified sites during field visits in March 2016, which is generally the driest month of the year (see Figure S1, supplementary material), to confirm their feasibility to serve as potential water source.

In addition, we used AGRI to assess the feasibility of potential water intake sites and conduction paths as identified by technicians without the assistance of a GIS-based tool such as AGRI. As mentioned in Section

2.4, we obtained a database of existing projects with farm locations along with their corresponding water intake sites and conduction paths (hereafter referred to as “technician sites” and “technician paths”, respectively). First, AGRI was used to assess the feasibility of the technician sites (89 in total), where a site in unprotected area and located at an altitude of at least 10 m above the farm was considered as feasible.

Then, we used AGRI to calculate alternative water conduction paths between feasible technician sites and the farm locations. The path lengths as calculated by AGRI were contrasted with the length of the technician paths, to examine AGRI’s potential to provide shorter, more cost-effective paths compared to technicians. In addition, we examined the viability of each alternative path identified with AGRI. In this regard, a path that goes over a peak which is 24 m higher relative to the water intake site was considered as not viable. We used 24 m because it is reported that SRTM DEMs have a vertical accuracy of 16 m (Farr et al., 2007), and technicians report that in the field, they can circumvent a peak of up to 8 m encountered on a path. The present design of AGRI does not allow for automatic recognition of paths that are not viable. Hence, the viability of the paths was manually examined by comparing the altitude of each water intake site with the highest peak in the path. The viability of technician paths could not be examined, as information on their positioning as proposed by technicians was unavailable (i.e. the database of existing projects only contained surface length information).

Subsequently, we used AGRI to identify potential water intake sites for the 87 farms included in the database and calculated their corresponding conduction paths (hereafter referred to as “AGRI sites” and “AGRI paths”, respectively). Also, the viability of each AGRI path was examined, following the criteria described above. We configured AGRI by specifying a minimum elevation difference between the water intakes and the farm of 10 m, and a maximum search radius of 10 km within which to identify potential water intakes. In addition, we specified a maximum of 10 water intake sites per farm location, which implies that more than one water intake site and conduction path per farm could be identified. As a final comparison, we contrasted the AGRI paths with the technician paths and examined the differences in their surface lengths.

### 3.2. Results

The field recognition of potential water intake sites identified by AGRI carried out in March 2016, allowed us to validate the threshold value used for the definition of the stream network, and the ability of AGRI to identify sites in streams where water availability is high. Out of the 27 sites visited, only two were located in dry channels. Both channels directly emerge from a spring, where the likelihood of water availability is usually lower compared to locations further downwards that are connected to multiple streams. Hence, the chosen threshold value of 500 (representing the number of pixels draining upstream of the pixel being analyzed) ensured a stream network for the study area with high probability of containing water in its channels. The drainage areas of the sites found by AGRI ranged considerably, from 1.4 km$^2$ to 57 km$^2$, showing the level of detail at which drainage areas could be defined. Despite the fact that agriculture in the study area is mostly implemented in hillside lands, AGRI performed well in identifying feasible water sources in streams. This capacity of AGRI expands the options of farmers to find potential sites that supply water required for crop irrigation.

With respect to the assessment of the water intake sites previously identified by technicians without the support of AGRI (technician sites), we found that by using AGRI, 25 out of 89 (~28 %) technician sites were found to be not feasible, either because they are located in protected areas or because they do not meet the requirement of ≥10 m elevation difference between the water intake site and the farm location (see Table 1). This is a significant finding, as it shows that using the AGRI tool helps to avoid the unnecessary installation of water intakes in locations from which it is anyway not feasible to transport water by gravity. As a consequence, the use of AGRI leads to substantial time and financial savings. Such problems were also reported during meetings with technicians who were dealing with hosepipes that had to be reinstalled due to the lack of water flow by gravity.

On the other hand, we used AGRI to provide potential alternatives for the water conduction paths as proposed by technicians (technician paths), using the “Calculate Final Path” tool. For the 64 technician sites that were found to be feasible by AGRI, 64 alternative paths were generated using AGRI. We found that 47 (~73 %) of them can be considered viable as they avoid peaks in the landscape of > 24 m relative to the water intake site. The other 17 alternative paths were found not to be viable, as they could not avoid peaks in the landscape > 24 m. Hence, although AGRI found those 64 technician sites to be feasible, the terrain conditions impede viable pipeline installations between 17 of them and their corresponding farm locations, which implies that for these farms, alternative water intake sites should be considered. In addition, we compared the technician paths with the alternative paths identified by AGRI in terms of surface length. Of the 63 technician paths for which surface length information was available, AGRI provided 44 (~70 %) viable shorter alternative paths, see Table 1. Again, this could reflect considerable gains, as for shorter paths less time and funds are needed for pipeline installation.

Apart from the assessment of technician sites and technician paths, we assessed AGRI’s ability to identify feasible water intake sites and viable paths for the same 87 farm locations (AGRI sites and AGRI paths, respectively). In this regard, we used AGRI’s “Calculate Best Paths” tool to identify the sites and the optimal paths to the farms. This resulted in a total of 794 feasible AGRI sites, with at least one feasible site per farm (see Table 2). Correspondingly, for 248 out of 794 feasible AGRI sites, at least one viable water conduction path to the target farm could be identified. We call these sites viable AGRI sites. Therefore, for 64 out of 87 (~74 %) farms, at least one viable path to a feasible AGRI water

**Table 1**
Overview of the feasibility analysis of technician sites, and comparison of technician paths with alternative paths as defined with AGRI.

| Farms | Technician sites | | | Technician paths | Alternative paths | |
|---|---|---|---|---|---|---|
| | No. of sites | Feasible | | Surface length information | Viable[1] | Shorter[2] |
| 87 | 89 | Yes (64) | | Yes (63) | Yes (46) | Yes (44)<br>No (2) |
| | | | | | No (17) | Yes (14)<br>No (3) |
| | | | | No (1) | Yes (1) | |
| | | No (25) | 4*<br>21** | | | |

* ≥10 m elevation difference between the water intake site and the farm location.

** Located in protected areas.

[1] A path that goes over a peak of < 24 m relative to the water intake site was considered as viable.

[2] The surface length of the technician paths is compared with the surface length of the alternative paths identified with AGRI.

**Table 2**
Overview of the number of sites and water conduction paths identified with AGRI.

| Farms | Feasible AGRI sites | Viable AGRI sites[1] | Farms with at least 1 viable AGRI path |
|---|---|---|---|
| 87 | 794 | 248 (viable)<br>546 (not viable) | 64 |

[1] An AGRI site is viable if a viable path exists (i.e., a path with no peak > 24 m relative to the water intake site).

**Table 3**
Comparison of technician paths and AGRI paths in terms of surface length.

| Technician paths | AGRI paths | | Surface length comparison[1] |
|---|---|---|---|
| 89 | 794 | 248 (viable) | Shorter (22) |
| | | | Longer (14) |
| | | | Both (27) |
| | | 546 (not viable) | Shorter (3) |
| | | | Longer (14) |
| | | | Both (8) |

[1] The surface length of the technician paths was compared with the surface length of up to 10 AGRI paths. "Shorter" indicates that AGRI found only shorter paths compared to technicians, "longer" indicates that AGRI found only longer paths, while "both" indicates that AGRI found both shorter and longer paths compared to technicians.

intake site could be found. The inability of AGRI to find viable paths for all farms should not be considered a flaw of the tool; it rather reflects the lack of adequate terrains in the surroundings of some of the farms that facilitate the installation of a hosepipe, even though the potential water intake point itself is feasible. For example, several farms were found to be located on hilltops or mountain peaks. Although AGRI was able to identify water intake sites at altitudes of at least 10 m above the farms in all cases (e.g. located on nearby peaks) with sufficient water supply, due to significant local peaks/depressions between the water intake sites and some farm locations, the installation of gravity-based irrigation systems will nonetheless be almost impossible or high costly.

Finally, we contrasted 88 technician paths with the AGRI paths in terms of surface length (for one technician path, surface length information was not available), where AGRI provided up to 10 paths for each farm location. Based on this analysis, we found that AGRI identified at least one viable shorter path compared to technicians in 49 out of 63 (~78 %) cases (see Table 3). This again confirms that AGRI allows for significant improvements in terms of water intake site identification and conduction path definition.

### 3.3. Further experiences, uses in practice and discussion

Since the release of AGRI in 2016, it has provided considerable support to cost-effective investments by government and development agencies. It has been used by at least 30 technicians, and at least 200 sites for diverting water for irrigated agriculture purposes have been identified. Similarly, some previously identified sites by technicians have been successfully changed to AGRI's identified locations. Meanwhile, it is important to note that AGRI does not replace the role of technicians, as the final decision on site selection and path definition remains with the technicians and their overall assessment of the study area. Importantly, also other aspects, for instance related to social impacts and local environmental regulations, are to be considered by technicians in the process of site assessment.

While AGRI is capable of identifying feasible water intake sites along with viable paths for pipeline installation (using the "Calculate Best Path" tool), it can also be used to determine the best path between a farm and a predefined water intake site (using the "Calculate Final Path" tool). This option is useful when field technicians have already established a suitable water intake, for which only the best (i.e. final) path between this point and the destination farm needs to be determined. On the other hand, we found that occasionally water intake sites identified by AGRI are located within streams on private property, where landowners may not be willing to cooperate with the installation of pipelines. For these cases, AGRI allows to manually relocate the coordinates of the water intake site within the same stream but outside the property boundaries, for which subsequently the final path can be calculated.

AGRI was designed to provide information for irrigation projects, however, the tool has been given other uses by local organizations. For example, AGRI has been used to determine the best path from a licensed superficial water source to a tank to store water for human consumption in a small community. This evidenced a new utility of AGRI, showing that in addition to irrigation projects, it can also help to identify water sources and conduction paths to support human drinking water needs. In addition, AGRI allows for the delineation of drainage areas, which may help environmental agencies to target local regulations that aim at the conservation of water resources.

While this article has demonstrated the strengths and potential of AGRI, some adjustments could be made to further improve the tool. The present design of AGRI solely allows for the identification of potential water intakes and the optimal transportation routes to the farm locations. To provide more understanding of the water quantity in streams and the potential for water harvesting, an extension of AGRI with a water balance model is currently under development. This extension will allow for estimations of the degree to which water from streams and harvesting sites can be captured and stored to support agriculture and household needs, while taking into account minimum ecological flows (Acreman and Dunbar, 2004) and the water supply requirements of downstream water users. Furthermore, identification of viable conduction paths, by comparing the altitude of the water intake site with the highest peak in the path, could be automated to automatically filter out non-viable paths.

Furthermore, the applicability of AGRI could be enhanced by incorporating case study-specific factors that could narrow down the number of candidate water sources, such as information on local land registry to define areas where private landowners may oppose to pipeline installations. Also, information on existing or future water infrastructures in the region could provide additional insights on the long term water provisioning potential of candidate water sources. The methodological framework, and the AGRI tool, are easily adaptable to include such concerns.

## 4. Conclusions

This article addressed the problem of identifying viable low-cost water provisioning solutions for smallholder farmers in developing countries. A GIS-based methodological framework was developed to support ongoing efforts oriented at determining suitable sites for establishing low-cost, gravity-based irrigation systems using water diverted from rivers. The implementation of this framework, and its use in practice, demonstrated its potential for assisting local field technicians in the process of identifying candidate water intake sites and the most cost-effective water conduction routes to the destination farm location. Although our work was motivated by a case study specifically focused on the Western part of Honduras, which has been exposed to severe water scarcity in the last couple of years, the framework is equally applicable to other regions that are subjected to similar water scarcity problems.

The main product obtained in this study is a geospatial tool named AGRI. This tool allows for the characterization of stream networks and drainage areas to simulate water flow over the land surface, while aggregating a number of landscape characteristics into a cost surface that imposes restrictions to this water flow. The result is the geographical localization of a point in a river or stream where sufficient water is likely available for crop irrigation, and the optimal path from this point to a farm along which a hosepipe can be installed. The tool was tested and evaluated in a large-scale case study in Western Honduras. Results show that AGRI was able (1) to identify sites in streams where water is available during the dry season, in 25 out of 27 cases, (2) to identify 25 out of 89 technician-identified water intake sites as not feasible, (3) to provide viable shorter alternative paths compared to technician-identified paths, between farms and technician-identified water intake sites, in 44 out of 63 cases, (4) to provide feasible alternative water intake sites with at least one viable path for 64 out of 87 farms (for other farms, likely no viable path exists due to local topography), and (5) to provide at least one shorter path between farms and AGRI identified sites, compared to technician-identified paths between farms and technician-identified sites, for 60 out of 88 cases. These results demonstrate AGRI's potential to reduce time and costs associated with field exploration and installation efforts, and thus contributes to the low-cost water provisioning solutions that are critically needed to address subsistence challenges in some of the world's most underdeveloped regions.

Although AGRI was developed using freely accessible datasets mainly obtained from public sources, in some regions it may be more difficult to obtain accurate spatial information, as public data might be less readily available. This could potentially be a limitation for the development of case study-specific tools for other study regions. On the other hand, an additional water balance component or additional information on external current and future pressures on water resources, and automation of filtering out non-viable paths, may improve the overall suitability and performance of the tool. Despite these possible improvements, AGRI has demonstrated to be a novel tool with major practical applicability in developing countries severely affected by water scarcity problems, where decisions on agriculture and natural resources management are often taken based on low quality information.

## Declaration of Competing Interest

No potential conflict of interest was reported by the authors.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106048.

## References

Acreman, M.C., Dunbar, M.J., 2004. Defining environmental river flow requirements? A review. Hydrol. Earth Syst. Sci. 8 (5), 861–876.

Bitterman, P., Tate, E., Van Meter, K.J., Basu, N.B., 2016. Water security and rainwater harvesting: a conceptual framework and candidate indicators. Appl. Geogr. 76, 75–84.

Bouroncle, C., Imbach, P., Rodríguez-Sánchez, B., Medellín, C., Martinez-Valle, A., Läderach, P., 2017. Mapping climate change adaptive capacity and vulnerability of smallholder agricultural livelihoods in Central America: ranking and descriptive approaches to support adaptation strategies. Clim. Change 141 (1), 123–137.

Cardona, A.J., 2010. Estrategia Nacional para el Manejo de Cuencas Hidrográficas en Honduras. Instituto de Conservación y Desarrollo Forestal, Áreas Protegidas y Vida Silvestre, Comayagüela, Honduras.

Choi, Y., 2012. A new algorithm to calculate weighted flow-accumulation from a DEM by considering surface and underground stormwater infrastructure. Environ. Model. Softw. 30, 81–91.

Collischonn, W., Pilar, J.V., 2000. A direction dependent least-cost-path algorithm for roads and canals. Int. J. Geogr. Inf. Sci. 14 (4), 397–406.

De Fraiture, C., Wichelns, D., 2010. Satisfying future water demands for agriculture. Agric. Water Manage. 97 (4), 502–511.

Dile, Y.T., Karlberg, L., Temesgen, M., Rockström, J., 2013. The role of water harvesting to achieve sustainable agricultural intensification and resilience against water related shocks in sub-Saharan Africa. Agric. Ecosyst. Environ. 181, 69–79.

Duarte, E.A., Díaz, O.O., Maradiaga, I.E., Casco, F.L., Fuentes, D.E., Galo, A.J., Avilés, P.E., Araneda, F.M., 2014. Sistema de Clasificación del Mapa Forestal y Cobertura de la Tierra de Honduras. Nota Técnica Nº 06, Programa Regional REDD/CCAD-GIZ. Antiguo Cuscatlán, El Salvador.. .

Esham, M., Garforth, C., 2013. Agricultural adaptation to climate change: insights from a farming community in Sri Lanka. Mitig. Adapt. Strateg. Glob. Chang. 18 (5), 535–549.

ESRI, 2013. Overview of Arc Hydro Terrain Preprocessing Workflows. Environmental Systems Research Institute, Redlands, USA.

FAO, 2012. Estudio de caracterización del Corredor Seco Centroamericano. Food and Agriculture Organization of the United Nations, Rome, Italy.

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., Alsdorf, D., 2007. The shuttle radar topography mission. Rev. Geophys. 45 (2).

Giordano, M., Barron, J., Ünver, O., 2019. Water scarcity and challenges for smallholder agriculture. In: Campanhola, C., Pandey, S. (Eds.), Sustainable Food and Agriculture: An Integrated Approach. Academic Press, Cambridge, USA, pp. 75–94.

Gourdji, S., Craig, M., Shirley, R., Ponce de Leon Barido, D., Campos, E., Giraldo, M., Lopez, M., Pereira de Lucena, A.F., Luger, M., Kammen, D.M., 2014. Sustainable Development Opportunities at the Climate, Land, Energy, and Water Nexus in Nicaragua. Paper No. 33. University of California, Berkeley, Center for Latin American Studies, California, USA.

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. 111 (9), 3251–3256.

Jackson, S., 2012. Designing an Optimal Pit Removal Tool for Digital Elevation Models. University of Texas at Austin, Austin, USA.

Jarihani, A.A., Callow, J.N., McVicar, T.R., Van Niel, T.G., Larsen, J.R., 2015. Satellite-derived Digital Elevation Model (DEM) selection, preparation and correction for hydrodynamic modelling in large, low-gradient and data-sparse catchments. J. Hydrol. 524, 489–506.

Jenks, G.F., Caspall, F.C., 1971. Error on choroplethic maps: definition, measurement, reduction. Ann. Assoc. Am. Geogr. 61 (2), 217–244.

Kahinda, J.M., Rockström, J., Taigbenu, A.E., Dimes, J., 2007. Rainwater harvesting to enhance water productivity of rainfed agriculture in the semi-arid Zimbabwe. Phys. Chem. Earth (2002) 32 (15-18), 1068–1073.

Lindsay, J.B., 2016. The practice of DEM stream burning revisited. Earth. Surf. Process. Landforms 41 (5), 658–668.

Maidment, D.R. (Ed.), 2002. Arc Hydro: GIS for Water Resources. Environmental Systems Research Institute Press, Redlands, USA.

Mapfumo, P., Adjei-Nsiah, S., Mtambanengwe, F., Chikowo, R., Giller, K.E., 2013. Participatory action research (PAR) as an entry point for supporting climate change adaptation by smallholder farmers in Africa. Environ. Dev. 5, 6–22.

Melles, S.J., Jones, N.E., Schmidt, B., Rayfield, B., 2011. A least-cost path approach to stream delineation using lakes as patches and a digital elevation model as the cost surface. Procedia Environ. Sci. 7, 240–245.

Metz, M., Mitasova, H., Harmon, R.S., 2011. Efficient extraction of drainage networks from massive, radar-based elevation models with least cost path search. Hydrol. Earth Syst. Sci. Discuss. 15, 667–678.

Murugani, V.G., Thamaga-Chitja, J.M., 2018. Livelihood assets and institutions for smallholder irrigation farmer market access in Limpopo, South Africa. Int. J. Water. Resour. Dev. 34 (2), 259–277.

NASA JPL, 2013. NASA Shuttle Radar Topography Mission Global 1 Arc Second [Data Set]. Available at. NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), Sioux Falls, USA. https://lpdaac.usgs.gov/dataset_discovery/measures/measures_products_table/srtmgl1_v003.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B.M., Colón-González, F.J., Gosling, S.N., Kim, H., Liu, X., Masaki, Y., Portmann, F.T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., Kabat, P., 2014. Multimodel assessment of water scarcity under climate change. Proc. Natl. Acad. Sci. U. S. A. 111 (9), 3245–3250.

Smits, S., Mejía, T., Rodríguez, S.E., Suazo, D., 2010. Effects of multiple-use of water on users' livelihoods and sustainability of rural water supply services in Honduras. Waterlines 29 (1), 37–51.

Soille, P., 2004. Optimal removal of spurious pits in grid digital elevation models. Water Resour. Res. 40 (12).

The World Bank, 2015. Project Appraisal Document to the Republic of Honduras: Corredor Seco Food Security Project. Report No: PAD949. The World Bank, Washington, USA.

Theobald, D.M., 2005. A note on creating robust resistance surfaces for computing functional landscape connectivity. Ecol. Soc. 10 (2) Available at. https://www.ecologyandsociety.org/vol10/iss2/resp1/.

Thornton, P.K., Jones, P.G., Ericksen, P.J., Challinor, A.J., 2011. Agriculture and food systems in sub-Saharan Africa in a 4 C+ world. Philos. Trans. A Math. Phys. Eng. Sci. 369 (1934), 117–136.

Wu, S., Li, J., Huang, G.H., 2008. A study on DEM-derived primary topographic attributes for hydrologic applications: sensitivity to elevation data resolution. Appl. Geogr. 28 (3), 210–223.

Zhang, H., Huang, G.H., Wang, D., 2013. Establishment of channel networks in a digital elevation model of the prairie region through hydrological correction and geomorphological assessment. Can. Water Resour. J. 38 (1), 12–23.