DEVELOPING AND IMPLEMENTING A GIS-BASED FRAMEWORK TO IDENTIFY OPTIMAL LOCATIONS FOR CLEAN WATER WELLS IN SUB-SAHARAN AFRICA

by

Jared Charles Hyneman

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LIST OF ABBREVIATIONS

ATP	Africa Topographic Position
DEM	Digital Elevation Model
MDG	Millennium Development Goal
NGO	Non-Government Organization
OSM	Open Street Map
RWSN	Rural Water Supply Network
SRTM	Shuttle Radar Topography Mission
SSI	Spatial Sciences Institute
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
USGS	United States Geological Survey
WHO	World Health Organization
WMO	World Meteorological Organization

ABSTRACT

In 2000 the United Nations (UN) created the Millennium Development Goals (MDGs) to focus on addressing major issues like poverty, education, children's health, sustainable environment, disease prevention, and economic development. One of the targets (7C) of the MDGs is to halve the portion of the population that does not currently have sustainable access to safe drinking water and basic sanitation by 2015. As a region, sub-Saharan Africa is not on track to meet the goal. In fact, the region has the lowest clean drinking water coverage of any region in the world. This project develops a general framework to improve water resource planning in sub-Saharan Africa. The project defines criteria, data and methods to improve planning for clean drinking water wells. The result is a general framework for 1) finding locations where contamination of water wells is least likely to occur, and 2) ensuring the benefits of clean water support overall community health and education. This is all with the aim to increase efficient water resource planning to support the MDG to increase safe drinking water coverage. The general framework is implemented as a model which is the functional component of the framework. The general framework was refined through the implementation of the model in a model fitting study in rural Uganda. The result of the implementation is a suitability map identifying locations where (1) risks to drinking water are minimized and (2) benefits to people living in the study area are maximized. The success of the model was evaluated by assessing the locations of existing wells against what the model identified as suitable well locations. The framework and model fitting process can be used as a tool by governments and non-government organizations (NGOs) to improve current water site suitability workflows.

CHAPTER 1: INTRODUCTION

The pressing global issues of poverty, inequitable education, and children's health have long spanned the world, affecting countless populations. In 2000 the United Nations (UN) created the Millennium Development Goals (MDGs) to focus on critical humanitarian issues including poverty, education, children's health, sustainable environment, disease prevention, and economic development. The MDGs serve as a global framework for development and also serve to guide the efforts of primarily developing countries to fight against obstacles that stand in the way of realizing and harnessing the full human potential. Additionally, from 2000 through 2014 there has been progress towards many of the targets of the MDGs, but other areas still require much attention.

One of the targets (7C) of the MDGs is to halve the proportion of the population that does not currently have sustainable access to safe drinking water and basic sanitation by 2015 (UN 2000). This effort does appear to have been successful in helping provide access to improved drinking water sources: the UN reports "more than 2.1 billion people have gained access to improved drinking water sources since 1990, exceeding the MDG target" (UN MDG Report 2013, 1). Between 1990 and 2010, the proportion of the global population using improved drinking water sources increased to 89 percent, up from 76 percent.

However, progress has not been universal, and problems remain. According to the UN's definition, a rural household is considered to have safe drinking water coverage if there is a safe water source within 1.5 km from the household (Adam et al. 2009). By this measure, sub-Saharan Africa has the lowest clean drinking water coverage of any region in the world (UNICEF and WHO 2012). For example, compared to the global average of 89 percent, in Latin

America coverage is 90 percent, but in sub-Saharan Africa, coverage is 61 percent. This means that 61 percent have safe water within 1.5km, but the remaining 39 percent have to go further to find safe water. Furthermore, countries that still have less than 50 percent coverage in water supply are almost all in sub-Saharan Africa (UNICEF and WHO 2012).

Additionally, the Democratic Republic of the Congo only has improved water sources for 16 percent of its population since 1995 (UNICEF and WHO 2012). This is not enough progress to be on track to meet the MDG in the region. It is widely recognized that there is a strong need for more effective planning and better decision-making if the MDGs of the UN are going to be met. Therefore, this project focuses on rural sub-Saharan Africa, the region of the continent of Africa to the south of the Sahara Desert, because it is the region with the least coverage of clean water wells.

1.1 The need for safe drinking water

Access to safe drinking water is a foundational first step to poverty reduction and decreased mortality rates. It can prevent the spread of waterborne and sanitation-related diseases. The World Health Organization (WHO) reports that around 2.2 million people die annually from water-related diseases (2014). When clean water is available, there are lower mortality rates due to water-related diseases including cholera, diarrhea and malaria (UNDP-UNEP, 2004).

As described above, clean drinking water can be a scare resource in parts of Africa and can require people to travel long distances to access a safe drinking source. It is common for people living in the sub-Saharan Africa to wake up early in the morning to travel to get clean water. One village chief describes the situation, saying “If you want clean water, then you rise up early at 4 a.m. and go to a borehole in the neighboring village" (Ariet village chief, 19 September 2008, conversation).

Women and girls are primarily responsible for the collection of water in sub-Saharan Africa (UNICEF and WHO 2012). Figure 1 shows a girl collecting water from an unprotected hand dug well in Ariet village, 315 km northeast Kampala, Uganda. Because of this responsibility, they are often put at greater risk for violence as a result of the distance that must be traveled to obtain clean water. This also limits their ability to attend school. Improving access to safe drinking water can serve as a way to keep girls in schools (Faeth and Weinthal 2012). Another of the MDGs, Goal 5, is to achieve gender equality. This goal includes addressing goals of eliminating violence against girls and women. Making progress in the availability of clean water will very likely provide benefits in this critical area as well.

Figure 1 Girl collecting water from an unprotected natural spring
Photographed by Simon Peter Esaku

1.1.1 Helping Provide Clean Water

While access to clean water is improving, there is still a great need for more access. Governments and non-governmental organizations (NGOs) are partnering to provide clean drinking water to communities in sub-Saharan Africa. GIS offers great opportunities to help agencies improve clean water resource planning.

While GIS-based models generally require large amounts of high-resolution data, the methods developed here are designed to be applied in data-deficient areas in sub-Saharan Africa. Because aid and development organizations working in these areas often lack funds to acquire commercial satellite data, the methods created here focus on using data that is available to the public and is available at no cost.

The framework created in this study is designed to address risks to clean water, improve sanitation at health facilities, and improve children's attendance at school through limiting the time required to travel to get safe drinking water. To increase performance in achieving greater access to safe, clean drinking water, the analytical methods developed here can be used to easily identify locations where demand for water is high (e.g. near schools) and there is a lower risk of contamination. The result is an affordable solution to help NGOs improve planning for water wells and thereby provide a better opportunity for communities to enjoy a higher quality of life.

1.1.2 Social Context of Clean Water

There are many perspectives on the effectiveness of the MDGs. This study uses the MDGs as a point of reference for the need, scope and general benefits of clean drinking water to a community. The discussion surrounding the MDGs is widely published. For an overview of the discussion, Shobha Raghuram, an independent researcher, responded to several articles published by the UN. In the article, there are both critical and positive appreciations of the efforts of the MDGs (National Institute of Advanced Studies 2008). Additionally, for a discussion on the MDGs in sub-Saharan Africa, retired professor of Education at the University of Zambia, Dr. Michael Kelly, describes several limitations and positive ways forward in his article for the Institute of Development Studies (2013).

Additionally, because of its scarcity, clean water can be a source of contention. There have been clashes between people over access to water, including incidents of violent conflicts in sub-Saharan Africa (BBC 2006). This highlights the social, cultural and political issues involved with water resources. However, it is beyond the scope of this project to consider all factors and it focuses on key environmental and social factors such as health and education.

1.2 Goal of this Project

The research goal of this project is to create a site suitability framework that, when implemented, will produce recommendations for optimal water well placement that minimize the risks and maximize the benefits for people. This is the study portion of the project. The framework is then applied to a specific context as a model. This implementation of the framework is the model fitting study. In the implementation of the framework, the model is refined to improve performance for when a user applies the framework to his or her context. In summary, this project has two components: (1) the development of the framework (study), and (2) the implementation of the framework (model fitting).

The model created in this project is in a GIS format that can be applied in data-deficient, developing regions. The intent of this effort is to produce information that can be used to improve water resource planning. The suitability map created can be used by NGOs as a precursor to well siting surveys, thus limiting the extent of the area that needs to be examined in costly and time-consuming detail.

An aim for the project is that the framework be easily implemented by interested NGOs. This project is intended for use by NGO practitioners and is written to be understood by technical experts in both GIS and non-GIS related fields. Therefore, Chapter 2 provides an introduction to relevant GIS concepts. Then in Chapter 3 and 4 the methods are described progressively in more detail. The methods are discussed in each of the chapters at increasing levels of specificity.

1.3 Scope of the Framework

Certainly, using data about groundwater is preferable when assessing locations for water wells. However, quality data on groundwater and sub-surficial geology are rarely available in this region. Rather than develop a model suitable for a data-rich context such as the United States and then apply it to data-deficient regions, a constraint was placed on the design to use data readily available for sub-Sahara Africa. This helps to ensure the methods used are suitable for the region. To this end, it was necessary to design a model that does not use groundwater, geology or high-resolution commercial satellite data. To ensure that the framework could be replicated globally, only publicly available datasets with global coverage were selected. Given these data limitations, rather than focusing on where clean water is likely to be found, the model identifies areas that are more likely to be free of contamination and easily accessible to the local population. Therefore, in order to find areas with minimal contaminants to drinking water and where benefits are maximal in terms of access, criteria were developed based on (1) contextual risks, (2) availability of data and (3) proximities to community infrastructure. How the criteria were selected is described in Chapter 3.

Moderate resolution digital elevation data was obtained through United States Geological Survey's (USGS) EarthExplorer program (http://earthexplorer.usgs.gov/). In addition to the globally available data sets, point locations of community infrastructure were used. It is an assumption in this study that an implementing agency will have this type of data. This includes data elements such as the location of schools, communities, existing water sources, latrines, and other facilities.

The general framework is designed to be applied throughout sub-Saharan Africa. To demonstrate its use and to evaluate its effectiveness, an area in the Nakasongla District of Uganda was selected as an example study where the generic framework can be applied. The area is typical of the region in that it demonstrates what data are available for contexts for which the generic framework is designed. The data about communities and schools was captured through a partnership between the community and a 501(c)3 non-profit humanitarian NGO, World Vision, whose goal is to improve the quality of life for children and families by tackling the causes of poverty and injustice.

Given the remoteness and data-deficient nature of the study region, the effectiveness of the general framework was evaluated by comparing the areas identified as having minimal risks and maximal benefits with the locations of existing water well sites. While this assumes that the existing wells are located at ideal sites, an assumption that is not likely to be universally correct, it does provide a way to refine the model and serves as one measure of success.

This study is the first part of a larger project. Future research will include a field evaluation of the results from the application of the framework. Areas that are identified as the most suitable locations for a clean water well will be tested in the field to determine if the locations are, in fact, the most suitable locations.

1.4 Project Workflow

GIS-based suitability projects often have similar workflows, and this project follows a basic approach, beginning with a detailed literature and methods review and the careful selection of the criteria to be analyzed. An outline of the project workflow is provided in Figure 2.

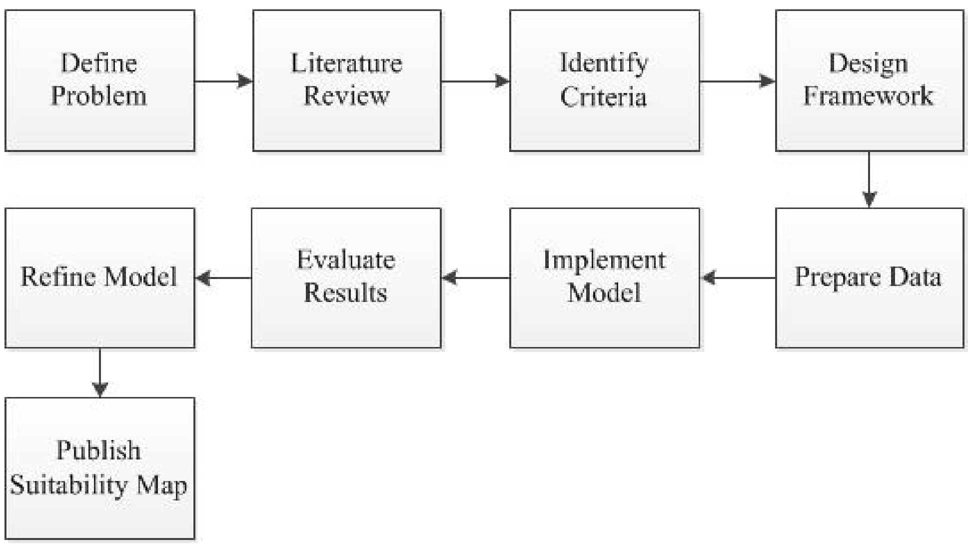

Figure 2 Overview of project workflow

1.5 Report Organization

This report continues on to Chapter 2 with a review of relevant published literature on the current water situation is sub-Saharan Africa, site suitability analysis, and modeling of risks to clean water. The third chapter describes the development of the general framework in terms of methodology, suitability criteria and data. The fourth chapter describes the implementation of the general framework. This includes sections describing the study area, the implementation, the evaluation of results, and model refining. This report concludes with a final chapter discussing research findings and areas for future work.

CHAPTER 2: RELEVANT BACKGROUND RESEARCH

This section presents a description of the potable water situation in rural Africa, followed by a review of current water siting practices. Then a report outlining guidelines for siting surveys for water wells is evaluated for its applicability in the sub-Saharan context. Next, previous research on risks to safe drinking water is summarized. Finally, the methods used for site suitability are reviewed.

2.1 Potable Water Situation in Rural Africa

Groundwater provides a high proportion of sub-Saharan Africa's population with a drinking water source. Groundwater, rather than surface water, is the preferred source of drinking water because aquifers and water wells have a degree of natural protection from contamination and drought (MacDonald, Davies and Dochartaigh 2002). Groundwater has the benefit of being naturally protected from bacterial contamination and is a reliable source during droughts (Lewis no date). Alternatively, surface water is often polluted, and infrastructure for water pipes is costly. Therefore, groundwater is likely to remain a reliable source of drinking water.

Nevertheless, groundwater aquifers can also become contaminated from sources such as latrines, garbage dumps, corrals, cemeteries, and through poorly constructed wells (UNICEF 1999). Additionally, water wells can serve as a channel to transmit contaminated surface water into an aquifer. Therefore, there is an increasing need to install wells in areas that are least likely to be contaminated.

The basic principle of a clean water well is that a hole is drilled into a groundwater source and water is then extracted with the help of a pump. Three types of wells are common to access groundwater in Africa. The most common type is a hand dug well (WaterAid 2008). These are normally uncovered and the most easily contaminated of the three types. While hand dug wells are not ideal, when installed correctly they can be effective. Because these wells are typically open, they require daily cleaning, which unfortunately is often not regulated (Awuah et al. 2008).

The second type of well is the shallow well. These wells cost more than hand dug wells but provide a more protected drinking water option. This type of well is created by drilling through dirt and installing a pump. Pumps can be manual or mechanized. In sub-Saharan Africa and other rural contexts, the diameter of a drilled well is usually 50 mm. The length of a drilled well can range between 35 m to 300 m. A concrete slab is normally used to cover the well. These wells are normally sealed and have higher protection against contaminants getting into the water supply. The wells are susceptible to contamination, however, if a seal breaks or if there is a crack in the pipes.

The third type of well, the deep well, is the most expensive. These wells can be over 270 m deep. These wells typically have a mechanized pump or pump house and can cost up to $30,000 USD (http://thewaterproject.org/). Therefore, since drilled wells (shallow and deep) are less susceptible to contamination compared to hand dug wells, the framework identifies suitable locations of shallow and deep wells to encourage the use of improved drinking wells. However, the framework developed in the study can also be used to identify suitable locations for hand dug wells.

2.2 Site Selection for Siting Water Wells

In 2010, the Rural Water Supply Network of Illinois published guidance on best practices for siting surveys for water wells. Even though this report is specific to Illinois and the geology and infrastructure referenced are different from the context where the general framework will be used, the workflow and many issues it discusses are still applicable. While the network describes the process as siting surveying, it is one form of site selection. The current standard workflow is outlined in Figure 3. There are four components to their standard workflow: (1) groundwater availability, (2) impacts and risks of a new well, (3) water use (requirements of a well) and (4) access to a source.

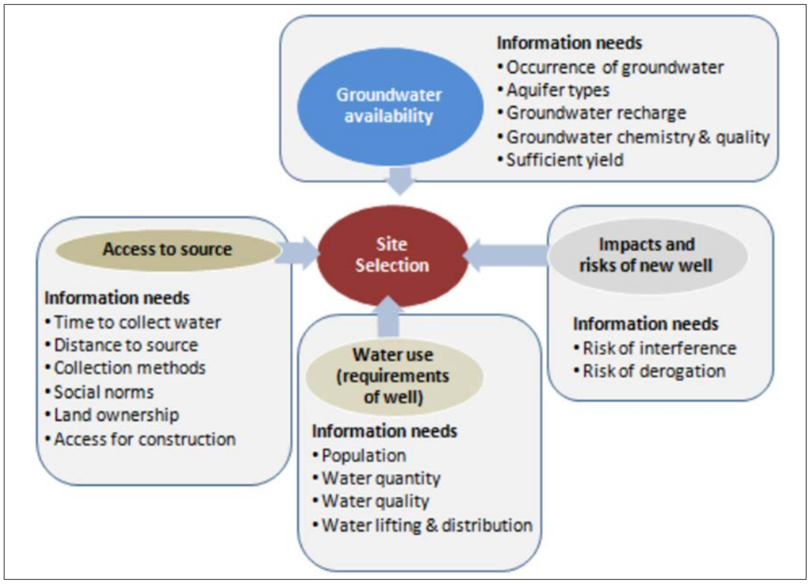

Figure 3 Components of current well site selection

Source: Rural Water Supply Network (2010)

The general framework developed in this study is intended to be a precursor to the site surveying work. While it does not replace any of the existing techniques, it does supplement them and can increase their effectiveness. When the general framework is implemented, it provides suggestions to siting survey teams of areas that have minimal risk and maximum potential benefits. Even with this information, geophysical data about groundwater depth, water quality and geologic formations is still required.

The first component of the site selection process addresses groundwater availability. In sub-Saharan Africa there are several challenges to effectively complete this first step. The reason for this challenge is a lack of universal information about groundwater. In fact, Adelana and Macdonald observe that in many areas of sub-Saharan Africa, there is relatively little attention paid to the systematic information gathering about groundwater resources (as cited in Danert 2014). Where there are maps available that identify groundwater sources, the accuracy of the information is not sufficiently reliable (MacDonald, Davies and Dochartaigh 2002). A model developed from the framework described in this study, however, can be used to identify sites that are likely to have minimal risks to the well. The siting team can then use the model to reduce the number of areas in which to do a physical siting survey. The model will, even in this first step, result in a more efficient use of resources in terms of time and money.

The second component of well site selection identifies the potential impact of a well on a groundwater source. It assesses the potential risks to groundwater that a new well might cause. It does not address actual risks to drinking water. Since this component does not address risks to drinking water, the framework developed in this study does not improve this component.

The third component evaluates the water at a site. The value added by the framework is the ability to evaluate a site for the contamination risk. The general framework improves this evaluation by pre-identifying risks to the clean water and identifying community needs for clean water (population and other factors). Water quality sampling is still required because it can determine whether it has high natural contents of arsenic, fluoride and iron. Arsenic and fluoride are toxic in high concentration, and their occurrence is related to hydrogeological conditions (Rural Water Supply Network 2010).

The Rural Water Supply Network's guidance also identifies the need to avoid point contamination sources such as pit latrines, septic tanks, livestock pens, and solid waste dumps identifying risks on a micro level, one site at a time. Therefore, there is a need for a macro level decision support tool (i.e., the application of the framework developed here) that is able to identify high-risk areas more broadly. This ensures new wells not only avoid contaminants, but are also installed to achieve maximum coverage (i.e. within 1.5 km of households).

The general framework developed here improves upon their method by using GIS to add multiple criteria (e.g. locations of schools and health clinics) to ensure the investment in clean water benefits the highest feasible number of community facilities. The map generated as a result of implementation of the framework can be used to engage community members and supplement discussions by providing quantifiable suggestions for where a well is most suitable.

As discussed, the framework does not replace the site suitability process identified by the Rural Water Supply Network—it improves upon it. The framework, when applied in a specific context, can supplement local knowledge and help drilling contractors reduce the number of siting surveys that must be conducted. This improvement in efficiency is possible because the framework pre-identifies the specific locations where there may be risks to water sources.

2.3 Previous Research on Risks to Drinking Water

To ensure a water source is protected, it should be upslope from a source of contamination (UNICEF 1999). As mentioned above, water wells are susceptible to contamination at three areas: the opening on the surface, the piping from groundwater to surface, and the groundwater source. As described above, groundwater is a good resource to help provide more clean water coverage. However, groundwater is not a fail-safe resource when it comes to providing clean drinking water. Groundwater can be contaminated when it is underneath areas containing pathogens and chemicals derived from fecal and other waste (Rural Water Supply Network 2010).

Furthermore, a report from the University of Illinois at Urbana – Champaign Water Resources Center identifies common sources of contaminants of drinking water. The list includes: septic tanks, road salt, underground gas storage tanks, manure piles, fertilized cropland, and solid waste disposal sites (1990). The report also provides recommended minimum distances between a well and a potential contamination source. The list of minimum distances is prefaced with the guidance that a well should be as far removed as possible from potential contamination sources. Table 1 shows the minimum setback for common sources of contamination using guidelines from the Illinois Water Resources Center.

Table 1 Minimum distance from sources in Illinois

Common Contamination Source	Minimum Distance
Sources and Routes of Contamination	61 m
Existing Cesspools	46 m
Leaching pits	31 m
Septic Subsurface seepage tile or manure pile	23 m
Sewer line and Septic Tank	15 m
Lakes, Ponds or Streams	8 m

Source: University of Illinois at Urbana – Champaign Water Resources Center (1990)

These distance recommendations are helpful in understanding the relative potency of a particular pollutant source, but because the distance recommendations are designed for a person installing a small well on personal property, the value of the specific recommendations is limited.

Finally, the University of Illinois Water Resources Center recommends that a well should be placed on the side of the contaminant source opposite the flow of groundwater. For example if groundwater flows to the south, a well should be placed as far north of the contaminant source as possible. This type of general consideration is included in the general framework.

Additionally, the U.S. Environmental Protection Agency (EPA) recommends that well owners have a zone of protection around a well to prevent contamination. The recommended distance designated to limit risk of groundwater contamination is 30 m (California State Water Resources Control Board 2011). Both the guidance from University of Illinois Water Resources Center and the EPA are recommendations to prevent groundwater contamination as opposed to surface water contamination. Since surface water can travel faster than groundwater, a contaminant can travel further than the minimum distances recommended by both agencies. Therefore, the framework described in the next chapter was built on the foundational principle that the greater the distance a well is located from a contamination source, the more suitable is the location.

2.4 Methods for Site Suitability Analysis

To find suitable locations, a user can overlay different layers in a GIS. Ian McHarg pioneered the use of overlay for suitability evaluation. In 1969, in his seminal work, *Design With Nature*, he showed how a user could superimpose a set of transparent layers, one for each criterion, to create an overall suitability map. This technique is regarded as a precursor of modern GIS overlay (Qiu et al. 2014).

There are several methods for modeling suitability. One method for modeling suitability divides locations into two groups, or sets: those that are suitable and those that are not. This method is known as Boolean overlay and it evaluates whether a location meets each criteria, on a yes/no basis (Mitchell 2012). This is a particularly useful method when boundaries or attributes of a criterion are crisp. Alternatively, where these are not crisp, there are two common methods that allow a user to rate locations on a scale from more suitable to less suitable. These two methods are weighted overlay and fuzzy overlay.

Weighted overlay allows a user to assign importance to a specific criterion. When a user assigns importance, a weight is assigned to the layer (Mitchell 2012). This is also known as the percentage of influence for each layer. When weighted overlay is applied in a raster context, cell values of each input layer are multiplied by their percentage influence, and the results are added together to create the output raster. For reasons described in section 3.1, weighted overlay was less suitable for this analysis.

Fuzzy overlay allows a user to rate suitable locations when criteria are hard to quantify or when the relationship between specific criteria and suitability are not well defined. Additionally, Mitchell points out, “fuzzy overlay is particularly good for creating a suitability model that attempts to capture the knowledge of experts in a particular field” (93). Fuzzy overlay was used in the general framework developed in this study. Fuzzy logic is built upon the concept of fuzzy sets which allow partial membership within a range of 0 to 1 to represent the extent to which an entity belongs to a certain class. In site suitability analysis, the degree of belonging is with respect to the set of suitable locations.

Fuzzy overlay has been used for suitability analysis for a wide range of applications including finding the best locations for wind power systems, rice growing areas, and solid waste landfill (Demesouka et al. 2014; Kihoro et al. 2013). Examples of the use of fuzzy logic to model risks include groundwater vulnerability risk mapping (Nobre et at. 2007) and landslide susceptibility modeling (Chalkias et al. 2014). In both studies, the use of fuzzy logic highlights how it can handle uncertainty where boundaries and attributes are difficult to define.

The application of fuzzy logic to model water resources was accomplished by Tsiko and Haile in 2011. The authors used fuzzy logic to model optimal sites for locating water reservoirs in Eritrea, in the Horn of Africa. That project is similar to this water well suitability project in that it develops a framework and then applies it to a real world context. One reason the authors selected fuzzy logic for water resource planning was because their decisions regarding criteria were accompanied by ambiguities and vagueness. This meant there was a lack of certainty about the measurement of the criteria. The authors note, “This makes fuzzy logic a more natural approach to this kind of Multi-criteria Decision Analysis (MCDA) problems” (Tsiko and Haile 2011, 257).

CHAPTER 3: A GENERAL FRAMEWORK FOR SITING CLEAN WATER WELLS IN SUB-SAHARAN AFRICA

This chapter describes the general fuzzy suitability framework developed here to identify locations where risks to clean water wells are minimized and benefits to people are maximized. It begins with sections that describe why fuzzy overlay was used. Next, the argument for modeling only surface and subsurface contaminant flows using surface slope derived from free, readily available global data is presented. Finally, the suitability criteria in the general framework, and the data limitations and availability for sub-Saharan Africa are discussed.

3.1 Fuzzy Overlay

The framework developed in the study relies on fuzzy membership functions to assign suitability to individual layers. If Boolean logic were used throughout the framework, it would not be able to capture the vagueness or continuous nature of the data required for the framework. Additionally, the use of fuzzy membership captures the nuances of partial goodness or badness of a location with respect to suitability. When evaluating suitability of a location, a user determines the method by which locations are evaluated for membership. Depending on the user’s decision, the strength of membership in the suitability set changes. For example, low membership would be assigned in the suitability set to locations that are near a risk.

Weighted overlay was not used for this project because information that can be used to assign the weights is not known for each specific context in which it might be applied. Additionally, due to the contextual nature of risks to clean water, the general framework developed in this study does not lend itself to setting weights that can be applied universally.

Fuzzy overlay was selected for the general framework for several reasons:

(1) Uncertainty of the available data to accurately represent a criterion.

(2) Uncertainty of a crisp break point between values for suitable areas and unsuitable areas.

(3) Continuous nature of some environmental phenomena which are represented as classified data. Wetlands and vegetation data are two examples of this in which the phenomena represented by the data can often have non-crisp boundaries where the change from one class to the next is gradual rather than abrupt (i.e. crisp). Crisp boundaries, on the other hand are well defined, it is evident when one phenomenon or class stops and another starts.

(4) Uncertainty whether the resolution of data can capture elevation heterogeneity. The suggested base data is a 90 m elevation layer and it is likely the resolution is unable to capture accurately the elevation change within a grid especially when the framework is applied to contexts with high frequency of elevation change.

In this project, fuzzy logic was used in two steps: assigning fuzzy membership and performing fuzzy overlay. The fuzzy membership codifies each of the values of each data layer on a scale of 0 to 1. This was done for each criterion. Most often in the framework the fuzzy aspect is the distance from a contaminant at which it is safe to install a well. The assignment of fuzzy membership for each criterion as it is applied in the implementation study is described in Chapter 4.

Furthermore, once all layers have been assigned individual fuzzy membership, then fuzzy overlay is used to combine multiple criteria into a single fuzzy membership layer. Each location is given a value representing the strength of membership in the set of suitable locations. As a result of the fuzzy overlay process, each cell is given an aggregate fuzzy membership value. Implementation of the fuzzy overlay process is discussed in Chapter Four.

3.2 Modeling Risks Where Groundwater Data is Limited

The goal of this project was to create a general framework that can be applied throughout sub-Saharan Africa to identify locations of minimal risks to water wells. The framework was designed to create a decision support suitability map to be used as a tool by NGOs and governments. Many NGOs and African governments have limited financial resources, so cost was an important factor in the framework design. By excluding areas that are unsuitable, NGOs and governments can save money by not undertaking water well site surveys in locations that are at high risk, or have minimal positive impacts on the community.

To be useable, the data of the framework must be openly accessible and affordable to users in sub-Saharan Africa. With an emphasis on low cost, and wide applicability, data sets were selected to fulfill this requirement. This excluded higher resolution data available through commercial companies from being used as input for the framework. Instead, lower resolution data was used to ensure the framework is usable, replicable and feasible for governments and NGOs in sub-Saharan Africa to implement.

As described above, there are three areas where a water source can be contaminated: surface opening of a well, the underground piping, and the groundwater itself. Groundwater contaminants usually form a concentrated plume underground that flows along the same path as the groundwater. Among the factors that determine the size, form and rate of movement of a contaminant plume are the number and type of contaminants and the speed of groundwater movement (Jakhrani et al. 2009). When choosing locations to drill for water, it is ideal to know where (1) the groundwater is least likely to be contaminated and (2) water most likely is to be found. In order to do this, a map of groundwater is required. Unfortunately, groundwater data is not available in many areas in rural sub-Saharan and therefore it could not be included as an input for the framework. This meant that an alternative method to model the movement of a contaminant was needed.

Elevation data that is now globally available through the Shuttle Radar Topography Mission provides an alternative. Surface slope does not always reveal the direction a pollutant might flow once it infiltrates the ground, but it can reveal the direction a pollutant might flow on surface or near-surface. Therefore, slope, derived from elevation data can be used to determine the surface and near surface flow of water and likely flow of a surface or near surface contaminant.

In this framework, to avoid contamination, a water well should be on the side of a contaminant source opposite the flow of surface or near-surface water. This decision is in line with the instruction manual for drilling of water wells commissioned by the PRACTICA Foundation, USAID, and UNICEF. The manual states, “It would not be good to place the well down-slope (downstream) of the latrine, but rather on the same level or higher up (up-slope) of the latrine” (Van der Wal 2010, 9).

Having presented the argument for modeling only surface and subsurface contaminant flows using surface slope, we now turn to a consideration of the general risks to clean water wells.

3.3 Suitability Criteria for the General Framework

This section describes the suitability criteria identified for use in the framework. There are two categories of criteria: places to avoid (risks) and places to favor, which includes locations near facilities providing public health and education and useful infrastructure locations which would maximize clean water coverage. There are thirteen criteria that comprise seven categories.

3.3.1 Locations to Avoid and the Implied Constraints

This section describes the risks to a safe drinking water supply in sub-Saharan Africa and implied constraints for the selection of a location for a well. In this section, eight factors are described: human waste, animal waste, solid waste dumps, agricultural fields, burial sites, wetlands, stagnant water and existing wells.

Human waste

Human waste can spread disease to a water supply. Bacteria from human feces are one of the most serious threats to clean water (UNICEF 1999). Bacteria from a latrine can contaminate a well when surface water or near surface water gets into the well (Korab 1999). Additionally, a well can be contaminated from a nearby latrine if the groundwater flows from a latrine toward a well. Bacteria, viruses and parasites, originating from a latrine will flow together with groundwater to a well (Van der Wal 2010). Other sources of contamination related to human waste include leaking septic systems or contaminated wells elsewhere in the groundwater system (EPA no date).

There are several types of latrines used in sub-Saharan Africa. The most common is the traditional pit latrine. This is a simple pit sometimes covered with logs (Farmer no date). Some latrines are lined to contain the waste while others are not.

One health problem heightened by poor sanitation in sub-Saharan Africa is cholera. In May 2013 there was a cholera outbreak in Uganda. Cholera is an infection in the small intestine that causes symptoms of diarrhea and vomiting. It is transmitted primarily through drinking water that has been contaminated by feces of an infected person.

As a result of all of the above, a suitable location for a well will avoid areas such as latrines and other sites of human waste.

Animal waste

Animal waste can contaminate a water source just as human waste can. It can carry several harmful pathogens; studies have linked waterborne transmission of diseases to animal waste (Dufour et al. 2012). Animal waste is a high-risk factor because it is typically not contained in the same way as human waste. Latrines for human waste can be cleaned and filtered to prevent the transmission of a pathogen into a water supply. However, animal waste is often perceived as less dangerous to human health and therefore monitored less. Additionally, animal waste is on the surface and more likely to travel with surface water. Therefore it is recommended that a well be placed away from an area with concentrations of animals waste.

Solid waste dumps

Waste dumps can contain metals, acids, and other chemicals that can pollute a water source. Dumps can pollute groundwater and surface water and therefore it is recommended that a well be placed opposite of the downslope flow path of water from a dump.

Agricultural fields

In order to increase crop yields, farmers use chemicals in many areas in sub-Saharan Africa. These on-farm chemicals can potentially contaminate the water supply. The nitrates in fertilizers, pesticides and herbicides can cause an imbalance in the natural environment and alter the quality of drinking water (Ongley 1996). To avoid farm chemical pollution, wells should avoid farms where chemicals are used.

Burial sites

The decay of human and animal corpses can have a negative impact on water (Üçisik and Rushbrook 1998). Contamination occurs as a result of germs and viruses that are generated during the process of decay. Water can carry the germs and viruses through soil to a water source. To avoid pollution, wells should avoid graves and burial grounds.

Wetlands

Flooding increases the spread of a pollutant. If a well is located in an area prone to flooding, the clean water in the well can be contaminated when water flows into the well. To avoid contamination, wells should avoid depressions in the surface and areas that experience seasonal flooding (Rural Water Supply Network 2010).

Stagnant water

Stagnant water is also a threat to community health. For children living in Uganda, malaria is the primary cause of death. Malaria is transmitted by female mosquitoes of the genus Anopheles which, for breeding, prefer permanent, stagnant water bodies such as shores of rivers and creeks or fish ponds (Uganda Ministry of Health 2014). Therefore, a clean water well should not be in an area with increased likelihood to have stagnant water.

Existing wells

The locations of existing water wells can be used to identify areas to avoid. This ensures that new wells will be installed at locations that improve clean water coverage and thus support the MDG goal to halve the proportion of the population without access to sustainable safe drinking water.

3.3.2 Locations to Favor

This section describes locations to favor. In these areas, when clean water is near, there are significant benefits to people living in the area. This section highlights the social aspect of the study and promotes health and sanitation by favoring locations near facilities that can benefit the general public by having safe drinking water. Installing a clean water source near a school or health facility can improve the sanitation practices at those locations. Therefore, locations to favor include low slope, hospitals/clinics, schools, roads and villages/ populated places.

Slope

A well location must be accessible to drilling equipment. A steep slope (greater than 20 percent) can cause problems when drilling and installing a well. Additionally, an area of low slope decreases the mechanical wear on the well equipment. Areas with 10 to 20 percent slope are feasible for installing a well, but will require increased earth moving and grading (Building Advisor no date). This increases labor and equipment costs. A user will need to determine an acceptable slope in his or her context, but due to the increased cost and risks, it is not recommended to install a well on greater than 20 percent slope. Therefore, to avoid additional installation and maintenance costs, a well should be in an area of low slope.

Hospitals/ Clinics

Clean water wells should be placed in areas that support public health. Therefore locations near hospitals are desired. This ensures patients are hydrated with clean drinking water and are less likely to drink unclean water that can delay recovery. Additionally, inadequate clean water, sanitation and hygiene can play a substantive role in propagating infections (Bartram and Platt 2010). Therefore locations near health facilities are desired.

Schools

Clean water wells should be placed in areas that support education. Children often miss school because their schools do not have adequate drinking water and or sanitation facilities (Hillie and Hlophe 2007). With clean water in proximity of a school, children are more likely to drink safe water and are less at risk to be ill due to water transmitted bacteria or disease. Therefore locations near schools are desired.

Road network

Major roads help determine accessibility. Some wells require a drilling rig be brought in. If a location has access to a major road, then drilling is more feasible and cost effective. To increase efficiency and drilling feasibility, a well should be near a major road.

Villages

Point locations of a village, typically captured at a city center or market, can ensure improved water coverage planning. Locations within 1.5 km of a clustering of households should be given high membership in the suitable set to improve clean water coverage as defined by the UN. Population data can also be associated with a village so that high population locations can be more strongly suitable.

Now that all criteria haven been discussed, they are organized into categories. Table 2 organizes these risks and benefits into selection criteria categories and provides more detail on how these criteria can be operationalized. Table 3 provides an overview of the general data sources. It describes potential data sources that can be used to analyze a criterion in sub-Saharan

Africa. This table highlights the challenge of finding sufficient data to analyze a criterion. Many of the criteria require data to be collected in the field to be provided by an NGO or government. In the Possible data values/attributes column, a list of suggested attributes for data layers is presented.

Table 2 General Criteria

Category	Criteria ID	Criteria	Summary Statement for Selection of Criteria
1. Avoid travel path of a contaminant from a source	1a	Should not be in the flow path of human waste	Human waste carries bacteria that can spread disease and cause illness if ingested.
	1b	Should not be in the flow path of animal waste	Animal waste, similar to human waste can spread disease and cause illness.
	1c	Should not be in the flow path of solid waste	Harmful chemicals such as metal deposits, acids, and other sources can be found in solid waste dumps and can cause illness if ingested.
	1d	Should not be in the flow path of farm chemicals	On-farm substances such as fertilizers, herbicides and pesticides contain chemicals that can be harmful if ingested.
	1e	Should not be in the flow path of decomposing carcasses	Germs and viruses generated from the process of decay can cause spread disease if ingested.
2. Avoid areas prone to flooding	2a	Should not be within a wetland	Water from flooding can seep into a clean water well and then contaminate the water in the well.
3. Avoid areas with an increased likelihood of a person contracting malaria	3a	Should not be within an area with stagnant water	Stagnant water is the preferred breeding area of female mosquitos which transmit malaria. Areas mosquitoes prefer should be avoided as a precaution to prevent exposure.
4. Select areas where drilling is feasible	4a	Should not be on a steep slope	The greater the slope, the higher the costs incurred, both in terms of access to drilling a well and drinking from a well. Additionally, a steeper slope correlates with increased mechanical wear on the well equipment.

Category	Criteria ID	Criteria	Summary Statement for Selection of Criteria
	4b	Should be near a major road	A major road in the general area ensures accessibility to a potential well site for a drilling rig.
5. Promote sanitation at hospitals	5a	Should be near a hospital	Clean drinking water promotes safe hydration for people recovering from illnesses.
6. Promote children’s health	6a	Should be near a school	A clean water well near a school decreases the likelihood a child will contract an illness from drinking water from an unclean source and be absent from school.
7. Maximize clean water coverage	7a	Should be near a populated place	A water well near a populated place supports the MDG goal to improve coverage of clean water.
	7b	Should not be near an existing water well	Installing a new well near an existing one creates redundancy and is unlikely to increase water coverage.

Table 3 General Data Sources

Criteria ID	Criteria	Suggested Map Layer	Justification for Selection of Data Layer	Possible Data Types	Possible data values/attributes
1a	Should not be in the flow path of human waste	Latrines	Latrines contain high levels of human waste. The types vary as well as their ability to contain and sanitize waste.	Point, Polygon	Location of latrine, type of latrine, # of pits,
1b	Should not be in the flow path of animal waste	Livestock pens, grazing areas	Areas with high concentration of animals, such as livestock pens and grazing areas, correlates to the amount of animal waste.	Point, Polygon	Location of pen, type of animals, size of the area, # of animals
1c	Should not be in the flow path of solid waste	Trash dumps	Solid waste accumulates at trash dumps. When these sites are not properly located they are a risk to surface and groundwater.	Point, Polygon	Location of dump, size of the dump
1d	Should not be in the flow path of farm chemicals	Agricultural Fields	In many cases farmers use chemicals to improve crop yields. When farmers are not trained to mix chemicals properly, there is an increased risk to water contamination. Even when used as directed, water can be contaminated.	Point, Polygon	Location of areas likely using farming chemicals, types of chemicals used, frequency of use, type of crops

Criteria ID	Criteria	Suggested Map Layer	Justification for Selection of Data Layer	Possible Data Types	Possible data values/attributes
1e	Should not be in the flow path of decomposing carcasses	Cemetery	Cemeteries or large burial sites have high concentrations of decomposing carcasses.	Point, Polygon	Location of burial grounds, # of carcasses, depth of carcasses, age of burial grounds
2a	Should not be within a wetland	Wetlands	Wetlands are more likely to flood than highlands.	Raster, Polygons	Elevation can be used to identify wetlands.
3a	Should not be within an area with stagnant water	Depressions	Areas with little drainage or no drainage accumulate water and cause water to pool.	Raster	Elevation can be used to identify areas where pooling of water can occur in depressions on the surface.
4a	Should be on a slope of less than 16 percent	Slope	Slope affects the direction of flow.	Raster	Percent slope
4b	Should be within 4000 m of a major road	Road Network	Access component to determine feasibility. It is probable costs will increase if no road exists in the general area of a potential well site.	Line	Location of a road
5a	Should be within 3000 m of a hospital	Hospitals/ Clinics	Clean water can help a person stay hydrated and recover from an illness faster. The high number of people at a hospital who are recovering from an illness or injury make it an ideal area to make a positive impact.	Point	Location of a hospital

Criteria ID	Criteria	Suggested Map Layer	Justification for Selection of Data Layer	Possible Data Types	Possible data values/attributes
6a	Should be within 3000 m of a school	Schools	Illness can prevent a child from attending school and/or prevent him or her from actively engaging with the educational material.	Point	Location of a school
7a	Should be within 1500 m of a populated place	Populated Places	To maximize coverage to the most people, villages or a clustering of households should be targeted for clean water wells.	Point	Location of a village
7b	Should not be within 1500 m of a water well	Existing Wells	To prevent installing a well where clean water exists, existing wells should be avoided.	Point	Location of a well

3.4 Appropriate Data for Analysis of Criteria

This section describes the different data layers that are appropriate for the analysis of each of the criteria. As mentioned above, the data suggested were chosen due to their availability and no cost. In some cases, there are several viable data options for a specific criterion. In those cases, a user can choose the layer that is best for his or her context.

The data for analysis of the criteria of contamination risks must be collected locally by field crews since data is site specific and is generally not available through public sources. Usually, locations of these facilities will be collected with GPS devices. This is also true for criteria of schools, hospitals, villages and existing water wells. There is no need for survey grade GPS equipment due to the scope and resolution of the general framework. Therefore, GPS-enabled smart phones and tablets can be used for mobile data collection. Where available it is suggested to supplement data with data from other NGOs or government ministries.

Regarding village data, it is likely an NGO's dataset will not include all populated places. Thus it may be helpful to enhance it. A suggested source is GeoNames, an international, database with global coverage of places (http://www.geonames.org/). Over 55 data sources are used by GeoNames including National Geospatial-Intelligence Agency (NGA), U.S. Geological Survey Geographic Names Information System (GNIS) and World Gazetteer. It is supported by over 60 national mapping agencies and is updated daily. Another method is to assess satellite imagery to identify clustering of households. Landsat 8 imagery at 30 m resolution can be used for this and is globally available.

For data on areas with an increased likelihood of flooding, there are three layers that can potentially be used. The first is the Africa Topographic Position (ATP) layer from USGS which is a binary raster layer where “lowland/depressions” indicates locations where water is likely to accumulate due to the elevation and slope in the area. These areas are given a value of 1. The other areas are categorized as “uplands” and are given a value of 2. This layer is different than a layer such as the normalized difference moisture index that uses climate or soil attributes to calculate moisture potential (USGS 2008). The ATP layer was created using a geographically derived measure of slope for each raster cell and the contributing area from "upstream" raster cells which expresses the potential for water flow to a location. To quality check the resulting surface, independent estimates of water accumulation from existing wetland boundaries were used (USGS 2008). For more technical details about how the data was created see Appendix 1.

A second viable option to identify lowlands is to use elevation data. A void-filled digital elevation model (DEM) is recommended for implementing the framework. A good source is the Shuttle Radar Topography Mission (SRTM). The original release of SRTM elevation data had many NoData cells known as voids, which caused errors during data analysis. To help in the use of this data, the USGS has produced void-filled SRTMs in which interpolation methods have been used to fill in the data gaps. There are several methods for this depending on the purpose of use. Several void filling interpolation methods are evaluated by Reuter et al. 2007. A void-filled DEM can also be used to identify slope for criterion 4a.

Another viable option to identify lowlands is a HydroSHEDS layer. HydroSHEDs provides hydrographic information in a consistent format for large portions of the earth. It is derived from the SRTM elevation data at 90 m resolution. Hydrologically conditioned HydroSHEDS are created using a sequence of automated procedures. Existing methods of data improvement and newly developed algorithms have been applied, including void-filling, filtering, stream burning, and upscaling techniques (USGS 2008). It was created to support regional and global watershed analyses, hydrological modeling, and freshwater conservation planning. More information about the data development of HydroSHEDS is in HydroSHEDS Technical Documentation v1.0. It is available for download at http://hydrosheds.cr.usgs.gov/datasets.php.

There are two sources for data on the locations of depressions. One method is to generate a sinks layer from a DEM. A sinks and depressions source layer can be created from a void-filled DEM, but not from a hydrologically conditioned DEM since sinks have been removed from them to improve the hydrological modeling process. Sinks can be a manifestation of error, but there can be sinks that are real. Real sinks are areas with no external drainage meaning they are depressions in the surface. Another option is the Africa ATP layer described above. This layer has data about lowlands and depressions. Since these are two different concepts, a user may desire to separate the ATP layer to analyze the lowlands and depressions separately. The decision to separate the layer, and the process used to do so, is described in Chapter 4.

Open Street Map (OSM) is a good source for data about public infrastructure. Data about roads, water boundaries, populated places, and administrative boundaries can be downloaded at no cost. OSM is a collaborative project to create a free, editable map of the world. It is maintained by contributors, often local knowledge holders who update the map. The rate at which an area is mapped is dependent upon what a user community uploads into the system. Even where communities are not active there is usually reliable data on roads, shorelines and administrative boundaries. These layers are mainly provided by governments who released their data into the public domain. The data can be downloaded for free and imported to ArcGIS through a simple process. Esri provides a free toolbox for importing and working with OSM data in ArcGIS 10.x. It can be found at http://www.arcgis.com/home/item.html?id=16970017f81349548d0a9eead0ebba39.

Table 4 below provides an overview of possible data sources to use when the model is implemented. The table summarizes information described above and describes how the data was created, the source, and resolution.

In summary, in this chapter, the general fuzzy suitability framework was presented. The selection of fuzzy overlay was explained, the rationale for modeling contaminant flow was described, and the general criteria to identify risks to clean water were discussed. In the next chapter, the implementation of the framework is described. As part of the implementation, the initial results are evaluated and the process used to refine the framework is described.

Table 4 Recommendations for Data

Criteria ID	Criteria	Suggested Map Layer	How Data was Created	Source	Resolu-tion	Extent of Coverage	Accessibility
1a	Should not be in the flow path of human waste	Latrines	Data should be collected in the field with GPS devices.	Government / NGO	6 m	Organization Dependent	Organization
1b	Should not be in the flow path of animal waste	Livestock pens	Data should be collected in the field with GPS devices.	Government / NGO	6 m	Organization Dependent	Organization
1c	Should not be in the flow path of solid waste	Trash dumps	Data should be collected in the field with GPS devices.	Government / NGO	6 m	Organization Dependent	Organization
1d	Should not be in the flow path of farm chemicals	Farms	Data should be collected in the field with GPS devices.	Government / NGO	6 m	Organization Dependent	Organization
1e	Should not be in the flow path of decomposing carcasses	Cemetery	Data should be collected in the field with GPS devices.	Government / NGO	6 m	Organization Dependent	Organization
2a	Should not be within a wetland	Wetlands	There are three options for this criteria: (1) Africa Topographic Position, (2) SRTM DEM or (3) Conditioned DEM through HydroSHEDS.	USGS, USGS, USGS	100 m, 90 m, 90 m	Africa	Public
3a	Should not within an area with stagnant water	Sinks/ Depressions	There are two options for this criteria: (1) Africa Topographic Position, or (2) SRTM DEM.	USGS, USGS, USGS	100 m, 90 m, 90 m	Africa	Public

Criteria ID	Criteria	Suggested Map Layer	How Data was Created	Source	Resolu-tion	Extent of Coverage	Accessibility
4a	Should be on a slope of less than 16 percent	Slope	SRTM 90 m or better DEM	USGS, USGS, USGS	90 m	Global	Public
4b	Should be within 4000 m of a major road	Road Network	Community mappers based on local knowledge where an active community exists	Open Street Map or Digital Chart of the World	6 m	Global	Public
5a	Should be within 1500 m of a hospital	Hospitals/ Clinics	Data should be collected in the field with GPS devices.	Government / NGO	6 m	Organization Dependent	Organization
6a	Should be within 3000 m of a school	Schools	Data should be collected in the field with GPS devices.	Government / NGO	6 m	Organization Dependent	Organization
7a	Should be within 1500 m of a populated place	Populated Places	Data should be collected in the field with GPS devices.	Government / NGO	6 m	Organization Dependent	Organization
7b	Should not within 1500 m of a water well	Existing Wells	Data should be collected in the field with GPS devices.	Government / NGO	6 m	Organization Dependent	Organization

CHAPTER 4: IMPLEMENTATION STUDY

In this chapter the general framework is implemented as a GIS model for a specific location in order to assess its feasibility. As explained in this chapter, the implementation identified weaknesses of the framework which led to modification of the model through an iterative model fitting process. This chapter begins with a discussion of the study area, the data used in the implementation and the fuzzy methods used. Then, the results are assessed and the model refinement is discussed. This includes a presentation of the performance for both the preliminary and refined model.

4.1 Study Area

A study area in central Uganda was selected to act a test case of an implementation of the framework. This area is representative of other contexts in sub-Saharan Africa where the framework might be applied. The area was also chosen because data to test the general framework was made available from an NGO. The study area is located about 160 km north of Kampala in the Nakasongola district (see Figure 4).

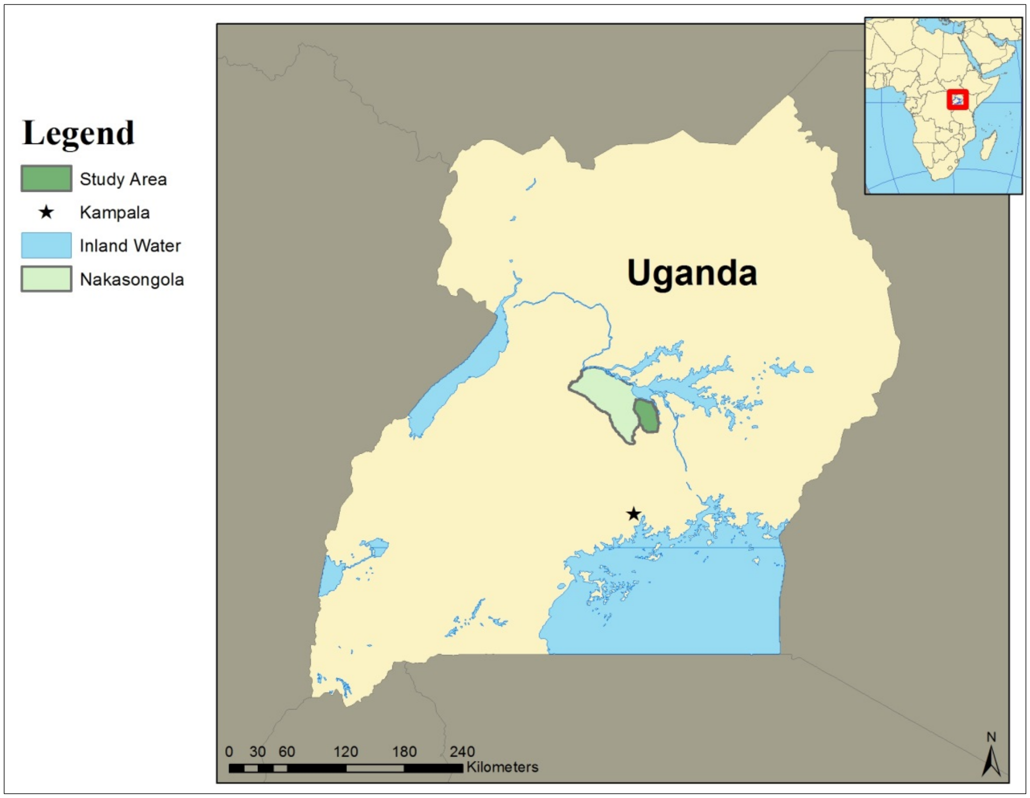

Figure 4 Overview of Study Area

The study area is approximately 630 sq km and is near the southwestern edge of Lake Kyoga (see Figure 5).

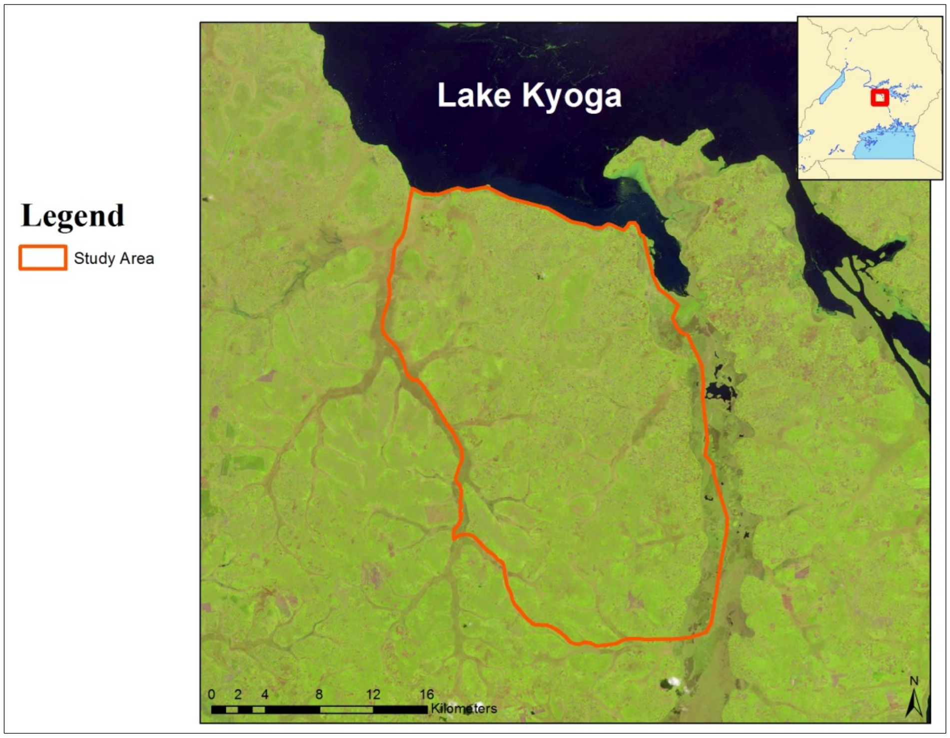

Figure 5 Overview of Study Area with Lake Kyogo

The region is one of Uganda's driest and is recognized as an area experiencing the effects of climate change, notably an increased frequency and severity of floods and droughts (Egeru and Majaliwa 2009). Historically, the region experiences two rainy seasons a year. The first season is March to May and consists of regular heavy rains. The second season is August to December and consists of irregular light rains. Inconsistent rainfall and intense rains make the area susceptible to flooding. Information about the weather near the study area was found using a weather station in Soroti, about 86 km northeast of the study area (see Figure 6).

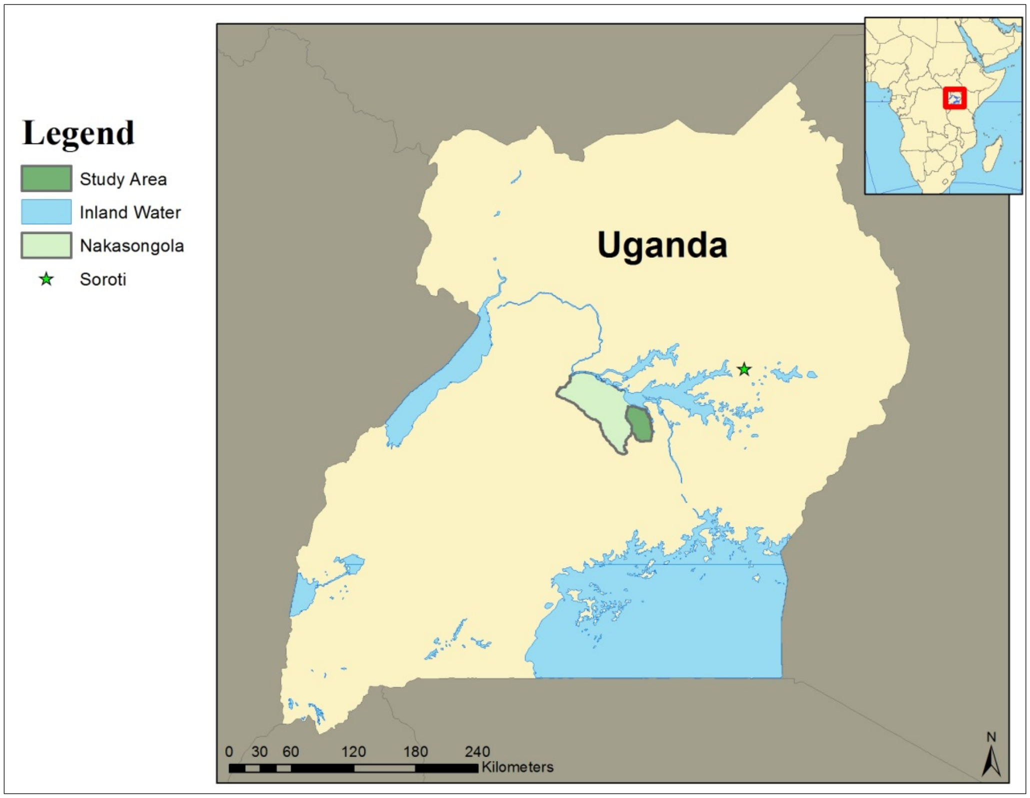

Figure 6 Weather Station in Soroti, Uganda

At the Soroti weather station, the recorded 30 year rainfall average is 53.7 inches. Additionally, the average number of rainy days is 126 and the average temperature is 76.9 degrees Fahrenheit. Figure 7 shows the average precipitation for the area by month.

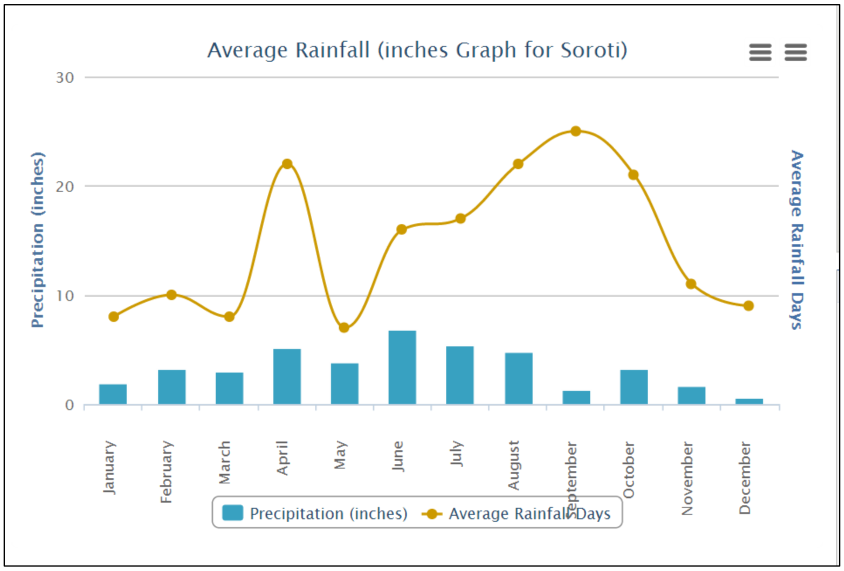

Figure 7 Overview of Average Rainfall in Soroti

Source: World Weather Online (2014)

The elevation in the study area ranges from 1028 m to 1271 m. The study area is generally flat with a few isolated areas with a slope greater than 6 percent. There are wetlands on the east and west of the study area (see Figure 5).

For their food and livelihood needs, residents rely on the natural resources from the land and especially Lake Kyoga. Livestock production is a major source of livelihoods and only one-third of the people are crop farmers in the district (Muruli 2009). Major food crops include cassava, maize, sweet potato, banana, potato, and millet. The area has suffered considerably from soil degradation and deforestation which has caused erosion in many areas.

4.2 Data

As with any implementation of a general framework, the implementation is limited to the data available. In this implementation study, due to limited availability of data, only seven criteria of the fourteen were used in the suitability model. An existing wells layer (for criteria 7b) was available but, as explained above, it is kept out of the analysis to use as a means of validation of the model. In the tables below, the Unique Criteria ID that were established in Chapter 3 are used throughout Chapter 4.

When the general framework is implemented, a user will also need make decisions about the specific distances used to analyze the criteria. In this study, different distances were tested until an acceptable result was identified. The preliminary model, along with the refining process, is discussed in the model fitting section (4.5) below. As mentioned above, the model was refined by comparing the proposed suitable sites against the location of existing wells in the study area. The distances reported below are from the final set of distances.

The figures below provide an overview of the data acquired through World Vision. The distribution of schools and health facilities are shown in Figure 8. The distribution of hygiene and sanitation related infrastructure is shown in Figure 9. The points are shown on two maps to reduce the overlap since many of the points are located close to one another.

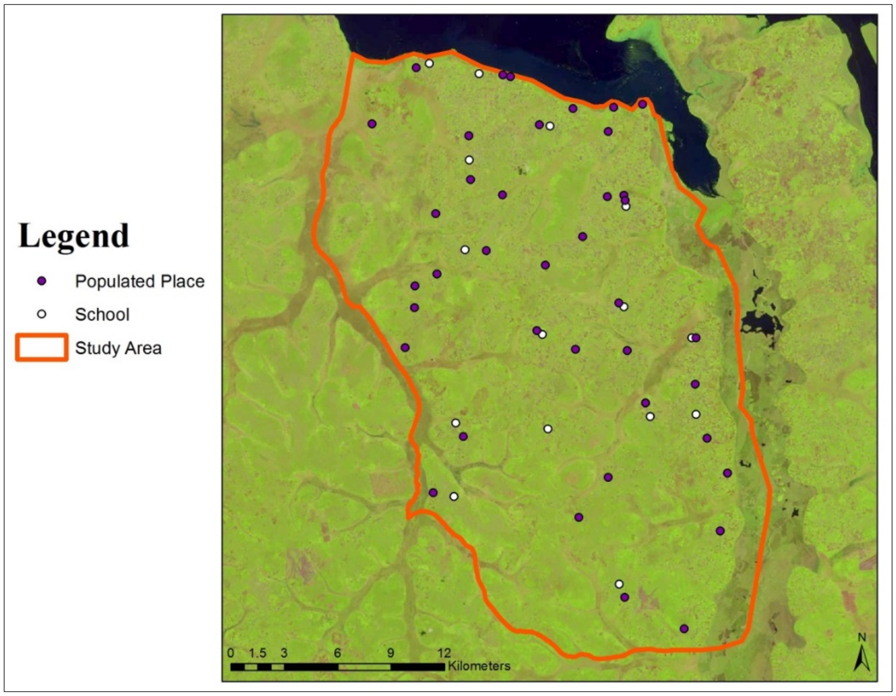

Figure 8 Map of Community Infrastructure

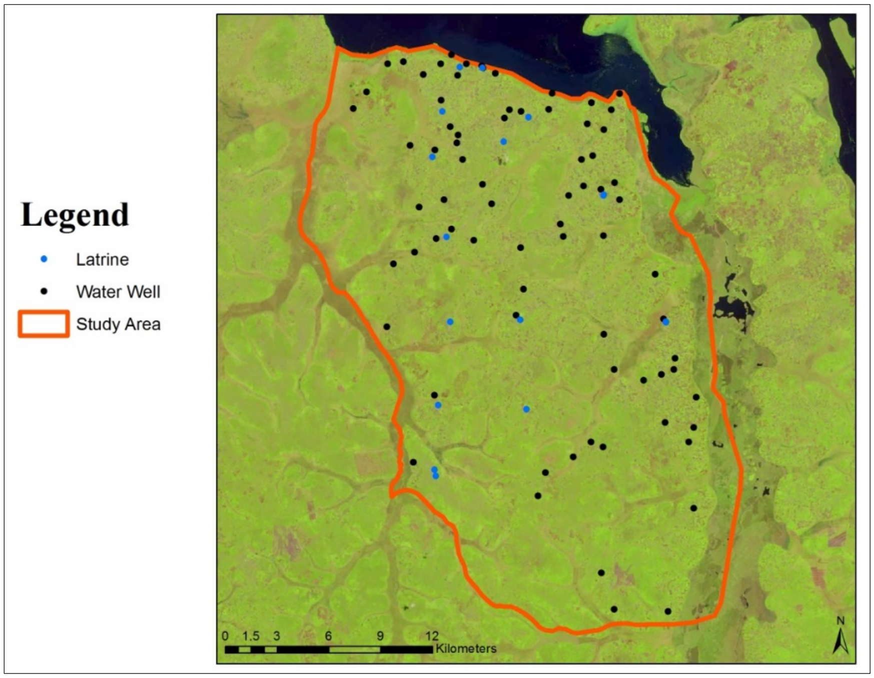

Figure 9 Map of Hygiene and Sanitation Infrastructure

The eight criteria (7 for the model plus wells) described in Table 5 were selected because of the data available in the study area. Some of the World Vision data was supplemented with public data as described in more detail below. The data used are explained in Tables 6 and 7.

Table 5 Suitability Criteria in Implementation Study

Category	Criteria ID	Criteria	Measure
1. Avoid travel path of a contaminant from a latrine	1a	Should not be in the flow path of human waste	Flow Distance
2. Avoid areas prone to flooding	2a	Should not be within a wetland	Yes/No
3. Avoid areas with an increased likelihood of a person contracting malaria	3a	Should not be within an area with stagnant water	Yes/No
4. Permit areas where drilling is feasible	4a	Should be on a slope of less than 16 percent	Percent rise
	4b	Should be within 4000 m of a major road	Distance from a major road (m)
6. Promote children's health	6a	Should be within 3000 m of a school	Distance from a school (m)
7. Should maximize clean water coverage	7a	Should be within 1500 m of a populated place	Distance from a populated place (m)
	7b	Should not be within 1500 m of an existing well	Distance from an existing well (m)

Table 6 Implementation Data Requirements

Criteria ID	Criteria	Specific Map Layer	Data Type	Possible data values/attributes
1a	Should not be in the flow path of human waste	Latrines	Point	Location of latrine
2a	Should not be within a wetland	Africa Topographic Position	Raster	The Africa Topographic Moisture potential layer categorizes the surface into two categories: Lowlands/depressions and highlands. Lowlands/depressions are given a value of 1 and uplands are given a value of 2.
3a	Should not within an area with stagnant water	Africa Topographic Position	Raster	The Africa Topographic Moisture potential layer categorizes the surface into two categories: Lowlands/depressions and highlands. Lowlands/depressions are given a value of 1 and uplands are given a value of 2.
4a	Should be on a slope of less than 16 percent	DEM	Raster	Percent slope
4b	Should be within 4000 m of a major road	Major Roads	Line	Location of road
6a	Should be within 3000 m of a school	Schools	Point	Location of a school
7a	Should be within 1500 m of a populated place	Populated Places	Point	Location of a village
7b	Should not be within 1500 m of an existing well	Existing Wells	Point	Location of a well

Table 7 Data Specifics

Criteria ID	Specific Map Layer	How data was created	Resolution/ Horizontal Accuracy	Quantity	Source	Extent of Availability
1a	Latrines	Data was collected in the field by World Vision staff with handheld GPS devices.	6 m	18	World Vision	Study Area
2a	Africa Topographic Position	This layer was derived from the Compound Topographic Index (CTI) which is a topographically derived measure of slope and the areas of "upstream raster cells" (USGS, 2009). Satellite Imagery was also used to create a wetlands layer.	100 m grid		USGS	Africa
3a	Wetlands Polygons	Layer derived from satellite imagery.	30 m		WRI	Uganda
4a	DEM, SRTM3N01E032V1	SRTM elevation data was derived using two radar images taken from slightly different locations to calculate the surface elevation (USGS, 2008).	90 m grid		USGS	Global
4b	Major Roads	Created by the community of Open Street Map Contributors	Unknown	4	Open Street Map	Global, Community Based
6a	Schools	The primary source was World Vision. These points are World Vision schools only. There are other schools not included in this layer because they were unavailable. The performance of the model is likely to improve with a more robust school layer.	6 m	15	Government / NGO	Study Area

Criteria ID	Specific Map Layer	How data was created	Resolution/ Horizontal Accuracy	Quantity	Source	Extent of Availability
7a	Populated Places	The primary source was World Vision.	6 m	99	World Vision	Study Area
		Landsat 8 satellite imagery was used to identify areas with clustering of households.			USGS	Global
		GeoNames data was used to supplement data where places seemed to be missing.			GeoNames	Global
7b	Existing Wells	Data was collected in the field by World Vision staff with handheld GPS units. Of the 76 wells only 7 were not installed through World Vision. Therefore the data is not likely to be complete.	6 m	76	World Vision	Study Area

4.3 Methodology

This section describes how fuzzy methodology was implemented in the implementation study. Table 8 provides an overview of the criteria used and describes the pre-processing of the data that was necessary before the fuzzy membership layers could be created. Following the table, several sub-sections describe the creation of each fuzzy membership layer.

Table 8 Overview of Fuzzy Methodology

Category	Criteria ID	Criteria	Source Layer	Pre-processing
1. Avoid travel path of a contaminant from a source	1a	Should not be in the flow path of human waste	Latrines	Path Distance with maximum distance set to 1000 (cost), horizontal factor to forward and vertical factor to linear. Output grid snapped to 90m DEM grid
2. Avoid areas prone to flooding	2a	Should not be within a wetland	Africa Topographic Position, WRI Wetlands	Obtained as 100m grid classified into two classes only. Wetlands masking. Required resampling after fuzzy membership assigned to register with other 90m grids.
3. Avoid areas with an increased likelihood of a person contracting malaria	3a	Should not within an area with stagnant water	Africa Topographic Position	Same as above
4. Permit areas where drilling is feasible	4a	Should be on a slope of less than 16 percent	DEM, SRTM3N01E032V1	Percent slope was derived from the 90 m DEM.
	4b	Should be within 4000 m of a major road	Major Roads	Polyline to Raster, Euclidean Distance
6. Promote health of children	6a	Should be within 3000 m of a school	Schools	Euclidean Distance
7. Should maximize clean water coverage	7a	Should be within 1500 m of a populated place	Villages, Geonames data, Landsat 8 imagery	Euclidean Distance
	7b	Should not be within 1500 m of a water well	Existing Wells	Euclidean Distance

In the following sub-sections, the creation of each fuzzy membership layer used to evaluate each criterion is described. Following the description for each criterion, there is a summary of how fuzzy membership was assigned in table form. Each of these tables is organized into the following rows:

- Values: the process by which the fuzzy membership values are derived from the pre-processed layer
- Source of Uncertainty: the elements of uncertainty reflected in the fuzzy measure used
- Definitely Suitable: the threshold value for areas that are most suitable
- Definitely Unsuitable: the threshold value for areas that are least suitable
- Suitability Range/Variation in Range: the ranges of values across which fuzzy membership varies from 0 to 1 and an explanation of the nature of that variation
- Membership Function: the logic for the selection of the fuzzy type and description of the specific algorithm used in the fuzzification of the input raster

4.3.1 Surface Flow of a Contaminant

A multi-step process was created to model the surface flow/ near surface flow of a contaminant. In this implementation study, only human waste from a latrine point was available for this criterion. To identify the flow path of human waste, the *Path Distance* tool was used. This tool calculates for each cell, the least accumulative cost distance from a source location to another. This tool is similar to *Cost Distance,* but it has added complexity because it is able to account for surface distance and horizontal and vertical cost factors.

Several steps were required to use the *Path Distance* tool. First, a constant raster to be used as the cost raster was created with all cell values set to one since the cost effect of slope is accounted for by other parameters. Next an aspect layer was created using the 90 m DEM. This is used to indicate the direction of downslope flow. Then, in the *Path Distance* tool, the horizontal factor parameter was set to forward. This meant that only forward (downslope) movement was allowed. The vertical parameter was set to linear so that the vertical factor of travel cost was dependent upon slope angle between the FROM cell and the TO cell. The maximum cost distance was set to 1000. Finally, the cell size and extent were set to the 90 m void-filled DEM.

The output raster is the travel cost of human waste based on flow path. The values range from 0 to 1000. Cells not in the calculated flow path were given a value of NoData by the *Path Distance* tool. Since these are suitable locations, they were subsequently assigned a value of 1000, the limit of the calculated cost distance.

To confirm the results of the Path Distance analysis are valid for this purpose, Figure 10 shows a close up view of the fuzzy membership layer overlaid on an elevation layer. In the figure there is no distance data (i.e. it is transparent) beyond the 1000 path distance. Note that the flow from this latrine bends around the hill on the east where the elevation is lower than the latrine. It also shows some depressions near the latrine sites where the flow is significantly restrained. While it appears the *Path Distance* tool is successful at representing the flow, this analysis highlights one of the challenges of using elevation data at a coarse resolution since the 90 m scale does not capture small scale elevation changes.

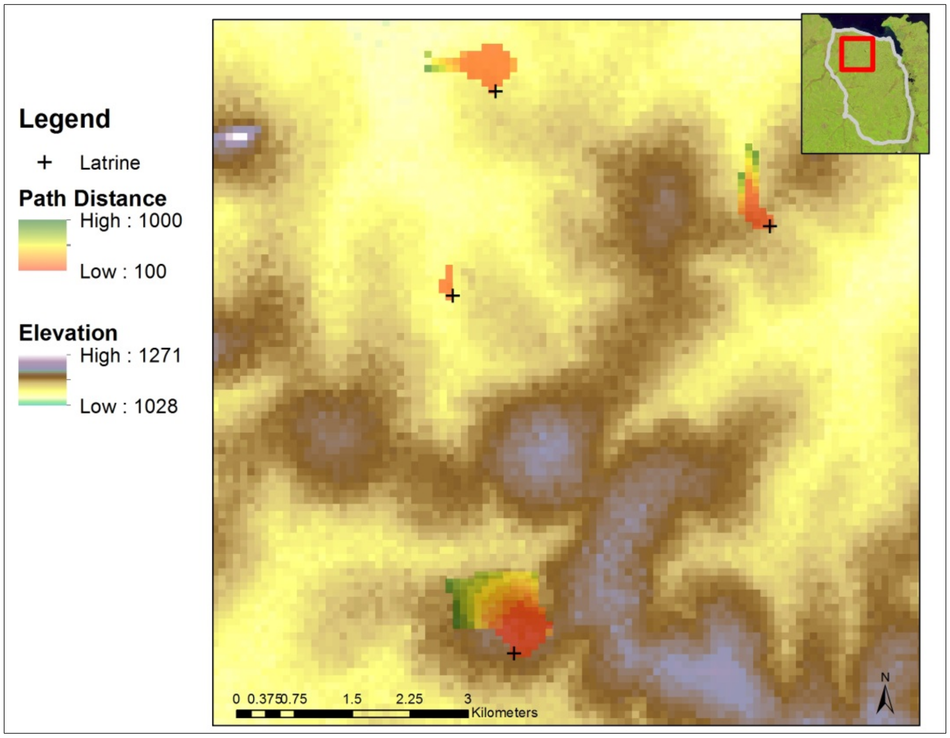

Figure 10 Flow Path Example Map

To ensure the maximum cost distance used is appropriate as a limit, it is recommended a user manually check the horizontal distance to this limit using *Measure* in ArcMap. In this study, the 1000 cost distances were sufficiently further than the distances suggested by the Illinois DOH and the EPA as described in Chapter Two. The shortest actual horizontal distance at which a cell with a value of 1000 was from a latrine was 686 m. Thus it was concluded that the 1000 cost distance limit is far enough to ensure that a well beyond this distance would not be located in the surface or near surface flow path from a contamination source. The analysis process, including the fuzzy membership process described in Table 9 below, is outlined in Figure 11.

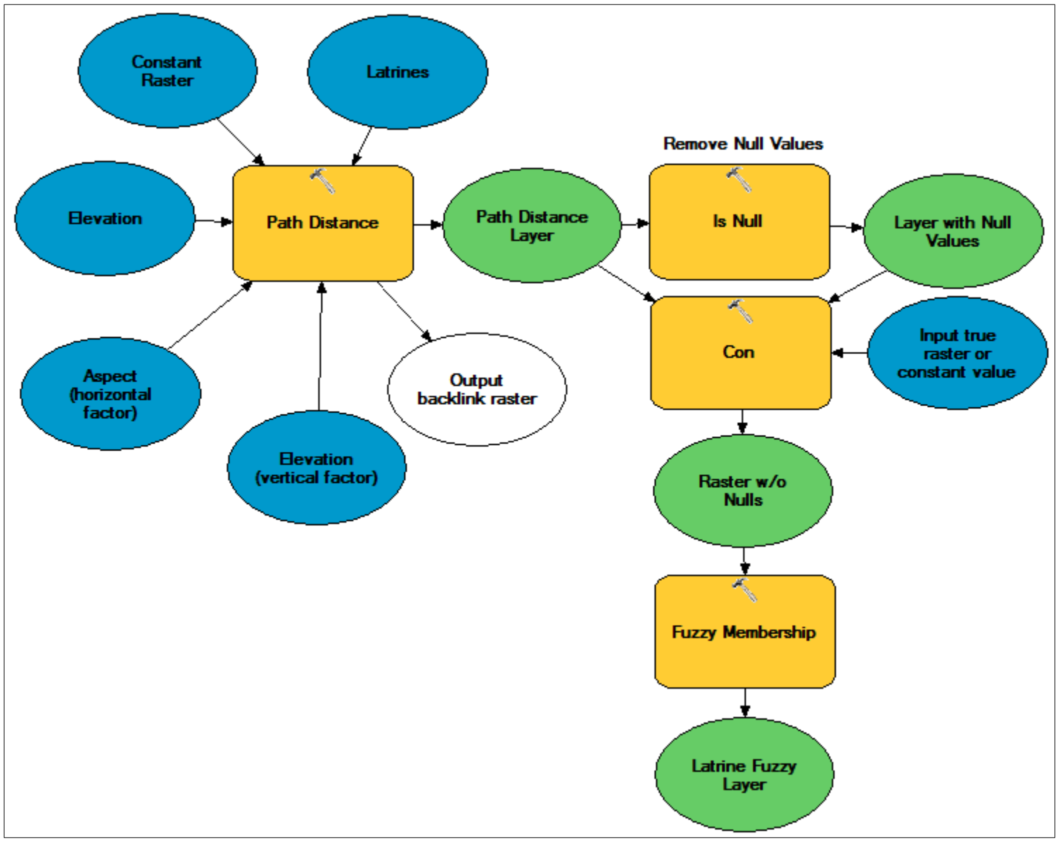

Figure 11 Overview of Contaminant Flow Analysis

Table 9 Contamination Source Criterion Fuzzy Assignment

Criteria	1a - Should not be in the flow path of human waste
Source Layer	Latrines
Values in source layer	The cell values are the cost distance a contaminant will travel from a latrine. The value of 1000 is assumed to represent the downslope distance beyond which a contaminant could travel and pollute a water well.
Source of Uncertainty	Given the coarse resolution of the DEM, it is uncertain that the tool accurately captures the specific path a contaminant will flow. It is also uncertain how far it will flow based on the amount of water it travels with and how much contaminant is moving. Therefore, the specific travel distances of the contaminant are uncertain.
Definitely Suitable	Areas greater than the cost distance of 1000 are definitely suitable.
Definitely Unsuitable	Areas less than 300 cost distance of a contaminant source are definitely unsuitable.
Suitability Range/ Variation in range	The acceptable suitability range is 300 to 1000. As described above, areas not within the direct flow path of the contaminant were assigned a value of 1000. Therefore, cell values range from 0 to 1000. Within the travel path the values are continuous from 0 to 1000.
Membership Function	The linear function was used for this criterion because it provided the ability to set a range of acceptable values. In this case, the range was between 300 and 1000. This gives full membership (1) to 1000 and higher and no membership (0) to 300 and below. The linear algorithm decreases membership from 1000 to 300.

It is useful to take some time here to explain the process of assignment of fuzzy membership values using the linear function that is used for several of the criteria. The fuzzy linear function applies a linear function between the specified minimum and maximum suitability values. Any value below the minimum is assigned a 0 indicating it is definitely not a member of the suitability set. Any value above the maximum is assigned a 1 indicating it is definitely a member of the suitability set. For example, in Figure 12, the blue line represents a positive sloped linear transformation with the minimum set to 30 and the maximum set to 80. Any value smaller than 30 was assigned a 0 and any value above 80 was assigned a 1. Values between 30 and 80 are in the transition zone and are given membership based on their value related to what is designated as suitable. The linear function uses a straight line for its membership slope. Then when the fuzzy membership tool is used, it assigns a membership value (between 0-1) based on the strength of membership in the suitability set. In Figure 12 there are two lines, the red line represents a negative slope and is used when a higher value is suitable (e.g. when a farness to a contaminant is preferred). The blue line represents a positive slope and is used for when a low value is suitable (e.g. when nearness to a school is preferred).

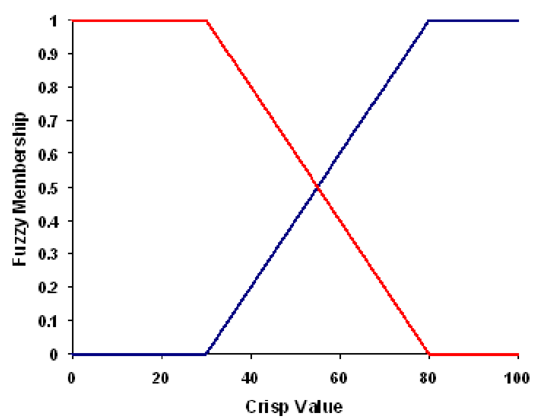

Figure 12 Fuzzy Linear Function

Source: Esri 2014

In the contaminant surface flow criterion above, the further the distance, the higher the value and the more suitable a location is. Therefore, the positive slope is used because the maximum input is 1000 and the minimum is 300. As explained later, in the criterion analysis of schools, higher membership is given to locations near a school (low distance value). Therefore a slope is negative because the maximum value (given membership of 1) is set to 0.

Figure 13 shows the membership layer overlaid on satellite imagery. The membership layer was clipped to the study area.

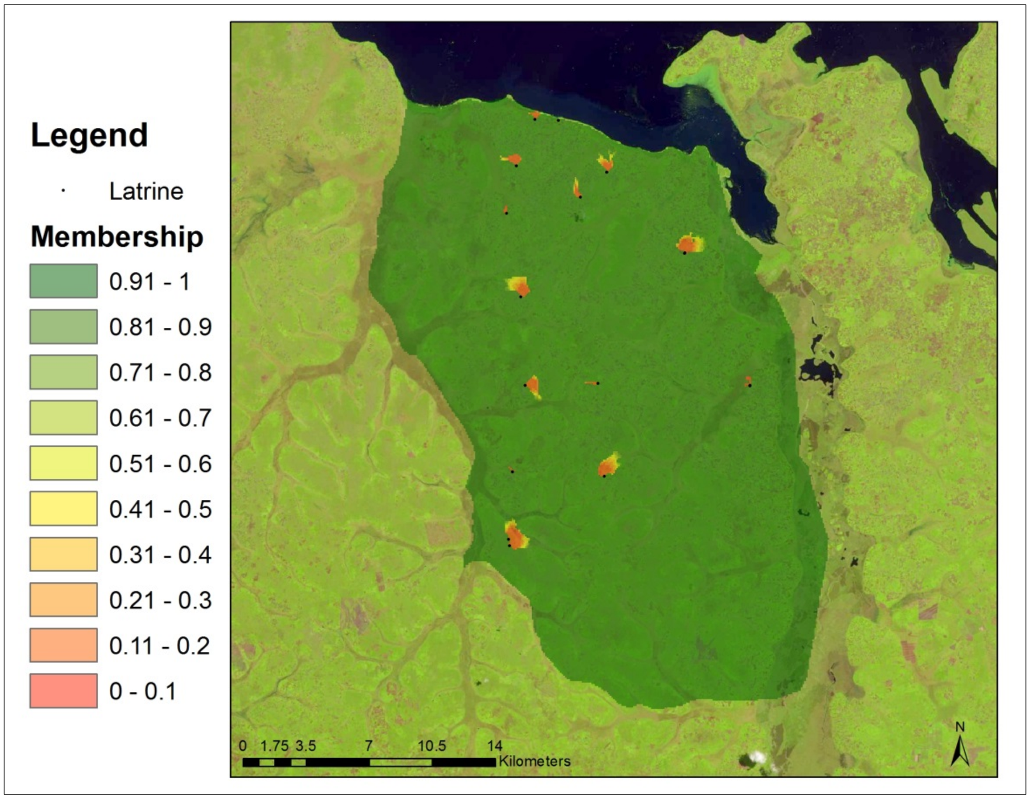

Figure 13 Criteria 1a Membership Layer Overlaid on Satellite Image

4.3.2 Wetlands and Depressions

The wetlands and depressions themes are discussed together because they are analyzed using the same source, the ATP layer. As noted above, the ATP layer has one value to designate areas that are either wetlands or depressions. In order to assign different fuzzy membership to these two different concepts, it was necessary to create two layers: (1) wetlands which was used to analyze the criterion about areas that are more likely to flood, and (2) depressions, which was used to analyze the areas where water is more likely to be stagnant. The process to separate the two layers is described below.

The ATP layer was used as a reference for the wetlands analysis and as a source for the depressions layer because it has a broad extent and was created by USGS, a credible source. The author tested several other data sources and methods but encountered problems of data availability, insufficient metadata, and the methods used to derive the data were not explained. Information about how the ATP layer was created is available through the USGS http://rmgsc.cr.usgs.gov/ecosystems/africa.shtml). Figure 14 shows the ATP data in the study area.

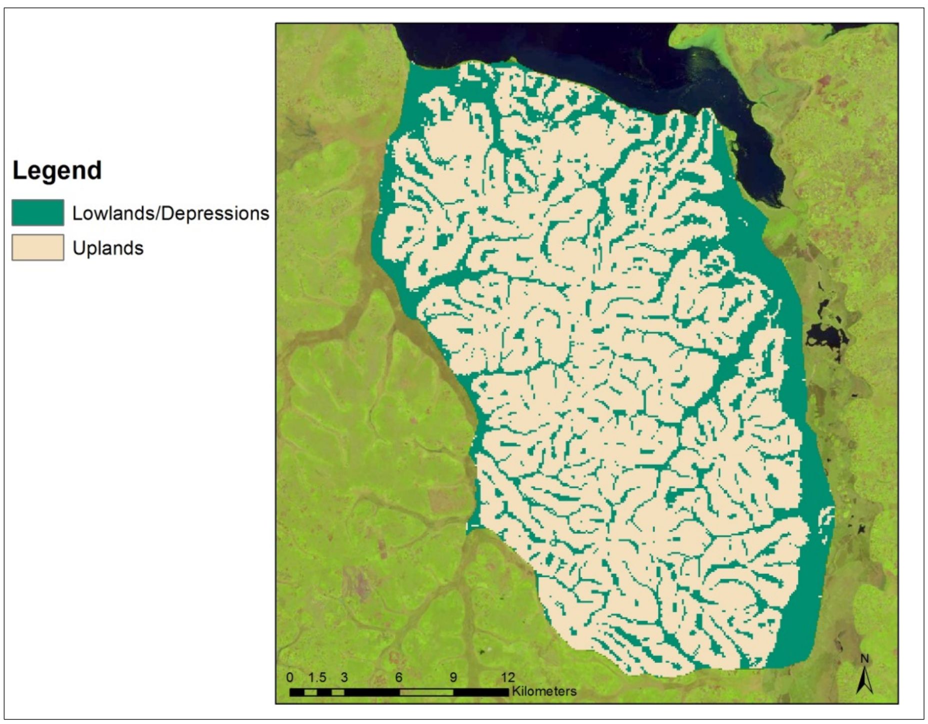

Figure 14 ATP Class Names

Separating the Wetlands

In order to separate lowland areas from depressions, each had to be distinguished from one another. To do this, an additional dataset was required. A wetlands layer for the region was acquired through the World Resources Institute (WRI). This layer consists of wetlands polygons derived from satellite imagery. When the framework is applied to a different context, it may be possible to find a similar wetlands layer for the region of interest because wetlands are areas of particular ecological concern in many countries.

Since the metadata associated with the WRI wetlands layer is limited, there was some question as to its accuracy. Therefore, the original ATP layer and the WRI wetlands polygons layer were compared. Since the ATP lowlands/depressions layer was created using the CTI threshold, the lowlands should be areas that have a steady state of wetness and therefore should be similar to the wetlands polygon from the WRI. However, these are not identified as wetlands but are classified as lowland/ depressions. The WRI wetlands layer is overlaid on the ATP layer in Figure 15. The overlay reveals the two layers have a clear overlap of wetlands and lowlands, though the coverage is not identical. This step validated the WRI wetlands polygons.

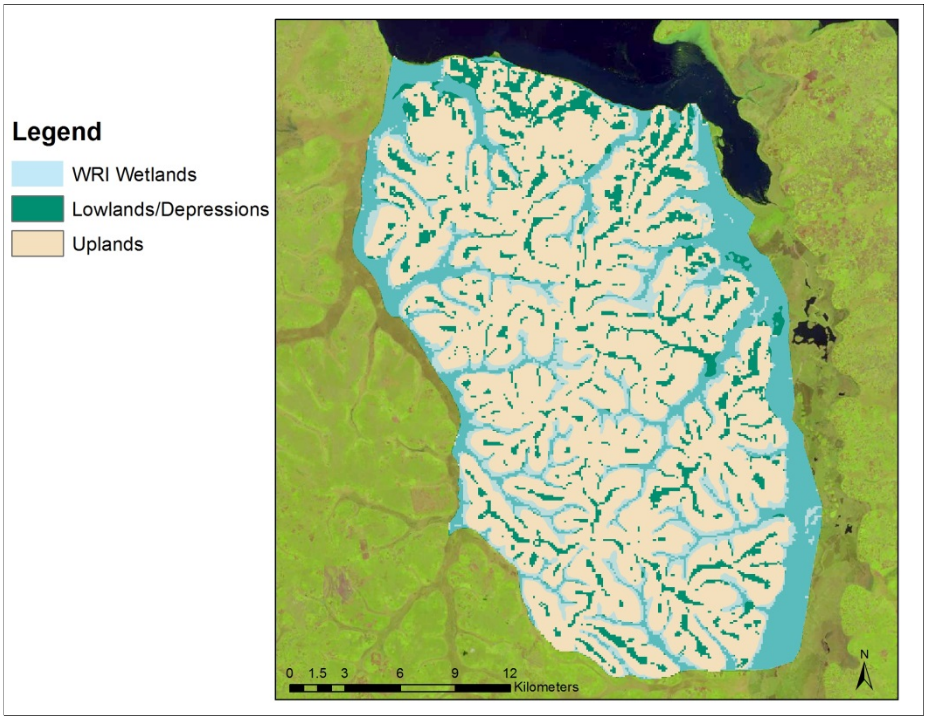

Figure 15 WRI Wetlands Polygon overlaid on ATP Layer

The *Raster to Polygon* tool was used on the WRI wetlands polygons layer. The cell size was set to 90 m. Once the tool was used, the wetlands areas were assigned a value of 0 (unsuitable) and the non-wetlands areas were assigned a value of 1 (suitable).

While this study used WRI wetlands to analyze areas where flooding might occur, there are other options that could have been used. One alternative is to use the WRI wetlands mask on the ATP layer to extract the wetlands for fuzzification. However, because the ATP layer does not actually classify wetlands, it was decided to use the WRI polygons as the source layer. Therefore, where the ATP layer and WRI wetlands do not align, the data in the WRI wetlands is used.

Separating the Depressions

Using the study area polygon layer, the *Erase* tool was used to erase wetlands polygons. What was left were study area polygons that were not within wetlands polygons. This created a polygon that was used to mask the original ATP layer. Then *Extract by Mask* was used to change the unmasked wetlands areas to NoData. The result is a raster with NoData values where there are wetlands. Therefore, the only cells left with the original class name of wetlands/depressions (value = 1) are now only depressions.

The areas of depressions were assigned a fuzzy membership value of 0.4, rather than the 0 fuzzy value that is assigned to the wetlands. This increases the membership of the depressions area in the suitability set because of the uncertainty about their exact location or severity of the risk. However because the masked ATP layer was stored as integer data, it was necessary to change the raster to a floating point type which would allow cell values to be either 1 or 0.4. Thus the cells were reclassified initially to 10 or 4. Then *Divide* was used to divide each cell by 10 and thus a raster with values of 1 or 0.4 was created. The process used to create the depressions layer is in Figure 16.

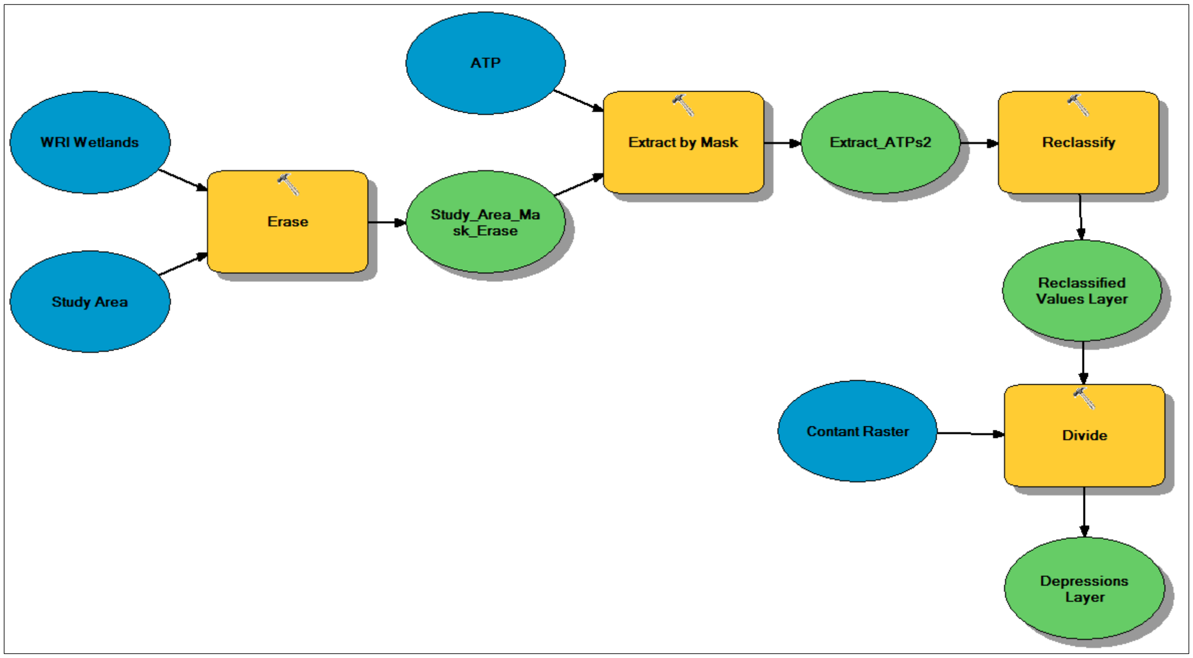

Figure 16 Overview of Process to Create Depressions Layer

Once the depressions layer was created, it was necessary to resample the original 100 m grid to a 90 m. The method chosen to *Resample* the cells was bilinear interpolation. This method uses the value of the four nearest input cell centers to determine the value on the output raster. The new value for the output cell is a weighted average of these four values and is adjusted to account for the distance from the four input cells. The smoothed values now ranging between 0.4 and 1 reflect the uncertainty of the location of the depressions within the grid cells given the resampling.

Table 10 summarizes the analysis of the wetlands criterion and the fuzzy assignments. Then Figure 17 shows the fuzzy membership values for the wetlands layer. Next, Table 11 shows the analysis of the depressions criteria and fuzzy assignments and Figure 18 shows the fuzzy membership values for the depressions layer.

Table 10 Wetland Criterion Analysis

Criteria	2a - Should not be within a wetland
Source Layer	WRI, Africa Topographic Position
Values in source layer	The layer is divided into two classes: 0 is wetland and 1 is upland.
Source of Uncertainty	There is uncertainty about how accurately the layer represents the phenomena. The source layer was a polygon was converted to a polygon and therefore the boundary is modified through the conversion process.
Definitely Suitable	Uplands areas are definitely suitable
Definitely Unsuitable	Wetlands are definitely unsuitable
Suitability Range/ Variation in range	The suitability range is 1.
Membership Function	No membership function was used. The source layer was used directly by the fuzzy overlay tool since values already ranged between 0 and 1.

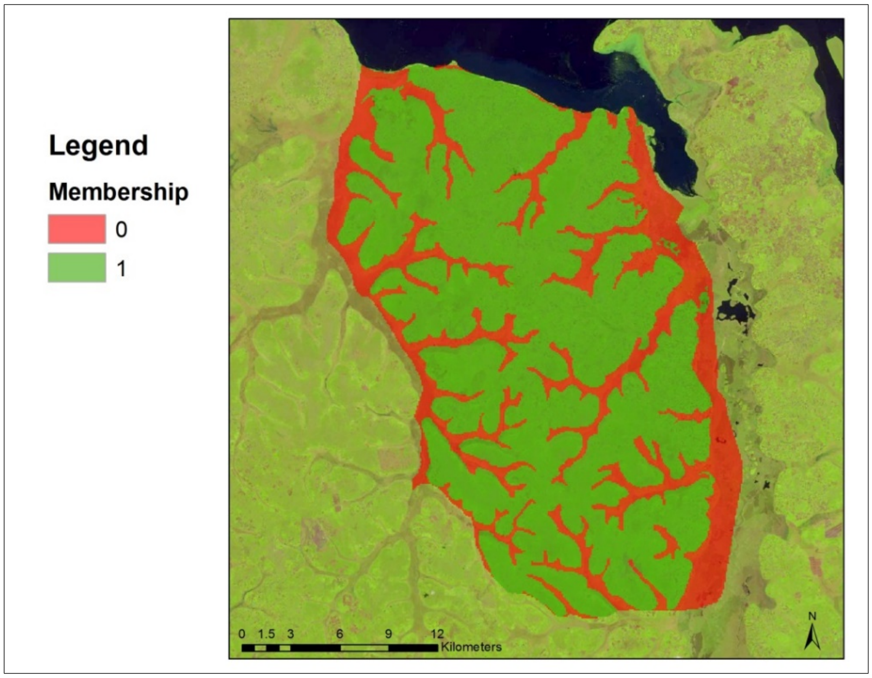

Figure 17 Map of Membership for Criterion 2a

Table 11 Depressions Criterion Analysis

Criteria	3a - Should not be within an area with stagnant water
Source Layer	Africa Topographic Position
Values in source layer	The values in the source layer are 1 (depressions/lowlands) or 2 (uplands)
Source of Uncertainty	There is uncertainty about how accurately the layer represents the phenomena. Additionally, the source layer was at 100 m grid and was resampled to 90 m. This caused the boundary of a depression to be more uncertain.
Definitely Suitable	Areas of no depression are definitely suitable.
Definitely Unsuitable	Depressions are definitely unsuitable, but the uncertainty of their location warrants better than 0, therefore .4 is assigned.
Suitability Range/ Variation in range	The suitability range is .4 to 1.
Membership Function	No membership function was used. The source layer was used directly by the fuzzy overlay tool since values already ranged between .4 and 1.

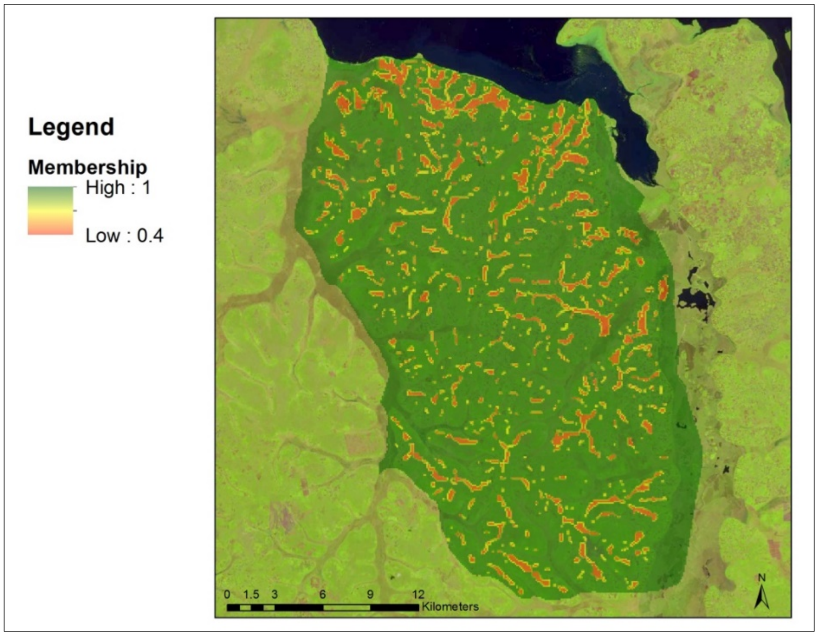

Figure 18 Map of Membership for Criterion 3a

4.3.4 Slope

For the slope analysis, a void-filled DEM was used to create a slope layer which was then used to create the fuzzy layer. The *Slope* tool was used to derive slope percent values for membership evaluation. Table 12 shows an overview of the criterion analysis. Figure 19 shows the fuzzy membership values for the slope layer.

Table 12 Slope Criterion Analysis

Criteria	4a - Should be on a slope of less than 16 percent
Source Layer	Void-Filled DEM
Values in source layer	The values are percent slope. Within the study area the values range from 0 to 22.
Source of Uncertainty	The slope change within a 90 m cell was uncertain. Therefore membership was given to cells that likely have less than 16 percent slope throughout a cell.
Definitely Suitable	Locations with 0 slope are definitely suitable.
Definitely Unsuitable	Areas with 16 percent slope or higher are definitely unsuitable.
Suitability Range/ Variation in range	The acceptable range is 0 to just under 16. The majority of the study area has less than 5 percent slope. There are a few areas spread throughout the study area with approximately 20 percent slope.
Membership Function	The linear function was used. The unsuitable locations with a value of 4000 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the value of 0.

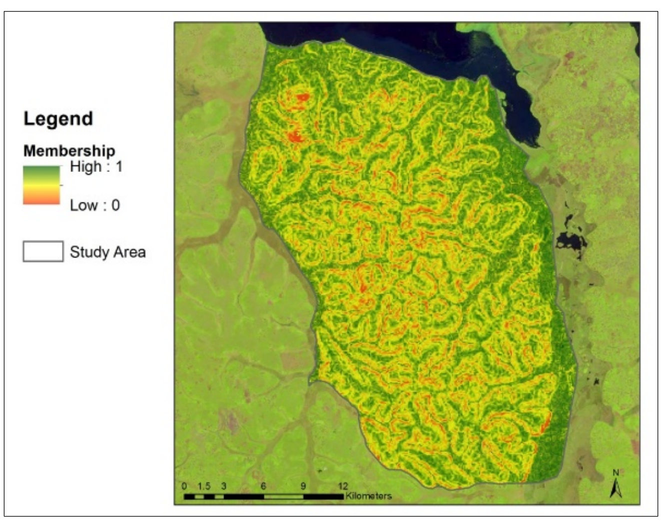

Figure 19 Map of Membership of Criterion 4a

4.3.5 Major Roads and Schools

A roads layer was downloaded from OSM. The locations of schools and existing wells were acquired through World Vision. The layer used for membership evaluation was created using *Euclidean Distance* within the study area.

Table 13 shows an overview of the criterion analysis. Then Figure 20 shows the fuzzy membership values for the major roads layer. Table 14 shows an overview of the criterion analysis for schools and Figure 21 shows the fuzzy membership values for the schools layer.

Table 13 Analysis of Major Road Criterion

Criteria	4b - Should be within 4000 m of a major road
Source Layer	Euclidean Distance from Major Roads
Values in source layer	The values are the distance of a location from a major road in meters. Within the study area the values range from 0 to 8596.
Source of Uncertainty	The road was converted to raster to use the *Euclidean Distance* tool. Each cell was given a value based on whether or not a road was contained within a cell. This caused the road to be visualized as 90m wide. Therefore, the boundary and distance of a location from the road is uncertain.
Definitely Suitable	Locations near a major road are definitely suitable.
Definitely Unsuitable	Areas further than 4000 m are definitely unsuitable. These areas are less accessible and increase costs.
Suitability Range/ Variation in range	The acceptable range is 0 to 4000 m. There are only 4 major roads in the study area. Most of the study area is further than 4000 m from a major road. The closer an area is to a road, the better, and therefore the value of 0 is assigned a membership rating of 1.
Membership Function	The linear function was used. The unsuitable locations with a value of 4000 were assigned a membership value of 0. Then a membership rating of 1 was assigned to the value of 0.

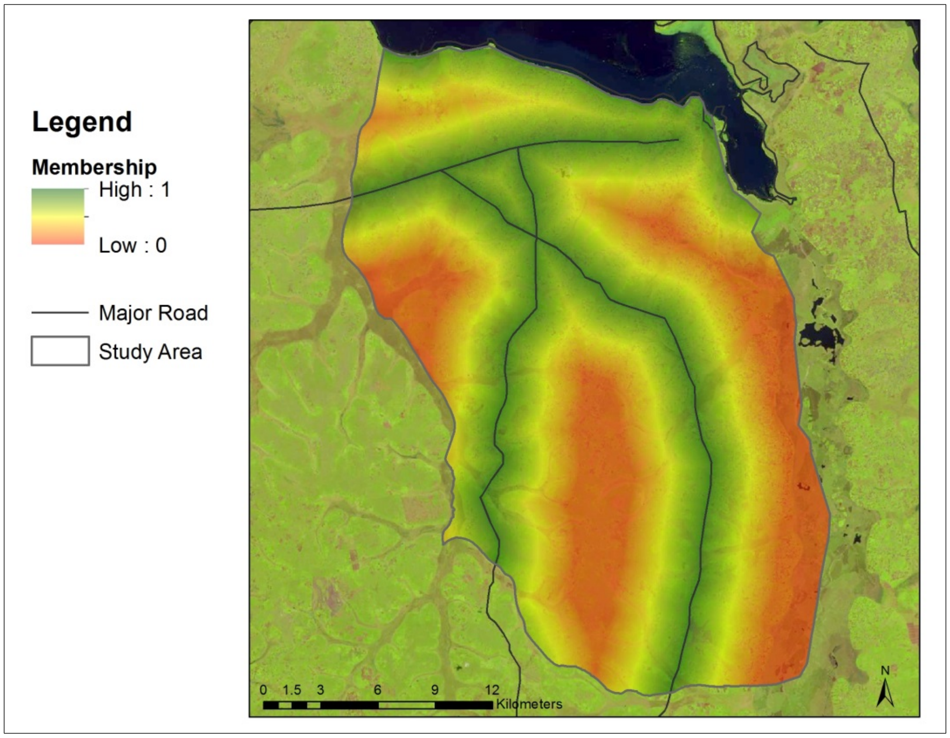

Figure 20 Map of Membership of Criterion 4b

Table 14 Analysis of School Criterion

Criteria	6a - Should be within 3000 m of a school
Source Layer	Euclidean distance from Schools
Values in source layer	The values are the distance, in meters, a location is from a school and range from 0 to 9,172.
Source of Uncertainty	The values are continuous and the breakpoint of a suitable and unsuitable distance of a well in relation to a school is not well defined.
Definitely Suitable	Locations near a school are definitely suitable.
Definitely Unsuitable	Areas further than 3000 m away from a school are definitely unsuitable.
Suitability Range/ Variation in range	Therefore the acceptable range is 0 to 3000 m.
Membership Function	The linear function was used. The unsuitable locations with a value of 3000 were assigned a membership rating of 0. A membership rating of 1 was assigned to the 0 value.

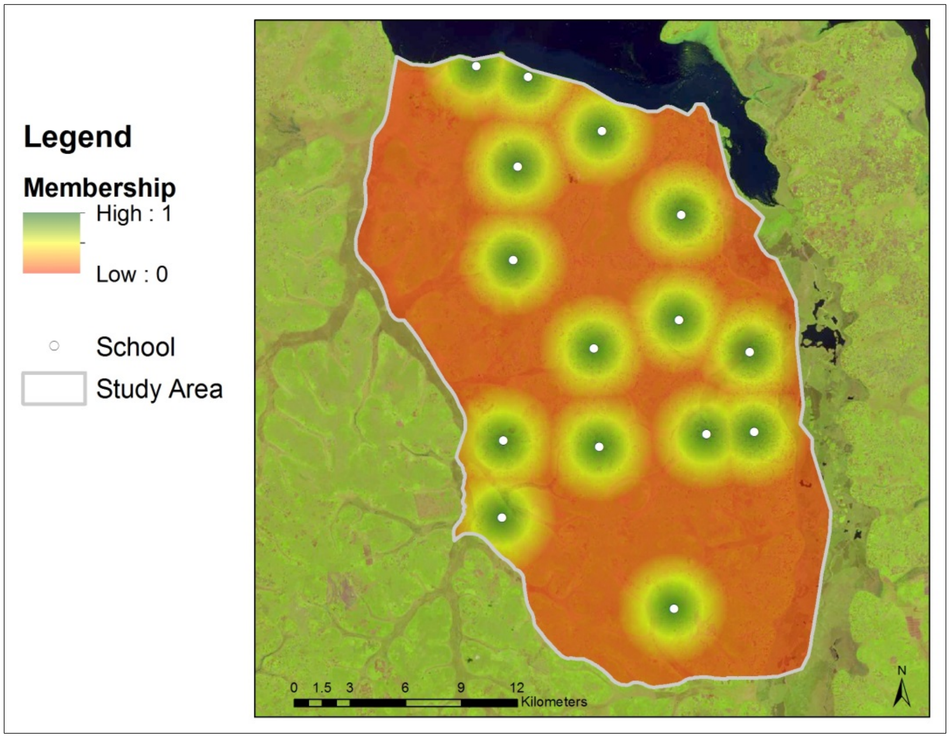

Figure 21 Map of Membership for Criterion 6a

4.3.6 Populated Places

The populated places data layer was enhanced by combining several sources. The primary data of villages was from World Vision. On inspection of this data, it was evident that some places were missing. As a result, GeoNames was used to add populated places that were missing. The following process was developed to identify duplicates. First, the attribute tables were imported into Excel for comparison. Four duplicate names were identified in both data sets. Then these were visualized in ArcMap to determine if the duplicate names were in the same general area of each other, which they all were. It was also confirmed that there was not a consistent positional shift between the two source layers indicating the use of different datums. The differences are likely because the locations of the points in the GeoNames dataset may have less positional accuracy than the field collected World Vision data since GeoNames is a global dataset. Therefore, the locations of these four duplicate places in the World Vision data were used.

A process was developed to determine if any of the points might represent the same place but have different names. This process was used to ensure no new places from GeoNames were added to what was already present World Vision data. First, duplicate names that were previously identified were selected on the map to determine the maximum distance between a World Vision point and a GeoNames point. This showed the positional shift of locations that are actually the same. The maximum distance was 2000 m. Therefore, no points were added if they were located within 2000 m of an existing place in the WV dataset. This is because it is possible that these are representing the same place at a different positional accuracy. Then, to supplement this rule, satellite imagery was used to examine where there were two places within 2000 meters and whether or not these were two distinct populated places. Where two distinct populated places existed, the point from GeoNames was added. In the implementation study, two populated places were identified within the 2000 m on satellite imagery, and were confirmed as separate places.

Table 15 shows an overview of the analysis of the populated places criterion and Figure 23 shows the fuzzy membership values for the populated places layer.

Table 15 Analysis of Populated Places Criterion

Criteria	7a - Should be within 1500 m of a populated place
Source Layer	Villages, supplemented with satellite imagery and GeoNames data
Values in source layer	Values are the distance in meters of a location from a populated place.
Source of Uncertainty	The values are continuous but the suitable break point is well-defined by the UN. This is the definition of water coverage.
Definitely Suitable	Locations near a village are definitely suitable.
Definitely Unsuitable	Areas further than 1500 m are definitely unsuitable.
Suitability Range/ Variation in range	The suitability range is 0 to 1500 m. The cell values range from 0 to 6000 because the distance extends outside of the study area.
Membership Function	The membership function used was linear. The maximum was set to 0 and the minimum was set to 1500.

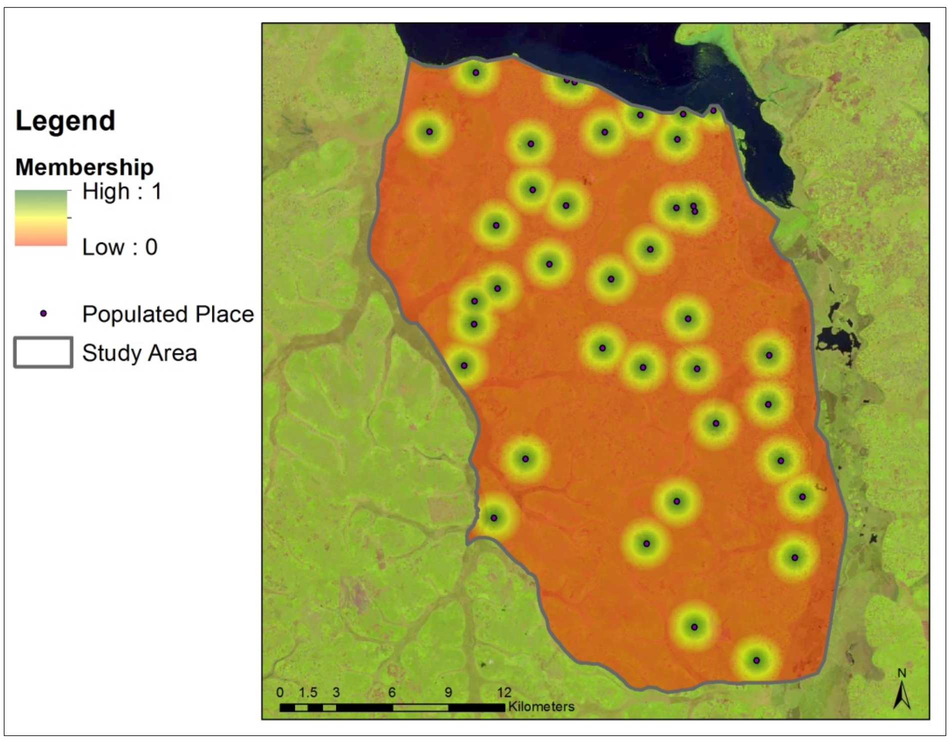

Figure 22 Map of Membership for Criterion 7a

Existing Wells

As mentioned above, the existing wells layer was used as a means to verify and refine the implemented model. Thus, during the development and implementation phase of the framework, it was withheld as a criterion. In the final suitability map, it was included as an input. For completeness in this section, Table 16 shows an overview of the analysis of the existing wells criterion.

Table 16 Analysis of Existing Wells Criterion

Criteria	7b - Should not be within 1500 m of a water well
Source Layer	Existing Wells
Values in source layer	Values are the distance in meters of a location from an existing water well.
Source of Uncertainty	The values are continuous and the breakpoint between a suitable distance for well in relation to an existing well is not well defined.
Definitely Suitable	Locations furthest from an existing well are definitely suitable.
Definitely Unsuitable	Areas within 1500 m from an existing well are definitely unsuitable.
Suitability Range/ Variation in range	The suitable range is 1500 m to the maximum distance in a study area. The Euclidean Distance layer was clipped to the study area to identify the furthest distance from a well within the study area. The cell values range from 0 to 6680 because the distance extends outside of the study area.
Membership Function	The membership function used was linear. The maximum was set to 6680 and the minimum was set to 1500.

Figure 23 shows the fuzzy membership values for the existing wells layer.

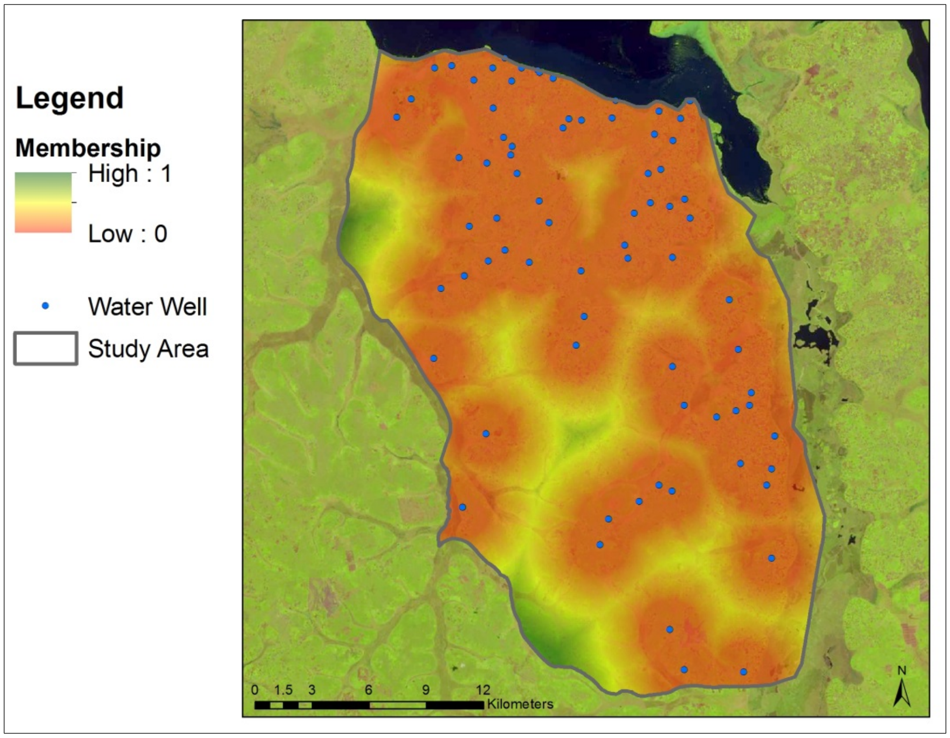

Figure 23 Map of Membership of Criterion 7b

4.4 Fuzzy Suitability Overlay Results

To combine the fuzzy membership layers, the *And* operator was used, which assigns the minimum values from all the input fuzzy membership layers to the output cell. This operator identifies the least common denominator for the membership criteria, producing a more conservative (or exclusive) result with smaller overall membership values. This allows cells with membership of a specific minimum value of a criterion to be identified. Figure 24 shows the suitability map resulting from the fuzzy overlay of all criteria except the existing wells.

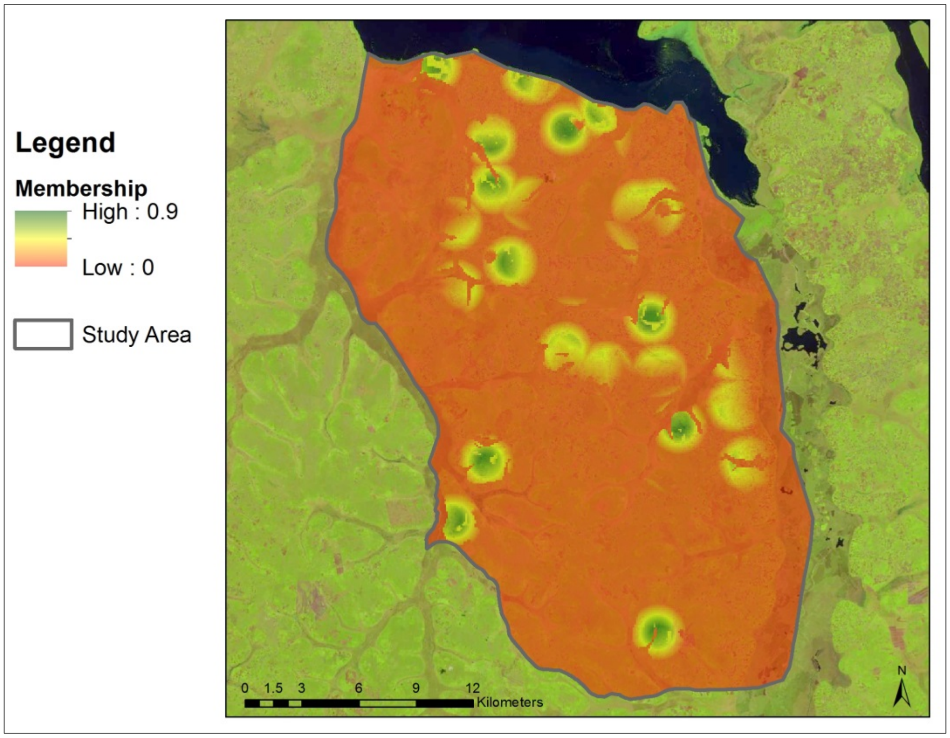

Figure 24 Overall Suitability Map based on Refined Model

Due to the exclusive nature of the *And* overlay type, and because it assigns values based on the lowest common denominator for all criteria, the majority of the study area has been disqualified. This is good because it removes from consideration a large part of the region and now the site survey teams can focus on a limited number of suitable areas.

The metric used to define suitable locations in this study is greater than or equal to.5. The suitability range above the .5 cut-off values shows up in most of the graphics below as values that are yellow to green.

While the study area is mostly unsuitable, it is not as exclusive at is appears. Many of the unsuitable locations are in remote areas where there is low need for water well. In more populated areas, where there is more need, the suitability map shows some range in suitability.

Figure 25 shows the distribution of populated places and schools and reveals the suitable membership values are generally aligned with the distribution of infrastructure.

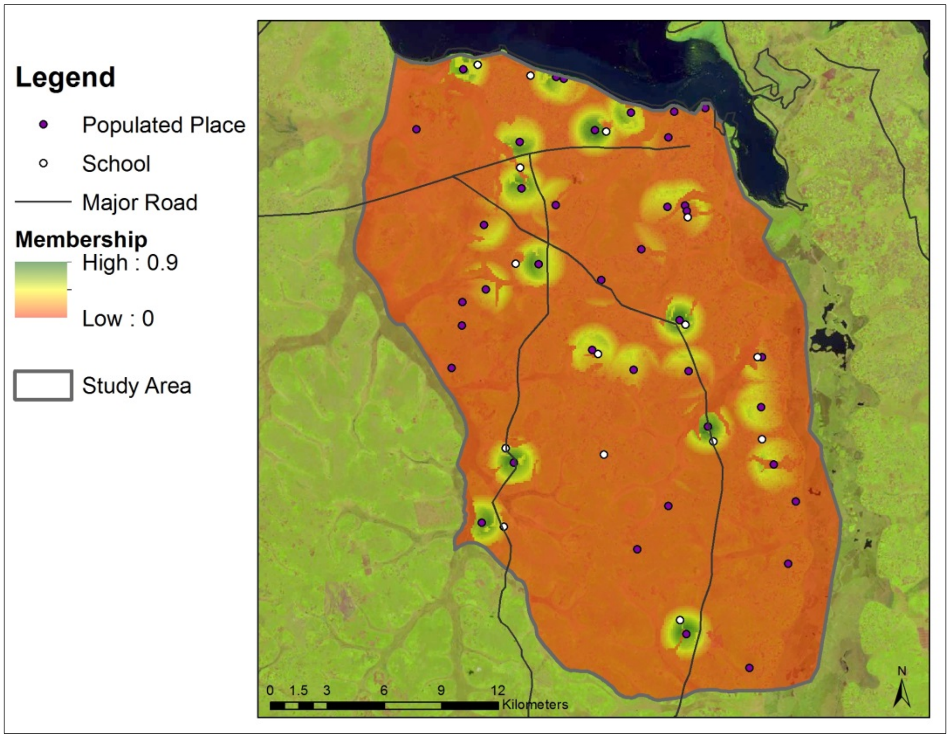

Figure 25 Membership based on Refined Model and Infrastructure

4.5 Iterative Model Fitting

As mentioned above, the distances and methods used to analyze a criterion were refined through an iterative process. In this section, the process used to refine the model is described. The results of the refined model are evaluated in the next section.

The first implementation using initial distance limits yielded poor results. When the existing wells were used to evaluate the results, there were no existing wells in what the model identified as suitable locations. Furthermore, the criteria and initial distances yielded a membership scale 0 to .4. This meant that there were no areas above .4 overall membership when all criteria are combined (see Figure 26).

By adjusting the distance limits and methods for the criteria, the refined implementation yielded 10 existing wells in locations deemed suitable by the model. This is 13 percent of the wells (see Figure 27). Additionally, the membership scale improved from .4 to .9. The iterative modeling fitting process used to improve the model is described below.

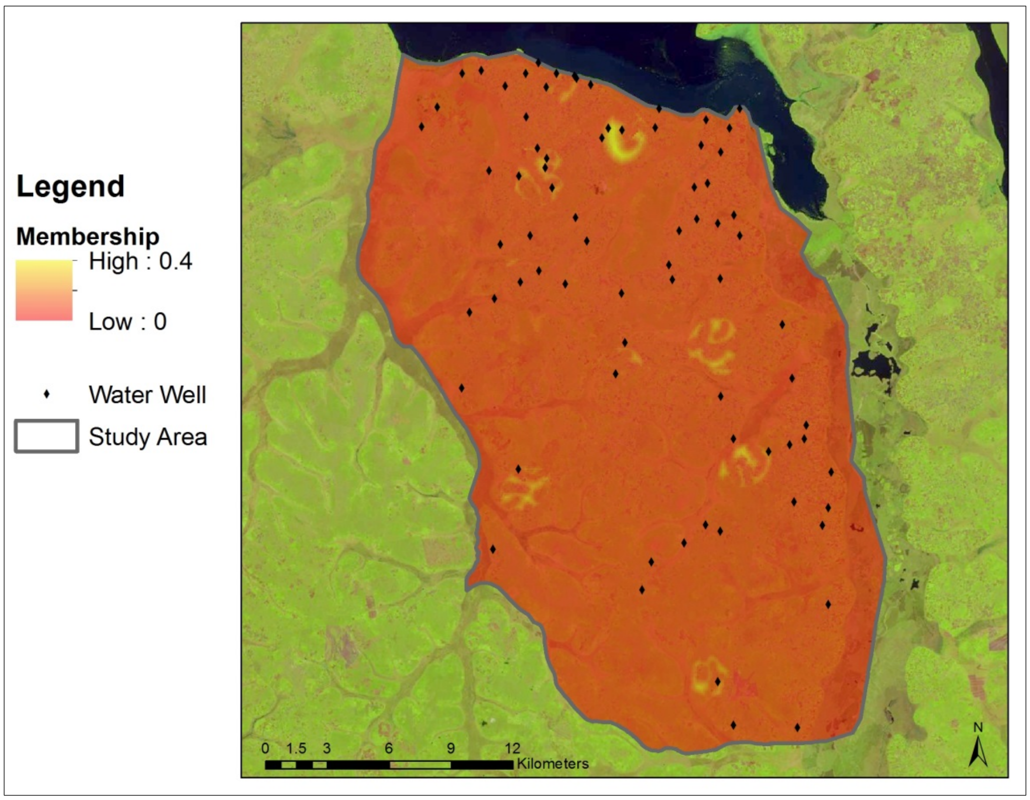

Figure 26 Preliminary Suitability Map

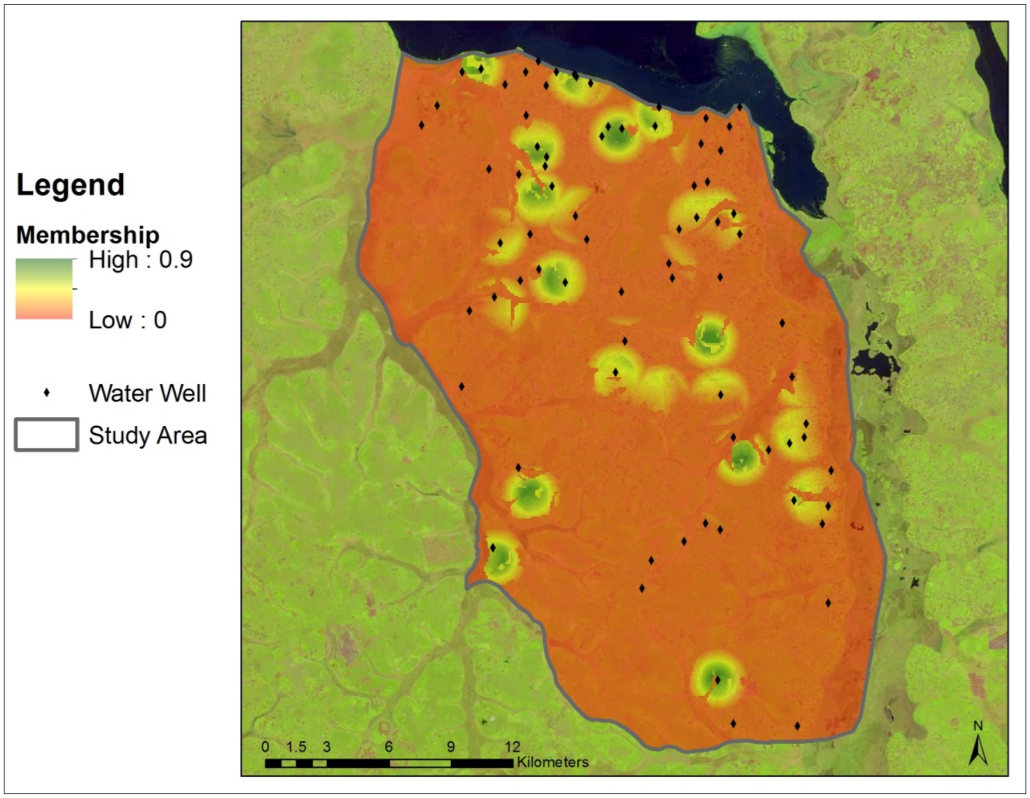

Figure 27 Refined Suitability Map with Existing Wells

In addition to evaluating the combined suitability score, each criterion was evaluated individually. Table 17 shows the performance of the preliminary and refined models for each criterion and lists the changes made in the refined model.

Table 17 Model Refinements and Improvements

Criteria	# of Wells in suitable areas		% Improved	Change in Method
	Preliminary Model	Refined Model		
1a - Should not be in the flow path of human waste	72	72	-	No Change
2a - Should not be within a wetland	0	69	N/A	The first implementation used the ATP layer for both the wetlands and stagnant water criteria. The refined model separated the layer. For the wetlands the grid was divided into yes/no. The first implementation used cost distance to buffer the distance. This was removed because it was identifying many existing wells that were located on the edge of a wetland.
3a - Should not be within an area with stagnant water	0	71	N/A	The refined model has higher uncertainty of the depressions areas. This is due to low confidence in the methods used to derive depressions.
4a - Should be on a slope of less than 16 percent	76	76	0%	No change
4b - Should be within 4000 m of a major road	32	46	18%	The first implementation set the suitability range to 2000 m. This was determined to be too exclusive and the range was increased to 4000 m.
6a - Should be within 3000 m of a school	11	31	26%	The suitability range was increased to 3000 m from 1500 m.
7a - Should be within 1500 m of a populated place	22	38	21%	The range was not changed because clean water coverage is defined by the UN as 1500 m. The populated places layer was enhanced with more populated places through methods described above.

In summary, after refinement, the count of existing wells located in areas identified as suitable (greater than or equal to .5 membership) increased from 0 to 10. Therefore based on the refined model, 13% of the 76 existing wells are in overall suitable areas.

The refined model clearly shows improvement with respect to the number of existing wells that fall in suitable locations. Refinement to produce the model described in this chapter was accomplished by modifying the suitability distances for individual criteria and analyzing the results. It is suggested that a user perform a similar model fitting refining process when the model is implemented.

4.6 Evaluating Results of Refined Model

In this section, the results of the refined model implementation are evaluated by assessing the suitability of the location of existing wells. To evaluate the results, values were extracted from all fuzzy layers for the 76 existing well point locations using the *Extract Multi Values to Points* tool. The resulting attribute table was imported into Excel for evaluation for analysis. When each of the 76 wells is considered individually on each of the 7 criteria (76x7 = 532 fuzzy membership estimates), 76 percent of the estimates are suitable (greater than or equal to 0.5 membership). This is an improvement of the preliminary model which resulted in 36 percent of the estimates being suitable. Table 18 shows the suitability classification used to evaluate the suitability of existing well locations. The values were summarized and are shown in Table 19. In the evaluation, areas with membership values of .5 or greater are considered suitable.

Table 18 Suitability Classification

Membership Range	Membership Index
.75-100	Most Suitable
.50 - 749	Suitable
.25 - .499	Not Suggested
0 - .249	Not Suitable

Next, the spatial distribution of existing wells is discussed individually for each criterion. Then following the figures and discussion, two summary tables are presented (Table 20 and 21). A complete list of existing wells and their membership values for each criterion is available in Appendix 1 and 2 for the preliminary model and refined model respectively.

Table 19 Existing Well Distribution in Suitable Zone

Criteria	Count of Wells in Suitable Locations	Percent in Suitable Locations
1a - Should not be in the flow path of human waste	72	95%
2a - Should not be within a wetland	69	91%
3a - Should not be within an area with stagnant water	72	95%
4a - Should be on a slope of less than 16 percent	76	100%
4b - Should be within 4000 m of a major road	46	61%
6a - Should be within 3000 m of a school	31	41%
7a - Should be within 1500 m of a populated place	38	50%
Total Suitability	10	13%

Figure 28 shows the spatial distribution of wells in the suitability zones for the human waste contaminant flow criterion. There are three wells close together in unsuitable locations in northern area of the study area. The reason for this grouping is unknown and should be investigated in a field visit if feasible. Additionally there are only a few wells in unsuitable locations dispersed throughout the study area in no apparent pattern. As the map shows, where an existing well is red (in an unsuitable location), there is generally a latrine located to the south-west of that well. This is consistent with the general slope of the area with a subtle decrease in elevation moving from the southwest to northeast (toward Lake Kyoga). Therefore the results of this membership criteria analysis are consistent with slope which was used to determine the direction of contaminant flow.

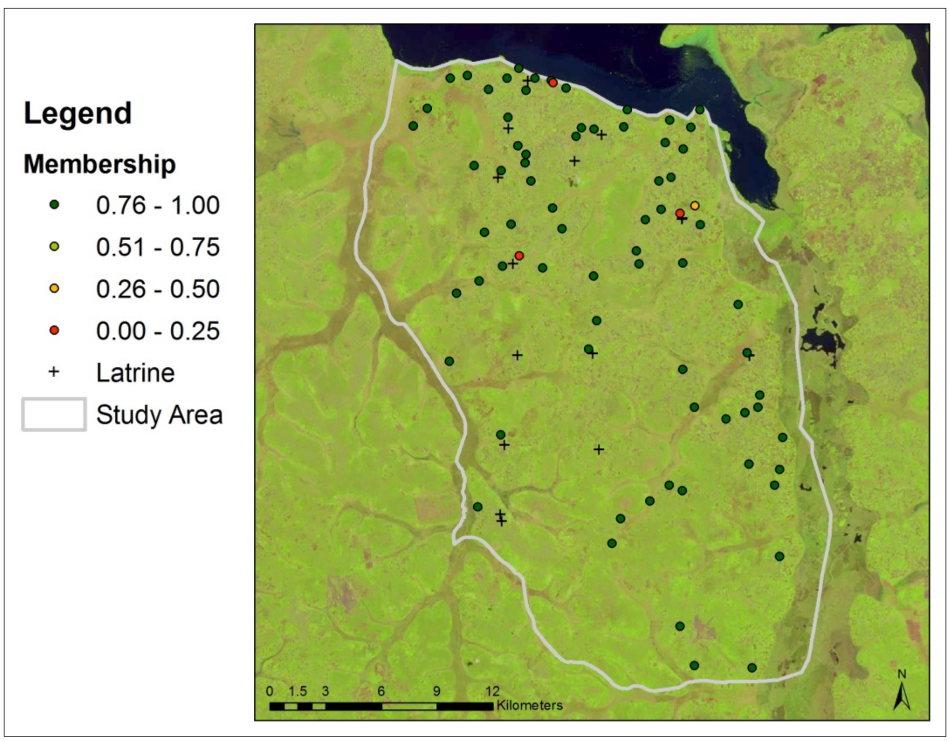

Figure 28 Existing Wells with Contaminant Flow Membership Value

Figure 29 shows the spatial distribution of wells in the suitability zones for the wetlands criterion. There are five wells located in unsuitable locations in the northern region of the study area. Further investigation is needed to understand these locations better. Visual analysis of the elevation data revealed non-suitable locations are located in areas that appear to be in lowlands.

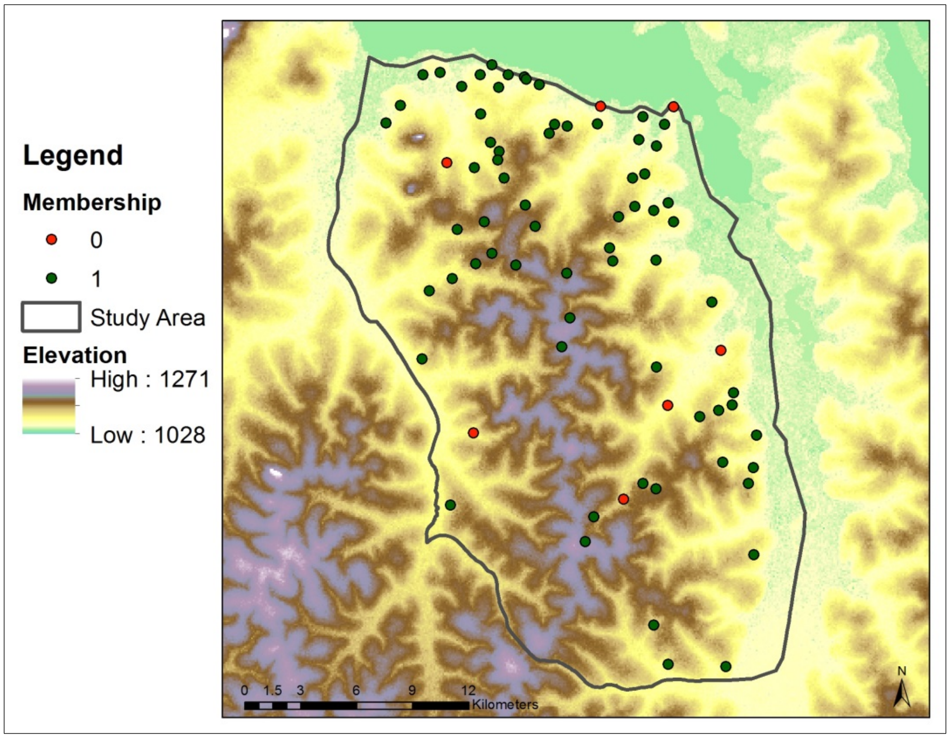

Figure 29 Existing Wells with Wetlands Membership Value

Figure 30 shows the spatial distribution of wells in the suitability zones for the stagnant water criterion. The membership scale ranges from .4 to 1 as described above. This is represented in the legend of Figure 30. An analysis of elevation data revealed the existing wells with low membership are in areas with lower elevations where slope is smaller.

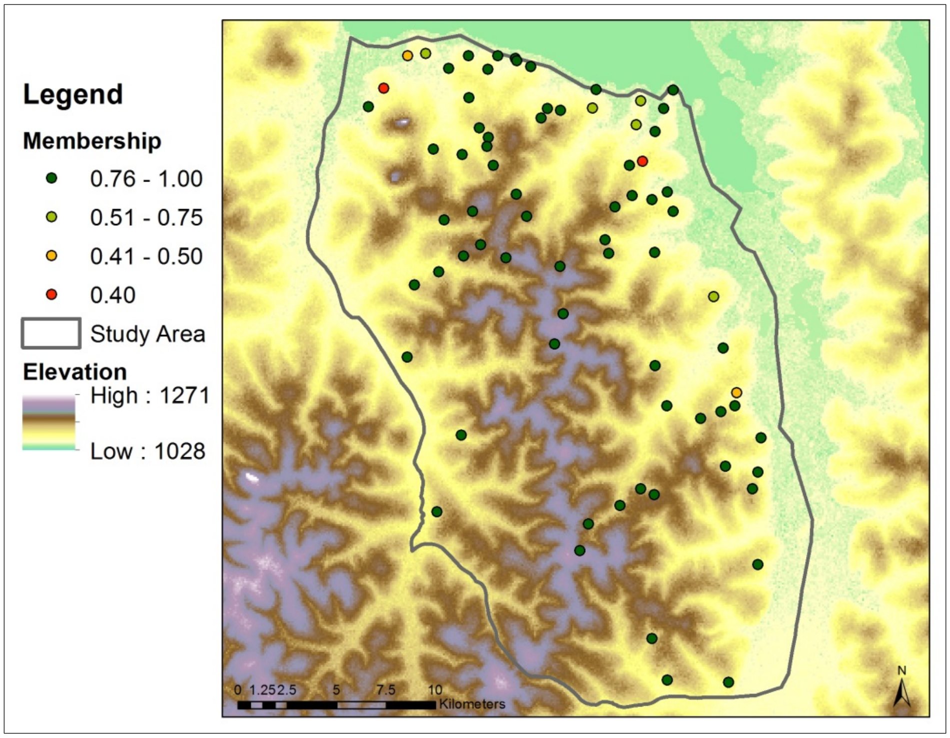

Figure 30 Existing Wells with Stagnant Water Membership Value

Figure 31 shows the spatial distribution of wells in the suitability zones for the percent slope criterion. The lowest membership for the slope criteria is .71. Therefore, there are only two categories symbolized in the map, suitable and most suitable. Percent slope did not disqualify any wells from membership in the study area. This is because the area is generally flat. However, the topography in other areas of sub-Saharan Africa can have a higher frequency of elevation change. Therefore it is likely to be more restrictive in other contexts.

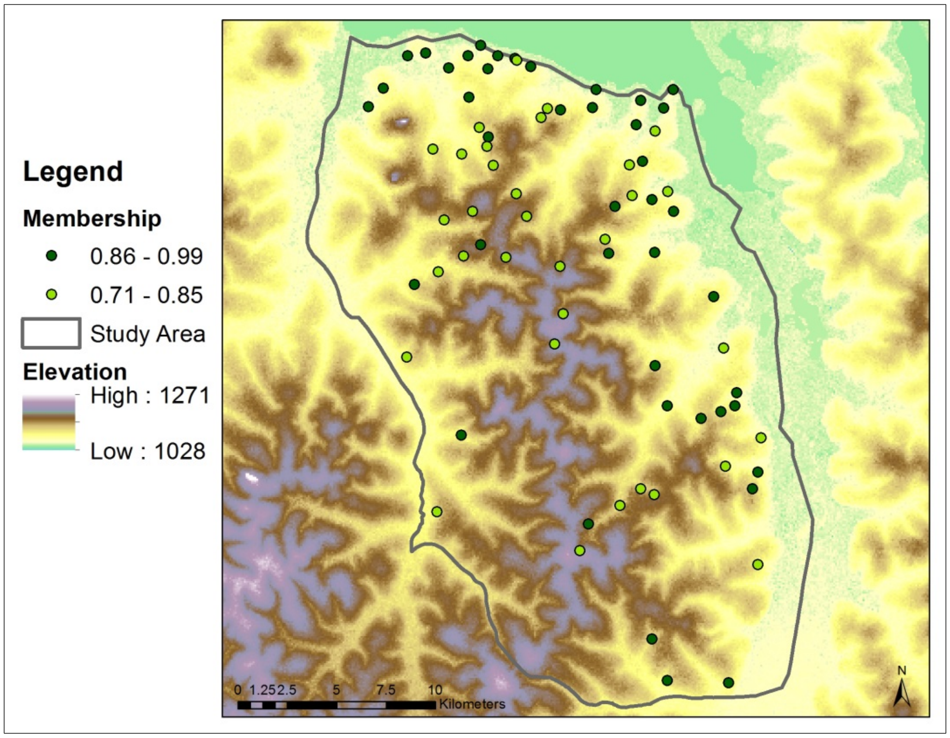

Figure 31 Existing Wells with Slope Membership Value

Figure 32 shows the spatial distribution of wells in the suitability zones for the major roads criterion. As discussed earlier there are four major roads in the study area. This criterion helps to identify and then disqualify more remote areas where the need is less severe. Of course, the extent this is true or valid depends on the number of roads in an area. The map shows the expected results that membership values depreciate the further a well is from a major road.

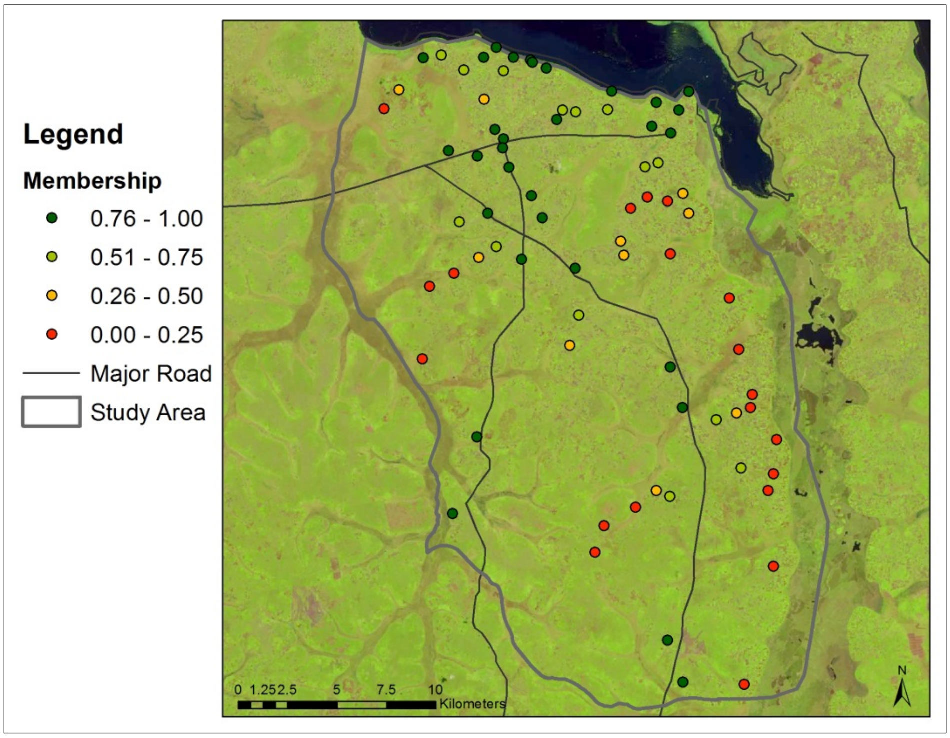

Figure 32 Existing Wells with Major Roads Membership Value

Figure 33 shows the spatial distribution of wells in the suitability zones for the schools criterion. The map shows the wells in proximity to schools are given membership into the suitability set. It is also observed that there is a higher rate of depreciation of membership outside of the 3000 m suitable area.

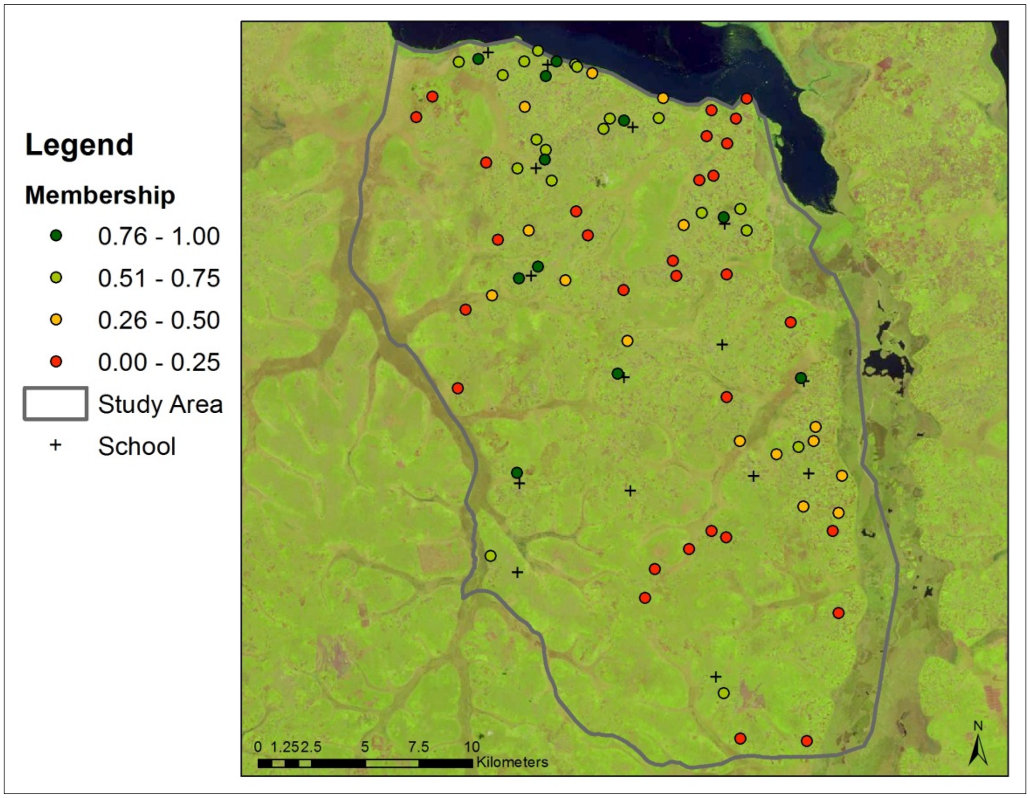

Figure 33 Existing Wells with the Schools Membership Value

Figure 34 shows the spatial distribution of wells in the suitability zones for the populated place criterion. The populated places are dispersed throughout the study area.

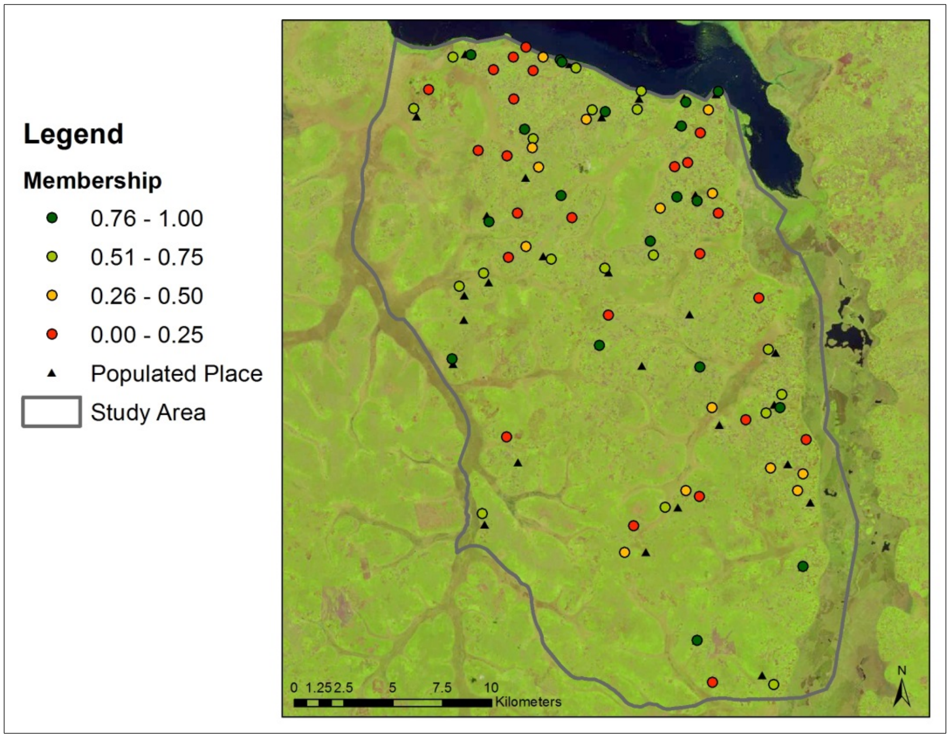

Figure 34 Existing Wells with the Populated Places Membership Value

After the review of all criteria and a cross evaluation with satellite imagery, it was confirmed the analysis of the criteria and the resulting membership values are congruent with what is known about the study area. For a numerical summary of the membership values, Table 20 shows the number of existing wells in each suitability zone and Table 21 shows the percentages. The second column shows the membership index created to assist in the visualization of the distribution of wells by suitability zones. These color ranges were used in Figures 28 to 34.

Table 20 Distribution of Existing Wells in Membership Zones by Criteria

Membership Range	Membership Index	Contaminant Flow	Wetlands	Stagnant Water	Slope	Schools	Roads	Populated Places
.75-100	Most Suitable	72	69	66	68	11	32	19
.50 - 749	Suitable	0	0	5	8	20	14	19
.25 - .499	Not Suggested	1	0	4	0	15	10	14
0 - .249	Not Suitable	3	7	0	0	30	20	24

Table 21 Percent Distribution of Existing Wells in Membership Ranges by Criteria

Membership Range	Membership Index	Contaminant Flow	Wetlands	Stagnant Water	Slope	Schools	Roads	Populated Places
.75-100	Most Suitable	95%	91%	87%	89%	14%	42%	25%
.50 - 749	Suitable	0%	0%	7%	11%	26%	18%	25%
.25 - .499	Not Suggested	1%	0%	5%	0%	20%	13%	18%
0 - .249	Not Suitable	4%	9%	0%	0%	39%	26%	32%

As Table 20 shows, there is a higher count of existing wells in the suitable zones for the of wetlands, stagnant water and slope criteria, while there is a lower count for the schools, populated places and roads criteria. The lower count is likely due to the restrictive distance metrics used to evaluate the criteria. The distribution of existing wells in membership ranges for the overlay suitability is in Appendix 3.

In this chapter, the general framework was implemented as a model in Uganda. The methodology and data used to evaluate criteria was described. Then the results of the refined model were discussed. Next, the iterative model fitting process was described and the resulting modifications to the model were presented. Even with the improvements, there is future work that can be done to improve the model. These opportunities are discussed in the next chapter.

CHAPTER 5: SUMMARY AND CONCLUSION

This study developed a general framework to identify potential water well sites where risks are minimized and benefits are maximized in rural sub-Saharan Africa. In summary, the research had a threefold purpose of: building upon current research on clean drinking water in sub-Saharan Africa and fuzzy methods for suitability analysis; creating a suitability framework that could be implemented by NGOs and governments throughout sub-Saharan Africa; and developing a refined model that applies the framework in a specific context in sub-Saharan Africa. The necessary research included reviewing literature on risks to clean water, developing a means to evaluate criteria, and developing methods to analyze the criteria in a GIS.

5.1 Assessment of model success

Fuzzy logic was a useful method for this application because it prevented a false appearance of confidence in the data. Fuzzy logic allowed for low confidence to be captured in the method. For example, due to low confidence of how the stagnant water data was derived, higher membership was assigned. Fuzzy methods were used to represent the fuzziness that was inherent in the data. This was especially useful for data layers that needed to be resampled to ensure co-registration.

In working to develop a suitability framework, a number of requirements were involved. The first focus of the framework was to approach suitability in a manner that minimized risk. This was done by identifying several potential sources of contamination in sub-Saharan Africa. Research into risks to clean water in sub-Saharan Africa yielded seven general risks to drinking water in the region. Several of these can be analyzed simply with widely available data (elevation and lowlands). Others are more difficult to analyze (such as the flow of a contaminant). Despite data limitations, in particular no data about groundwater, a method was created to predict a probable path of a surface or near-surface contaminant. In the implementation of the model, it was shown how globally available 90 m DEM can be used to model the likely flow path of a surface or near surface contaminant based on slope.

The second focus of the framework was to maximize the benefits by identifying areas where access to clean water would most benefit people living in an area of interest. To support this, schools, health facilities, and populated places were identified as places near which clean water would be a particular benefit. Using the standard definition of clean water access, an ideal location for a clean water well will, thus, be within 1.5 km of a populated place.

The application of this data to the specific context of this remote area in Uganda revealed some areas of success and some areas that needed adjustments. The improvements made to the poorly performing preliminary model through a process of model fitting and evaluation using locations of existing wells in the study area resulted in a better model. The preliminary model used distances and methods that were revealed to be too exclusive to yield helpful results. The criteria used to analyze the probable flow path of a surface/near surface contaminant yielded good results and did not need to be modified. The buffer initially used around the wetlands was removed because a significant number of existing wells are located near the edge of a wetland. The membership scale for the stagnant water criteria was modified due to uncertain methods used to derive the layer. There was no change to the slope layer. The suitability buffer was extended for the major roads, and schools. There was no change to the populated places criteria to ensure the model supports the 1.5 km definition of access to clean water.

The refined model more capably identifies suitable locations of existing wells. The model fitting process led to the overall suitability membership scale increasing from .4 to .9 (using the And operator). It also led to 10 existing wells being in locations deemed suitable by the model, this was up from 0. Additionally, it led to 76 percent of the criteria estimates being suitable, which is an increase from 36 percent. This 76 percent is helpful to evaluate the distance and method to evaluate a criterion. When all of the layers are combined to one suitability map, the percent goes down substantially from 76 percent average per criteria to 13 percent. This shows that while the model operates at an acceptable rate (76 percent) on an individual criterion basis, adding more criteria makes the model more exclusive.

An overall suitability analysis using all eight criteria, including proximity to existing wells, creates an exclusive result. The membership scale ranges from 0 to 0.3 (see Figure 35), with no locations achieving the 0.5 suitability cut-off value. The majority of the study area has very low membership.

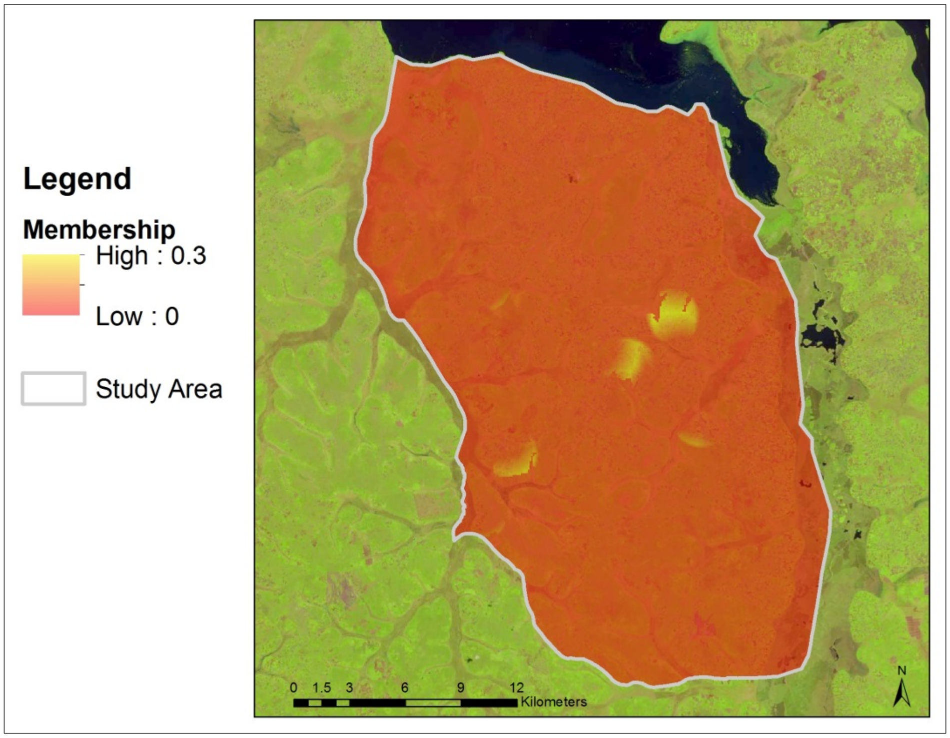

Figure 35 Suitability Map with Existing Wells Criteria

This demonstrates the value of including an evaluation mechanism in the model development process. In this study, the locations of existing wells were used to evaluate the model, but a better option for future work is to field test the results.

5.2 Future Work

While the refined model showed better performance, it can be further improved in several ways. Field research for further investigation into the wells that scored low on the membership scale is needed. This can provide more information about why the wells were installed in areas deemed unsuitable by the model. It can also identify how the wells are constructed and protected, and can confirm if they need to be relocated. Field research can also help identify inappropriate criteria in the general framework.

Once a field check is completed, the results of a model, such as the suitability map created in this implementation study, can be used as a decision support tool for water well planning. The model was able to identify areas of high risks based on multiple criteria. As higher resolution data and more types of data become available, the criteria can be modified and improved. It is hoped the general framework and the implemented model outlined here can serve as a foundational tool that NGO practitioners will continue to improve.

The framework was developed remotely and can therefore continue to be improved with local knowledge. It is likely that as research continues more criteria will be added to the framework. Additionally, a user in the field may also be able to acquire higher resolution data that will likely improve the performance of the framework.

5.3 General applicability of this research

Since many of the risks to clean water also exist outside of sub-Saharan Africa, the framework can be used in other regions. The thirteen criteria were developed by researching universal risks to clean water and risks specific to sub-Saharan Africa. Using this general framework, a user is easily able to select only the relevant risks and to add additional ones that may be appropriate.

The use of the fuzzy membership function is an important part of the framework because it allows a user to set membership ratings based on whether or not a criterion is about a risk or a social benefit. The shape of the membership function can be chosen for each criterion based on knowledge about the uncertainty. Here the linear function was deemed most appropriate. The framework included suitability factors that are good and bad and therefore the ability for a user to set each membership value uniquely with a positive or negative slope based on input values was critical. When a user implements the framework, the choice of fuzzy membership function will be a key component of the framework.

When the framework is implemented it can improve the workflow used by an NGO or government to determine where a well should be located. The benefits of using the framework include disqualifying for consideration locations that have higher risks or do not provide high social benefits. The framework also demonstrates how a GIS based tool can be used to evaluate several criteria with one suitability map.

The tool does not however capture all the dimensions involved in deciding where a clean water well should be. As mentioned earlier, there are several cultural, political, and social elements that factor into the decision. The framework can however, be used to supplement decision making as a macro level tool.

At the beginning of this project, the goal was for the model to perform with better results. As expected, data availability was a challenge, but this challenge was mitigated by creating alternative methods and using different data to analyze risks to clean water. Thus, it is felt that this general framework can be of use to an NGO despite poorer results than desired in the implementation study.

The work in this project lays the foundation for future developments. The criteria in the general framework and the measures used in the model can continue to be refined by users as they customize the model for their context. While the model performed at an adequate level, the work generally offers some suggestions for how such a GIS-based conceptual framework can be used by NGOs and governments to improve water well planning to provide better coverage of safe drinking water in sub-Saharan Africa.

REFERENCES

Adam, S., N. Henninger, and F. Landsberg. 2009. *Mapping a Healthier Future: How Spatial Analysis Can Guide Pro-Poor Water and Sanitation Planning in Uganda.* Uganda Ministry of Health, Uganda Ministry of Water and Environment, Uganda Bureau of Statistics, International Livestock Research Institute and World Resources Institute. http://www.wri.org/publication/mapping-healthier-future (last accessed 23 October 2014).

Awuah, E., K. Nyarko, P. Owus, and K. Osei-Bonsu. 2008. Small town water quality. *Desalination* 248 (1): 453-459.

Bartram, J. and J. Platt. 2010. How health professionals can leverage health gains from improved water, sanitation and hygiene practices. *Perspectives in Public Health* 130(5): 215-221.

BBC. 2006. Somalis clash over scarce water. *BBC News*. February 17, 2006. http://news.bbc.co.uk/go/pr/fr/-/1/hi/world/africa/4723008.stm (last accessed 10 October 2014).

California State Resources Control Board. 2011. *A Guide for Private Domestic Well Owners*. http://www.waterboards.ca.gov/gama/docs/wellowner_guide.pdf (last accessed 14 August 2014).

Chalkias, C., M. Ferentinou, C. Polykretis. 2014. GIS Supported Landslide Susceptibility Modeling at Regional Scale: An Expert-Based Fuzzy Weighting Method. *International Journal of Geo-Information* 3(2): 523-539.

Danert, K. 2014. Drilling Deep in Sub-Saharan Africa. *Water World* 26(1): no page.

http://www.waterworld.com/articles/wwi/print/volume-26/issue-1/regional-spotlight-middle-east-africa/drilling-deep-in-sub-saharan-africa.html (last accessed 27 August 2014).

Dufour, A., J. Bartram, R. Bos and V. Gannon. 2012. *Animal Waste, Water Quality and Human Health*. Emerging Issues in Water and Infectious Disease Series, World Health Organization.

Demesouka, O., A. Vavatsikos and K. Anagnostopoulos. 2014. GIS-based multicriteria municipal solid waste landfill suitability analysis: A review of the methodologies performed and criteria implemented. *Waste Management & Research* 32(4): 270-296.

Egeru, A., and M. Majaliwa. 2009. Landuse/Cover Change Trend in Soroti District Eastern Uganda. *Journal of Applied Sciences and Environmental Management* 13(4): 79.

EPA (Environmental Protection Agency). No date. *Getting Up to Speed: Ground Water Contamination*. http://www.epa.gov/region1/students/pdfs/gwc1.pdf (last accessed 26 July 2014).

Esri. 2014. *How Fuzzy Membership works*. http://resources.arcgis.com/en/help/main/10.1 /index.html#//009z000000rz000000 (last accessed 21 October 2014).

Faeth, P. and E. Weinthal. 2012. How Access to Clean Water Prevents Conflict. *Solutions* 3(1): no page. http://www.thesolutionsjournal.com/node/1037 (last accessed 10 October 2014).

Farmer, S. No date. *Ventilated Improved Pit Latrine.* Schumacher Centre for Technology & Development. https://www.engineeringforchange.org/static/content/Sanitation /S00040/vip_latrines.pdf (last accessed 30 July 2014).

Hillie, M. and M. Hlophe. 2007. Nanotechnology and the challenge of clean water. *Nature Nanotechnology* 2(11): 663-664.

Jakhrani, A., S. Samo, and I. Nizamani. 2009. Impact of Wastewater Effluents on Physico-Chemical Properties of Groundwater**.** *Sindh Univ. Res. Jour. Sci. Ser.* 41(1): 75-82.

Kelly, M. 2013. The MDG Enterprise: Experiences and Thoughts from Zambia. *IDS Bulletin* 44(5-6): 34–41.

Kihoro J., N. Bosco and H. Murage. 2013. Suitability analysis for rice growing sites using a multicriteria evaluation and GIS approach in great Mwea region, Kenya. *SpringerPlus* 2:265. http://www.springerplus.com/content/2/1/265 (last accessed 24 July 2014).

Lewis, L. No Date. *Rural and Urban Water Issues in Africa*. The Water Project. http://thewaterproject.org/pdf/rural-and-urban-water-issues-africa.pdf (last accessed 24 July 2014).

MacDonald, A, J. Davies, and B. Dochartaigh. 2002. *Simple methods for assessing groundwater resources in low permeability areas of Africa.* British Geological Survey, Department for International Development. http://www-esd.worldbank.org/esd/ard/groundwater/ pdfreports/Simple_%20methods_African_lowperm_areas_Pt1.pdf (last accessed 23 October 2014).

Mitchell, A. 2012. *The Esri Guide to GIS Analysis, Volume 3: Modeling Suitability, Movement, and Interaction*. Redlands, CA: Esri Press.

Muruli, J. 2009. *Higher Local Government Statistical Abstract: Nakasongola District.* Uganda Bureau of Statistics. http://www.ubos.org/onlinefiles/uploads/ubos /2009_HLG_%20 Abstract_printed/Nakasongola-Final%208-02-10.pdf (last accessed 27 August 2014).

Nobre, R., O. Rotunno Filho, W. Mansur, M. Nobre, and C. Cosenza. 2007. Groundwater vulnerability and risk mapping using GIS, modeling and a fuzzy logic tool. *Journal of Contaminant Hydrology* 94(7): 277-292.

Olsen, J., and L. Berry. 2004. *Uganda - Extent and impact of Land degradation*. Food and Agriculture Organization of the United Nations. http://www.fao.org/nr/lada/index.php?option=com_docman&task=doc_download&gid=481&Itemid=165&lang=en (last accessed 24 July 2014).

Ongley, E. 1996. *Control of water pollution from agriculture*. Rome: Food and Agriculture Organization of the United Nations. http://www.fao.org/docrep/w2598e/w2598e00.htm (last accessed 23 October 2014).

Qui, F., B. Chastain, Y. Zou, C. Zhang, and H. Sridharan. 2014. Modeling land suitability/capability using fuzzy evaluation. *GeoJournal* 79: 167–182. http://www.utdallas.edu/~ffqiu/published/2014QiuetalGeoJournal.pdf (last accessed 14 August 2014).

Raghuram, S. 2008. The MDGs in a World of Multiplying Inequalities and Differentiating Complexities. *Development* 51 (2): 241-244.

Reuter H., A. Nelson, and A. Jarvis. 2007. An evaluation of void filling interpolation methods for SRTM data. *International Journal of Geographic Information Science* 21(9): 983-1008.

Rural Water Supply Network. 2010. *Siting of Drilled Water Wells. A Guide for Project Managers.* http://www.sswm.info/sites/default/files/reference_attachments

/CARTER%20et%20al%202010%20Siting%20of%20Drilled%20Water%20Wells.pdf (last accessed 26 July 2014).

Tsiko, R., and T. Haile. 2011. Integrating Geographical Information Systems, Fuzzy Logic and Analytical Hierarchy Process in Modelling Optimum Sites for Locating Water Reservoirs. A Case Study of the Debub District in Eritrea. *Water* 3(1): 254-290.

Üçisik, A., and P. Rushbrook. 1998. *The Impacts of Cemeteries on the Environment and Public Health.* WHO Regional Office for Europe. http://whqlibdoc.who.int/euro/1998-99/eur_icp_ehna_01_04_01(a).pdf (last accessed 12 August 2014).

Uganda Ministry of Health. 2014. Malaria Prevention in Uganda. http://health.go.ug/mcp/mpre.html (last accessed 24 July 2014).

UNICEF (United Nations Children’s Fund). 1999. *Towards Better Programming: A Water Handbook.* United Nations Children’s Fund Programme Division. http://www.sswm.info/sites/default/files/reference_attachments/UNICEF%201999%20Water%20Handbook.pdf (last accessed 15 July 2014).

UNICEF and World Health Organization. 2012. *Progress on Drinking Water and Sanitation. 2012 Update*. WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation. http://whqlibdoc.who.int/publications/2012/9789280646320_eng_full_text.pdf?ua=1 (last accessed 16 June 2014).

United Nations. 2000. *United Nations Millennium Declaration.* General Assembly Agenda item 60 (b) 00 55951. Resolution adopted by the General Assembly. http://www.un.org/millennium/declaration/ares552e.pdf (last accessed 23 October 2014).

--------. 2012. *The Millennium Development Goals Report 2012.* http://www.un.org/millenniumgoals/pdf/MDG%20Report%202012.pdf (last access 24 July 2014).

--------. 2013. *The Millennium Development Goals Report 2013*. http://www.un.org/millenniumgoals/pdf/report-2013/mdg-report-2013-english.pdf (last accessed 24 July 2014).

UNDP (United Nations Development Programme). 2004. *Water Resources Management, Environmental Degradation and Human Welfare: Lessons Learned from the Lake Kyoga Catchment in Uganda.* Policy Brief. UNDP-UNEP Poverty-Environment Initiative. http://www.unpei.org/sites/default/files/e_library_documents/Uganda-Policy-brief-WaterResourceManagement.pdf (last accessed 14 August 2014).

University of Illinois at Urbana – Champaign Water Resources Center. 1990. *Planning Your Well: Guidelines for Safe Dependable Drinking Water.* http://web.aces.uiuc.edu/vista/pdf_pubs/PLANWELL.PDF (last accessed 7 October 2014).

USGS (United States Geological Survey). 2008. Shuttle Radar Topography Mission. http://srtm.usgs.gov/mission.php (last accessed 24 July 2014).

--------. 2014. Elevation Derivatives for National Applications (EDNA): Compound Topographic Index (CTI). http://edna.usgs.gov/edna/datalayers/cti.asp (last accessed 24 July 2014).

Van der Wal, A., 2010. *Understanding Groundwater & Wells in manual drilling: Instruction handbook for manual drilling teams on hydro-geology for well drilling, well installation* *and well development.* Papendrecht, The Netherlands*:* PRACTICA Foundation. http://www.unicef.org/wash/files/04.pdf (last accessed 23 October 2014).

WaterAid. 2008. *Technology Notes*. WaterAid. http://www.sswm.info/library/3546 (last accessed 4 July 2014).

WHO (World Health Organization). 2014. Water Sanitation Health. Water-related diseases: information sheets. http://www.who.int/water_sanitation_health/diseases/diseasefact/en/ (last accessed 23 October 2014).

World Weather Online. 2014. Soroti Monthly Climate Average, Uganda. http://www.worldweatheronline.com/Soroti-weather-averages/Soroti/UG.aspx (last accessed 23 October 2014).

APPENDIX 1 PRELIMINARY MODEL EXISTING WELL SUITABILITY VALUES

This data in the table below is of six criteria because in the preliminary model, the wetlands and stagnant water criteria were only treated as one criterion.

ID	Water Point Name	Wetlands	Slope	Roads	Schools	Populated Places	Contaminant Flow
1	Kazwama	0.1	0.9	0.9	0.4	0.6	1.0
2	Kamiga	0.0	0.8	0.7	0.0	0.8	1.0
3	Iryema	0.1	0.8	1.0	0.4	0.4	1.0
4	Kabandi	0.3	0.9	0.0	0.0	0.0	1.0
5	Kitaleba	0.0	0.9	0.8	0.0	0.0	1.0
6	Kalongo TC	0.0	0.8	0.8	0.0	0.3	1.0
7	Kiwambya	0.0	0.9	0.0	0.0	0.0	1.0
8	Nakinyama	0.1	0.9	0.0	0.0	0.0	1.0
9	Kinamwanga	0.0	0.8	0.3	0.0	0.0	1.0
10	Nakataka	0.1	0.9	0.0	0.3	0.4	0.2
11	Bagambira	0.1	0.9	0.9	0.0	0.8	1.0
12	Lutengo	0.0	0.9	0.0	0.0	0.5	1.0
13	Wanzogi	0.2	0.8	1.0	0.0	0.0	1.0
14	Rukooge	0.0	1.0	0.0	0.0	0.0	1.0
15	Kaisolo	0.2	0.9	0.0	0.0	0.0	1.0
16	Kiranga	0.0	0.9	0.0	0.0	0.6	1.0
17	Kigejjo	0.1	0.9	0.0	0.0	0.0	1.0
18	Kalalu	0.2	0.9	0.0	0.0	0.0	1.0
19	Kamirampango	0.0	0.8	0.0	0.0	0.0	1.0
20	Nalubobya	0.1	0.7	0.0	0.0	0.0	1.0
21	Kiwoole	0.1	1.0	0.1	0.0	0.0	1.0
22	kabazi	0.0	0.8	0.0	0.0	0.0	1.0
23	Kyalusaka Primary School	0.1	1.0	1.0	0.0	0.2	1.0
24	Kyalusaka	0.0	1.0	0.6	0.0	0.3	1.0
25	Irima	0.0	0.9	0.6	0.0	0.2	1.0
26	Kigazi	0.0	0.9	0.8	0.0	0.9	1.0
27	Bagambira Kyakabona	0.1	0.9	0.6	0.0	0.2	1.0
28	Dagala	0.0	0.9	0.9	0.4	0.0	1.0
29	Madaali	0.0	0.9	0.4	0.6	0.0	1.0
30	Kapundo	0.1	0.9	0.2	0.2	0.0	1.0
31	Ninga	0.0	0.9	0.5	0.6	0.0	1.0

ID	Water Point Name	Wetlands	Slope	Roads	Schools	Populated Places	Contaminant Flow
32	Kisenyi	0.0	0.9	0.4	0.2	0.0	1.0
33	kakoola	0.0	1.0	0.5	0.2	0.0	1.0
34	Nakinyama	0.0	0.8	0.6	0.0	0.0	1.0
35	Kigali	0.0	1.0	0.8	0.2	0.9	1.0
36	Ruunyu	0.0	0.7	0.8	0.7	0.4	1.0
37	Kyakabombo	0.2	0.8	0.0	0.0	0.0	1.0
38	Kisweramainda	0.0	0.9	0.9	0.6	0.1	1.0
39	Kaleire	0.1	0.8	0.6	0.0	0.0	1.0
40	Kigejjo	0.0	0.9	0.0	0.0	0.0	1.0
41	Nalukonge	0.2	0.9	0.0	0.0	0.0	1.0
42	Kinamwanga	0.0	0.8	0.3	0.0	0.0	1.0
43	Namungolo	0.0	0.9	0.0	0.0	0.3	1.0
44	Nakatuba	0.0	0.9	0.0	0.0	0.0	1.0
45	Kasozi	0.4	0.8	0.4	0.2	0.6	1.0
46	Iryema	0.1	0.9	1.0	0.7	0.4	1.0
47	Kabaandi	0.1	1.0	0.0	0.0	0.0	1.0
48	Kanyonyi	0.1	0.9	0.0	0.6	0.0	1.0
49	Rukooge	0.0	0.8	0.0	0.0	0.0	1.0
50	Kisenyi TC	0.0	0.9	0.9	0.0	0.0	1.0
51	Kasozi	0.1	0.8	0.4	0.6	0.8	1.0
52	Kalungi	0.0	0.8	1.0	0.0	0.0	1.0
53	Kitaleeba /katuugo	0.1	0.9	0.9	0.4	0.0	1.0
54	Kanyonyi	0.1	0.8	0.4	0.6	0.0	0.0
55	Nakataka	0.0	0.9	0.0	0.3	0.2	1.0
56	Kamirampango PS	0.1	0.9	0.0	0.8	0.0	1.0
57	Kaisolo	0.1	0.8	0.6	0.0	0.0	1.0
58	Nakataka	0.1	0.9	0.0	0.7	0.9	0.0
59	Bulwandi	0.2	0.8	0.0	0.0	0.9	1.0
60	Kasambya SW	0.0	1.0	0.8	0.1	0.9	0.0
61	Lutengo	0.0	0.8	0.0	0.0	0.9	1.0
62	Bagaya primary school	0.0	0.7	0.0	0.8	1.0	1.0
63	Bamungolode	0.0	0.9	0.7	0.5	0.9	1.0
64	Wanzogi primary schoo	0.1	0.9	0.3	0.0	0.8	1.0
65	kiranga	0.1	0.9	0.8	0.0	0.0	1.0
66	kyakabombo	0.0	0.9	0.0	0.1	0.0	1.0
67	Ndaiga DWD	0.0	0.9	0.9	0.0	0.9	1.0

ID	Water Point Name	Wetlands	Slope	Roads	Schools	Populated Places	Contaminant Flow
	41739						
68	Kiswerwa DWD 41743	0.2	0.7	0.8	0.0	0.9	1.0
69	Namungolo DWD 41742	0.2	0.8	0.0	0.2	0.9	1.0
70	Kalungi DWD 41740	0.1	0.8	0.7	0.0	1.0	1.0
71	DWD 41738	0.0	1.0	0.7	0.1	0.9	1.0
72	DWD 41771	0.1	0.8	0.1	0.0	0.0	1.0
73	DWD 41773	0.2	0.9	0.6	0.0	0.5	1.0
74	DWD 41770	0.1	0.9	0.4	0.0	0.1	1.0
75	DWD 41741	0.2	0.9	0.3	0.0	0.0	1.0
76	DWD 41772	0.0	0.8	0.0	0.0	0.0	1.0

APPENDIX 2 REFINED MODEL EXISTING WELL SUITABILITY VALUES

ID	Water Point Name	Contaminant Flow	Wetlands	Depressions	Slope	Schools	Roads	Populated Places
1	Kazwama	1.0	1.0	1.0	1.0	0.7	1.0	0.6
2	Kamiga	1.0	1.0	1.0	0.9	0.3	0.9	0.7
3	Iryema	1.0	1.0	1.0	0.8	0.7	1.0	0.4
4	Kabandi	1.0	1.0	1.0	0.9	0.0	0.0	0.6
5	Kitaleba	1.0	0.0	1.0	0.8	0.2	0.9	0.0
6	Kalongo TC	1.0	0.0	1.0	0.9	0.4	0.9	0.3
7	Kiwambya	1.0	0.0	1.0	0.8	0.0	0.2	0.5
8	Nakinyama	1.0	1.0	1.0	0.7	0.0	0.1	0.8
9	Kinamwanga	1.0	1.0	0.4	1.0	0.2	0.7	0.0
10	Nakataka	0.4	1.0	1.0	0.8	0.7	0.4	0.4
11	Bagambira	1.0	1.0	1.0	0.8	0.0	0.9	0.7
12	Lutengo	1.0	1.0	0.9	0.9	0.0	0.4	0.6
13	Wanzogi	1.0	1.0	1.0	0.8	0.3	1.0	0.0
14	Rukooge	1.0	1.0	0.9	0.9	0.0	0.2	0.7
15	Kaisolo	1.0	1.0	1.0	0.9	0.2	0.2	0.0
16	Kiranga	1.0	1.0	1.0	0.9	0.0	0.1	0.6
17	Kigejjo	1.0	1.0	1.0	0.9	0.1	0.2	0.4
18	Kalalu	1.0	1.0	1.0	0.8	0.5	0.0	0.0
19	Kamirampango	1.0	1.0	0.5	0.9	0.3	0.2	0.6
20	Nalubobya	1.0	1.0	1.0	0.8	0.0	0.0	0.3
21	Kiwoole	1.0	1.0	1.0	0.8	0.0	0.6	0.2
22	kabazi	1.0	1.0	0.7	0.9	0.1	0.1	0.0
23	Kyalusaka Primary School	1.0	1.0	1.0	0.8	0.0	1.0	0.2
24	Kyalusaka	1.0	1.0	1.0	0.9	0.0	0.8	0.3
25	Irima	1.0	1.0	0.7	0.9	0.0	0.8	0.8
26	Kigazi	1.0	1.0	0.7	0.9	0.0	0.9	0.9
27	Bagambira Kyakabona	1.0	1.0	1.0	0.8	0.0	0.8	0.1
28	Dagala	1.0	1.0	0.5	0.9	0.7	0.9	0.0
29	Madaali	1.0	1.0	0.9	0.9	0.8	0.7	0.0
30	Kapundo	1.0	1.0	1.0	0.9	0.6	0.6	0.0
31	Ninga	1.0	1.0	0.6	0.9	0.8	0.7	0.8
32	Kisenyi	1.0	1.0	0.5	0.9	0.6	0.7	0.6
33	kakoola	1.0	1.0	1.0	0.9	0.6	0.8	0.0
34	Nakinyama	1.0	1.0	0.4	1.0	0.5	0.8	0.6

ID	Water Point Name	Contaminant Flow	Wetlands	Depressions	Slope	Schools	Roads	Populated Places
35	Kigali	1.0	1.0	1.0	0.9	0.6	0.9	0.9
36	Ruunyu	1.0	1.0	1.0	0.9	0.8	0.9	0.4
37	Kyakabombo	1.0	1.0	1.0	0.9	0.5	0.2	0.8
38	Kisweramainda	1.0	0.0	1.0	0.9	0.8	0.9	0.0
39	Kaleire	1.0	1.0	1.0	0.8	0.5	0.8	0.6
40	Kigejjo	1.0	1.0	0.9	0.9	0.3	0.1	0.4
41	Nalukonge	1.0	1.0	1.0	0.9	0.0	0.0	0.0
42	Kinamwanga	1.0	1.0	1.0	0.7	0.2	0.6	0.0
43	Namungolo	1.0	1.0	1.0	0.9	0.4	0.1	0.3
44	Nakatuba	1.0	1.0	1.0	0.9	0.3	0.4	0.0
45	Kasozi	1.0	1.0	1.0	0.8	0.6	0.7	0.6
46	Iryema	1.0	1.0	1.0	0.8	0.8	1.0	0.3
47	Kabaandi	1.0	1.0	1.0	0.8	0.3	0.2	0.6
48	Kanyonyi	1.0	1.0	1.0	0.8	0.8	0.5	0.0
49	Rukooge	1.0	1.0	0.4	0.9	0.0	0.4	0.0
50	Kisenyi TC	1.0	0.0	1.0	0.9	0.3	1.0	0.7
51	Kasozi	1.0	1.0	1.0	0.9	0.8	0.7	0.8
52	Kalungi	1.0	1.0	0.9	0.8	0.5	1.0	0.7
53	Kitaleeba /katuugo	1.0	1.0	1.0	0.7	0.7	0.9	0.0
54	Kanyonyi	0.0	1.0	1.0	0.9	0.8	0.7	0.3
55	Nakataka	1.0	1.0	1.0	0.9	0.6	0.3	0.2
56	Kamirampango PS	1.0	0.0	1.0	0.8	0.9	0.2	0.7
57	Kaisolo	1.0	1.0	1.0	0.8	0.5	0.8	0.6
58	Nakataka	0.0	1.0	1.0	0.9	0.9	0.2	1.0
59	Bulwandi	1.0	1.0	1.0	0.8	0.0	0.0	1.0
60	Kasambya SW	0.0	1.0	1.0	0.8	0.5	0.9	1.0
61	Lutengo	1.0	1.0	1.0	0.7	0.0	0.4	1.0
62	Bagaya primary school	1.0	1.0	0.8	0.7	0.9	0.3	1.0
63	Bamungolode	1.0	1.0	1.0	0.9	0.7	0.8	1.0
64	Wanzogi primary schoo	1.0	1.0	1.0	0.8	0.2	0.7	0.8
65	kiranga	1.0	1.0	1.0	0.9	0.0	0.9	0.0
66	kyakabombo	1.0	1.0	1.0	0.9	0.5	0.4	0.6
67	Ndaiga DWD 41739	1.0	0.0	1.0	0.9	0.0	0.9	0.9
68	Kiswerwa DWD 41743	1.0	1.0	1.0	0.9	0.2	0.9	0.9

ID	Water Point Name	Contaminant Flow	Wetlands	Depressions	Slope	Schools	Roads	Populated Places
69	Namungolo DWD 41742	1.0	1.0	1.0	0.8	0.6	0.2	1.0
70	Kalungi DWD 41740	1.0	1.0	1.0	0.8	0.1	0.9	0.9
71	DWD 41738	1.0	1.0	1.0	0.8	0.6	0.8	1.0
72	DWD 41771	1.0	1.0	1.0	0.8	0.5	0.6	0.4
73	DWD 41773	1.0	1.0	1.0	0.7	0.5	0.8	0.4
74	DWD 41770	1.0	1.0	1.0	0.9	0.5	0.7	0.1
75	DWD 41741	1.0	1.0	1.0	0.7	0.4	0.7	0.0
76	DWD 41772	1.0	1.0	0.9	0.7	0.0	0.4	0.3

APPENDIX 3: OVERALL SUITABILITY OF EXISTING WELLS BY REFINED MODEL

Membership Range	Membership Index	Overall Suitability
.75-100	Most Suitable	0
.50 - 749	Suitable	10
.25 - .499	Not Suggested	11
0 - .249	Not Suitable	55

Membership Range	Membership Index	Overall Suitability
.75-100	Most Suitable	0%
.50 - 749	Suitable	13%
.25 - .499	Not Suggested	14%
0 - .249	Not Suitable	73%