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THE USE OF JATROPHA CURCAS TO ACHIEVE A SELF SUFFICIENT WATER DISTRIBUTION SYSTEM: A CASE STUDY IN RURAL SENEGAL

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THE USE OF *JATROPHA CURCAS* TO ACHIEVE A SELF SUFFICIENT WATER DISTRIBUTION SYSTEM: A CASE STUDY IN RURAL SENEGAL

By

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A THESIS

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This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Environmental Engineering.

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Preface

The author served as a Peace Corps Volunteer in Senegal for two years as part of the Peace Corps Master's International Program at Michigan Technological University. She was assigned through the Ministry of Agriculture to serve as an Agroforestry Extension Agent in Keur Samba Ndioumbane (Keur Samba), a rural village located in the Kaffrine Region. The author's primary focus was to promote the adoption of agroforestry technologies by Senegalese farmers in the management of their field crops, gardens, and compounds as a method of combating food insecurity.

The biggest challenge the author faced over her two years was the unreliability of the village's water distribution system. The water system relies on diesel to supply a generator powered pump; however, either due to lack of funds or a lack of available diesel in the nearest city, the water distribution system often did not provide water to the communities reliant on the system.

The health of the community, as well as the ability to grow dry season vegetables and trees, was constantly threatened by this lack of available water. When the community faucets were not working, the community was forced to rely on three groundwater wells for all water needs. With a population of over 1000 people, the wells were overcrowded forcing families to survive off limited water from unimproved water sources.

These circumstances prompted the author to identify opportunities for the village to improve their water distribution system. At the root of the problem was the ability of the village to provide diesel to power the pump. Combining the author's work with local tree species and the need for her community to become fuel self-sufficient, the following case study resulted.

Acknowledgements

I would like to thank my advisor, Dr. Brian Barkdoll, for providing immense support before, during, and especially after my Peace Corps Service. I would also like to thank my committee members, Dr. Kari Henquinet and Dr. Robert Handler. Thank you for dedicating time and energy into helping me with this thesis.

I would like to thank all of the Peace Corps Senegal staff, but especially Cherif Djitte for the information he sent me regarding Senegal's Jatropha initiative; along with, Sidy Touré and Yoro Sow for teaching me the Wolof language and culture. My counterparts in country were Yaaya Bâ and Yoro Camara. These men inspired me with their energy, friendship, and generosity.

I would like to thank my mom, Jill, and sister, Anna, for visiting me and sharing in the amazing experience of my village in Keur Samba. I am also grateful to my dad, for his weekly letters that provided a soap-opera-like update of life in Kansas and the happenings of our busy family; along with the rest of the Archer crew for phone calls and coffee care packages!

Finally, my host mother, Ndaye Binta Ngome, who made my time in Senegal filled with love. *Jerejeff sama yaay*. Finally, to all my Senegalese family and neighbors for their friendship, love, and especially the patience and forgiveness they bestowed on the well-meaning, but often confused and frustrated *toubab* that shared their homes, food, and laughs for two years.

Abstract

The use of *Jatropha curcas* as a source of oil for fueling water pumps holds promise for rural communities struggling to achieve water security in arid climates. The potential for use in developing communities as an affordable, sustainable fuel source has been highly recommended for many reasons: it is easily propagated, drought resistant, grows rapidly, and has high-oil-content seeds, as well as medicinal and economic potential. This study uses a rural community in Senegal, West Africa, and calculates at what level of *Jatropha curcas* production the village is able to be self-sufficient in fueling their water system to meet drinking, sanitation and irrigation requirements. The current water distribution system was modelled to represent irrigation requirements for nine different *Jatropha curcas* cultivation and processing schemes. It was found that a combination of using recycled greywater for irrigation and a mechanical press to maximize oil recovered from the seeds of mature *Jatropha curcas* trees, would be able to operate the water system with no diesel required.

Chapter 1 - Introduction

Access to clean and safe drinking water has been a primary goal in international development resulting in improved water supplies across the globe. However, disparities still exist; most notably between urban and rural populations, and between males and females. As the primary water gatherers in many societies, women and school-aged girls suffer the most from water inaccessibility resulting in missed school days and opportunities to pursue income-generating activities. Of those water distribution systems implemented, many have broken or are out of service from missing parts, lack of fuel, etc. The high percentage of failed water projects has left many rural villages without a reliable, improved water source.

The current water distribution system in Keur Samba, Senegal operates intermittently, exposing residents to water contamination risks and forcing the female population of the village to spend long hours waiting in line for water access. Water security is central to improving food production and achieving food security. The motivation of this report is to help the village of Keur Samba develop a self-sustaining water distribution system by cultivating a locally grown tree that produces seeds that can be used as an oil in diesel engines. The community of Keur Samba, like many rural villages across Africa, is caught in the vicious circle of water and food insecurity; in order to profit from their agricultural systems, a reliable water system is needed for irrigation, and in order to pay for the diesel to power the water system, farmers need to have a surplus harvest to reap profits.

This paper investigates the feasibility of combining a locally available renewable energy resource with the existing water distribution system. A hydraulic model of the current water distribution system was created using EPANET 2.0 and combined with an economic and agricultural study of the plant, *Jatropha curcas*, to predict at what level of production, if any, a village is able to achieve self-sufficiency. EPANET was used to simulate the current water delivery system and then adjusted to reflect an improved system, providing enough water to meet the WHO guidelines for basic access, 20 liters per person per day, while also supplying enough water to irrigate *Jatropha curcas* for seed production

(WHO/UNICEF 2012). The existing water distribution system was also expanded to provide continuous delivery, therefore minimizing the amount of time women of the village must spend gathering water every day.

Global water disparity

A broken water distribution system is not unique to the village of Keur Samba. FairWater, a water and sanitation foundation, estimates that 50,000 dysfunctional water supply infrastructures exist across Africa (Skinner 2009). This not only has an impact on the lives and health of impacted populations, but has financial repercussions of US$215-360 million in failed investments. While significant progress has been made toward improving access to safe drinking water, a disproportionate amount of rural populations are still reliant on contaminated or unreliable water sources. Of the current populations living without safe water, four out of five people reside in rural areas (WHO/UNICEF 2012). In Senegal, 39.7% of rural populations rely on an unimproved drinking water source, compared to only 7.5% of urban populations (Agency 2011).

Figure1.1*Young girl carrying water in Keur Samba while school (pictured in background) is in session (photo by author)*

The high percentage of failed water projects has left many rural villages without a reliable water source. Why are so many of these systems, including Keur Samba's, failing? According to Skinner (2009), "[…] much of Africa's water supply infrastructure is failing for a simple and avoidable reason: lack of maintenance." In Senegal, as in many West African countries, government policy is to delegate the control of water systems to local communities. While it is important that local communities are involved, without appropriate technology and local capacity to repair and maintain a system, once a problem arises, communities are often left with non-functioning water systems. The three key elements in a successful, sustainable water distribution system are: the right technology, ownership by the communities involved, and local capacity to repair and maintain the system (Skinner 2009). Water security is central to improving food production and achieving food security. The use of *Jatropha curcas* as a diesel substitute integrated into

the system provides communities like Keur Samba, with the ability to be self-sufficient, improve their agriculture lands, and profit from the multiple uses of *Jatropha curcas* trees through side economic projects.

Chapter 2 - Background

Figure 2.1 *Location of Senegal in Africa with inset image of country (Adapted from Google Maps)*

Senegal

The French-speaking country of Senegal, officially the République du Sénégal, is the most westerly country in mainland Africa and is home to over 13 million people. Senegal has a rich history that has resulted in the current challenges facing the country today: population pressures, deforestation, and climatic changes.

Government

Senegal is often regarded as a model for one of the more successful, post-colonial democratic transitions in Africa. Despite conflicts in the southern region, Casamance, Senegal remains one of the most stable democracies in Africa. In 1960, Senegal gained independence from France and Léopold Sédar Senghor became the first President (Church 2002). Senghor, a poet, contributed to a governing culture where intellect and eloquence were valued over brute force, power, or money. There have been only three presidents since Senghor: Abdou Diouf, Abdoulaye Wade, and Macky Sall who is still serving today.

Population

The largest single ethnic group in Senegal is the Wolof, making up 43.3% of the population. Also present are the Pulaar, Serer, Jola, Mandinka, and Soninke ethnic groups. Even with the presence of various, dynamic ethnic groups, inter-ethnic conflicts are virtually nonexistent and the Senegalese have a strong sense of national unity (Agency 2011). Senegal recognizes French as the official language, but other national languages include Wolof, Pulaar, Jola, and Mandinka. French remains a language for the urban centers and literate, but for the country as a whole, Wolof is the true national spoken language. Religion is a powerful, unifying force: over 95% of Senegalese are Muslim and practice a form of the religion that is very specific to Senegal. This form of Islamic practice requires membership into different religious brotherhoods, each dedicated to their religious leader or *marabout.* The *marabouts* are believed to have spiritual and healing powers and can grant special salvation to their followers. *Marabouts* hold strong political influence in the country and are prominent in private business and government decisions (Trémolet 2006). Senegal has a predominantly young population, over half (62.5%) are under the age of 24 (Agency 2011).

Economy and Climate

Senegal’s economy is predominantly dependent on agriculture and therefore the country is vulnerable to climatic variations and changes in world commodity prices. The agricultural

sector comprises 77.5% of the labor force. The major agricultural products are peanuts (groundnuts), millet, corn, and sorghum. Inadequate water resources limit the potential for economic development throughout the country and keep Senegal heavily reliant on donor assistance and foreign direct investment (Trémolet 2006). An estimated 54% of the population lives below the poverty line (Agency 2011). The climate varies widely, from the comparatively cool coastal regions to the hot and dry inlands. The semiarid transitional region between the southern end of the Sahara desert and the wetter Savannah zones is known as the Sahel, which stretches from the Atlantic Ocean and northern Senegal in the west reaching as far as east Sudan. Precipitation amounts range from 250-500 mm in the arid Sahelian zones in the north of the country and 900-1100mm in the southern zone of the country. (Cisse and Hall 2002). Over the past 50 years, rainfall has decreased from 30 billion cm^3 to just 10 billion cm^3 (Trémolet 2006). These climatic changes have stressed the country's environmental resources, especially in a population so reliant on agricultural production for survival.

Water Development in Senegal

Senegal experienced severe, regional droughts throughout the 1970s and early 80s, and as a result of these droughts a policy decision was made in the 1980s to create new water schemes using deep, pumped boreholes. A typical scheme included a 100-300 meter deep borehole combined with a diesel-engine driven pump. Water is then pumped to an aboveground tower, typically 15 m high and with a volume of 100-200 cubic meters, and then supplied to multiple villages via pipelines (Smith et al. 1994). The rural piped water systems also included fixed water payments and village management committees.

Up until the year 1984, water supply had been free of charge. From 1984 to 1996, fixed charges were introduced and water systems were managed by water committees. In 1996, Senegal entered into a public-private partnership with *Senegalaise des Eaux* (SDE), a subsidiary of Saur International, on a 10-year lease contract with the Senegalese government, and more changes were made in rural areas. Legally instituted water users' associations, *Associations d'usagers de forages ruraux* (ASUFOR), were now required to

sign maintenance contracts with private companies to ensure the upkeep of their systems and user payments became based on volume using a metering system. Users were also required to open a bank account (Trémolet 2006).

Fresh surface water in the arid interior of Senegal throughout the dry season is virtually non-existent placing heavy pressure on the performance of piped water systems. When piped water systems are not available or are out of service, communities turn to other available water sources, such as shallow, hand-dug wells. (Youm et al. 2000).

Biofuels Initiative in Senegal

Bioenergy production shows promise for use in developing countries primarily because of its ability to help regions achieve sustainable development, reduce greenhouse gas emissions, increase regional development, improve the agriculture economy, and secure an energy supply. However, biofuels can also take away from land needed to produce food, diminish feed for cattle, and negatively impact limited available water resources. The rise in the global bioenergy market is driven by concerns of energy security, rising fossil fuel prices, and climate change; for these reasons, the global bioenergy market is predicted to further expand in the coming years (Achterbosch 2013). In 2008, Oxfam produced a report condemning biofuels as being unsustainable and leading to competition with food production, as well as contributing to the rise in global food prices (OxfamNovib 2009). The majority of the world's food insecure people live in Africa, and in the Sahel it amounts to around 20 million people (FAO, 2013). This makes it extremely important that any crop recommended for biofuel will not negatively impact food production or water resources. While keeping in mind Oxfam's cautionary report, it should be noted that the production of plant biomass for energy use does not have to compete with food production, but can actually help a community toward improving food security. For these reasons, the crop Jatropha curcas has received attention as a suitable biofuel crop for use in the Sahel.

In 2007, Senegal adopted ENDA, the Energy, Environment, and Development Program with the aim of guaranteeing Senegal's self-sufficiency in biodiesel through the production of 1,190,000 liters of crude Jatropha oil by 2012. This five-year program was implemented

through the Ministry of Agriculture and included representatives from rural organizations, professional agricultural organizations, local chiefs, and NGOs, as well as representatives of development projects and programs (ENDA 2007) . The Senegalese Institute for Agricultural Research, *Institut Sénégalais de Recherches Agricoles* (ISRA) was delegated with the responsibility of providing seedlings for the country through *in vitro* cultivation systems totaling 25 tons of seedlings. As a result of ISRA's involvement in the biofuel initiative, a biofuels research program was created and charged with developing one billion *Jatropha curcas* plants for the pilot production program. In addition, Senegalese farmers that have *Jatropha curcas* nurseries will receive trainings given by ISRA, in collaboration with Senegal's Department of Horticulture, the Senegalese Irrigation Authority (SAED), and the Regional Rural Development Offices, increasing the farmers' technical knowledge (ENDA 2007).

Figure 2.2 *Jatropha curcas nursery located near study site for improved seed production. Field managed by the author's Peace Corps work counterpart (photo by author)*

The primary objective of Senegal's biofuel initiative is to ensure Senegal's self-sufficiency in biodiesel. By introducing the Jatropha program in 2007, Senegal's Ministry of Agriculture sought to diversify cash crop production, reduce household energy bills and dependence on imported energy, while also improving Senegal's international trade and balance of payments. Additionally, the Ministry recognized that a successful implementation of the Jatropha program would contribute towards reducing environmental pollution caused by vehicle engines, and help ameliorate country-wide poverty and inequality between the rural and urban areas (ENDA 2007).

According to a report produced by the National Renewable Energy Laboratory, substituting biodiesel, even as a blend with diesel fuel, reduces the following emissions: particulate matter, carbon monoxide (CO), hydrocarbons (HC), sulfur oxides (SOx), nitrogen oxides

(NOx), and air toxics therefore reducing public health risks associated with air pollutants (Sheehan et al. 2000).

Jatropha curcas in Senegal

Jatropha curcas was selected as a promising biofuel plant in Senegal because it is well adapted to the climatic, social, and economic conditions of the country. *Jatropha curcas*, or *tabanani* as it is called in Wolof, is a non-edible, drought-resistant perennial shrub, or small tree, of the Euphorbia family suited to tropical and sub-tropical climates. The branches of the tree contain latex which is useful in repelling animals attempting to break through a *Jatropha curcas* hedge (Henning 2004). *Jatropha curcas* requires a minimum of 500 mm of annual average rainfall and annual average temperatures above 20° C (Simpson 2009). Figure 2.3 shows the average precipitation data by month for the Koungheul Region (TheWorldBankGroup 2015). *Jatropha curcas* is well suited for growth on degraded and/or dry lands with potentially positive impacts on biodiversity and soil resources through reclaiming these wastelands and providing biological homes for other organisms (Maes et al. 2009). Due to a single deep taproot and four shallower lateral roots, *Jatropha curcas* can prevent and control soil erosion caused by wind and water (Achten et al. 2008). Marginal or degraded lands are typically characterized by lack of water, low soil fertility or high temperatures. Bioenergy crops like *Jatropha curcas* that can tolerate these extreme environmental conditions, where food crops might fail, may offer the opportunity to put to productive use land that presently yields few economic benefits (FAO 2008).

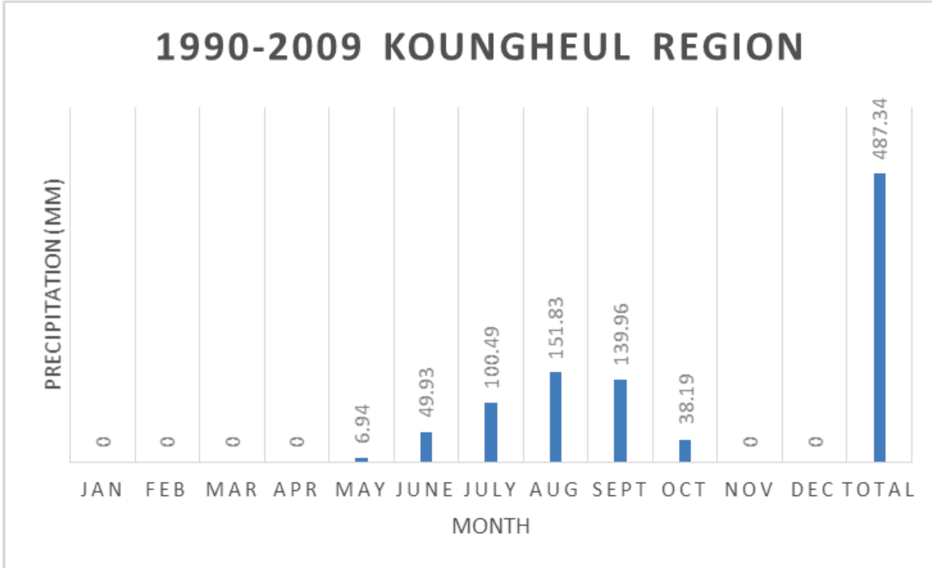

Figure 2.3 *An average from 1990-2009 of the annual rainfall data for study site (TheWorldBankGroup 2015)*

Oil Production

Jatropha produces seeds with a high oil content (30-35%) that can be transformed into biodiesel fuel that has been used to power Multi-Functional Platforms (MFPs) and water pumps for irrigation (Adhikari and Wegstein 2011). *Jatropha curcas* oil can be used directly in older diesel engines or engines running at a constant speed like pumps or generators (Achten, Verchot et al. 2008). *Jatropha curcas* oil can also be used as substitute for the 'gazoil' mixture used throughout Senegal and rural Mali where it fuels diesel engines that drive water pumps and grain mills (Henning 2004).

Secondary Benefits

Jatropha curcas has the climatic capability of being locally produced in semi-arid communities, where land production is low and poverty levels are high. According to the Commission on Sustainable Development (2007), it will allow these communities to achieve a greater level of independence and assure a second source of fuel if diesel is either too expensive or simply not available (Eckart and Henshaw 2012). The integrated approach of using *Jatropha curcas* for rural development ensures that by planting hedges,

economic and environmental benefits are also achieved. Four critical aspects of rural development are positively impacted by cultivating *Jatropha curcas* (Henning 2004):

- Energy supply in the rural area;
- Environment, when used to control erosion;
- Gender empowerment, when used by women for local soap production;
- Poverty reduction, when used to generate income through the selling of seeds and providing employment through the various stages of processing (harvesting, processing, etc…)

Other uses of *Jatropha curcas seeds* include: as a living fence controlling livestock, for delineating fields, as an herbal medicine from the latex in leave, and residue from oil pressing has been used as a fertilizer for use in gardens because of its high nitrogen content. (Jongschaap et al. 2007). In order to maximize the benefits of incorporating *Jatropha curcas* into Senegalese farmers' field crops or garden spaces, the whole value chain ought to be considered, as oil, biodiesel, soap, seedcake, and charcoal are all potential products from the trees (Simpson 2009)

Economic Potential for Senegal

Senegalese farmers traditionally incorporate tree species as windbreak and hedgerow protection. From these trees, farmers are using small amounts of diesel to fuel motorcycles, and women's groups are profiting by process the seeds into soap and selling in local markets. Additionally, farmers in Senegal rely on producing cash crops such as groundnuts or sugarcane. For these reasons, combined with the availability of land and the motivation of the Senegalese Ministry of Agriculture to pursue a biofuel directive, rural Senegalese farmers are positioned to gain from the production of *Jatropha*.

Limitations to Senegalese production of Jatropha curcas

The five year initiative of ENDA ended in 2012 and there is little biodiesel production in the country to show for the effort. A Mission Report (Simpson 2009) requested by USAID noted the following weaknesses in the initial biofuel government initiative in Senegal:

- Insufficient knowledge for managing *Jatropha*
- Lack of data predicting economic outcomes of growing *Jatropha*
- No clear policy on biofuels in Senegal
- Non-existent value chain and market available for *Jatropha*

The following were potential threats as perceived by the Mission Report:

- Lack of clear policy regarding biofuels
- Unrealistic yield expectations
- Threat of plant disease when Jatropha is planted on a large scale
- Low prices of crude oil
- The replacement of fuel crops
- Problems in product utilization

While the aforementioned problems are no doubt significant, the objective of this study was primarily to evaluate the fuel requirements of the existing water pump while supplying different quantities of water and to estimate the potential that crude *Jatropha* oil could be used as a renewable energy source to power the current water distribution system. The corresponding agricultural area, irrigation requirement, and processing time needed to support this fuel production was calculated to ascertain the feasibility of producing

Jatropha curcas as a means of achieving fuel self-sufficiency in rural water distribution systems in Senegal.

Case Study: Keur Samba, Senegal

Figure 2.4 *Study region with red rectangle encompassing Peanut Basin and yellow pin indicating study site, Keur Samba (Image source: Google Earth)*

The Peanut Basin

Keur Samba Ndioumbane, situated roughly halfway between the major cities of Kaolack and Tambacounda, is located in the agricultural heart of the country, known as the Peanut Basin. The Peanut Basin falls in the semi-arid central region of Senegal where precipitation can range from 350-700mm. Keur Samba is reliant on rain-fed agricultural systems typical of this region where over 90% of arable lands are used for cultivation. Major crops include millet (*Pennisetum typhoides*), groundnuts (*Arachis hypogaea*), sorghum (*Sorghum bicolor*) and cowpeas (*Vigna unguiculata*). Figure 2.5 is a photograph of groundnut harvesting in Keur Samba. The rainy season occurs between July until September or October with average annual rainfall varying from 350-700 mm. The high degree of

precipitation variation, both spatially and temporally, leave this region of Senegal at a high level of risk for crop failure (Tschakert, 2004).

Figure 2.5 *Harvesting peanuts in Keur Samba (photo by author)*

Keur Samba is made up mostly of the Wolof ethnic group with a small percent of Pulaar (<10%) represented in the population of approximately 1000 inhabitants. The village is located 15 kilometers from the *route nationale* or national highway. The *route nationale* is a trade corridor extending from Mali to Dakar, the largest city and capitol of Senegal and the westernmost point in Africa. Keur Samba is also 15 kilometers from the nearest town, Koungheul, where residents of Keur Samba can access the internet, public transportation, electricity, and a hospital and pharmacy. A weekly market just 8 kilometers away allows the village residents a second option to purchase food items and farm implements in the rural village of Njaptow. Keur Samba also has a small daily market (Figure 2.6) where

seasonally produced vegetables or fruit are available. Four small shops provide the village with daily food needs including rice, dried fish, sugar, and peanut butter (Figure 2.7).

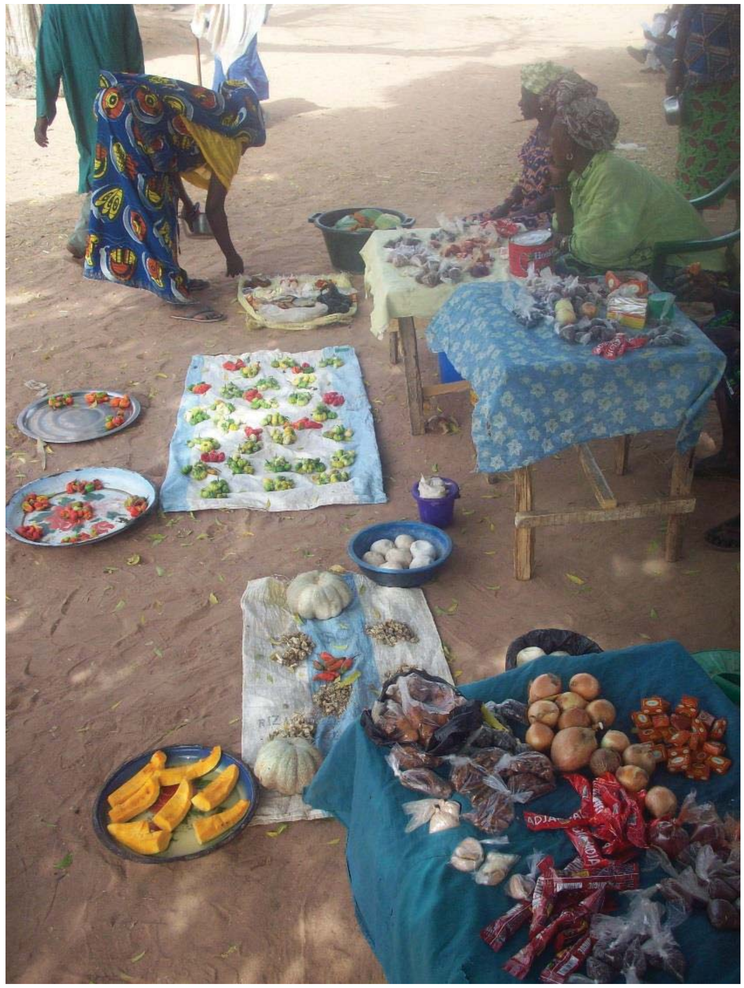

Figure 2.6 *Daily market in Keur Samba typically includes onions, hot peppers, soap made from peanuts, garlic, and various spice packets (photo by author)*

Figure 2.7 *Typical small shop located in Keur Samba with items for sale such as sugar, tea, oil, macaroni, and batteries (photo by author)*

Keur Samba is the second largest populated village in the Koungheul region; however, it has one of the least reliable water distribution systems.

Keur Samba Water Distribution System

Water distribution systems across Senegal are typically multi-village systems, meaning there is one central village which houses the water tower with pipes extending to surrounding villages. There are three different types of water access points in Keur Samba: a hand pump, a system of pipes and faucets, and three wells with pulleys, with the only reliable source being the wells. Figure 2.8, Figure 2.9 and Figure 2.10 are all photographs of the three systems present in Keur Samba.

Figure 2.8 *Abandoned hand pump installed by World Vision in Keur Samba (photo by author)*

The village has three wells where water is pulled by hand from a depth of 20 meters below the surface (Figure 2.9). While Keur Samba has a water distribution system in place, the wells are the most frequented source of water owing to a variety of factors such as: unreliability of faucets, cost, (there is no fee for pulling water from the wells), personal preference and time constraints. The wells are in use from before sunrise to after sunset every day of the year. During high-traffic times (mornings and evenings) women can wait at the well for several hours for their turn to pull enough water for their households. With a population of over 1000 and only 3 wells as the reliable water supply in Keur Samba, over 300 people are reliant on a single well for all their water needs. Women are the only water gatherers, with young females often shouldering most of that responsibility. Research has found that on a global scale each year 40 billion hours are spent by women and girls collecting water and 448 million school days are missed by young children, especially girls, collecting water (Hope, Foster, and Thomson 2012). With the women and girls of Keur Samba spending hours at the well each day, they have less time for school, or

participating in small income-generating activities, such as soap making, small garden projects, or laundry.

Figure 2.9 *Women pulling water at the well in Keur Samba (top) and well with primary school in background (bottom), located in Keur Samba (photo by author)*

The village also has a system of water faucets where residents can buy water at a price of 10 CFA or USD 0.02 for 30 liters. There are four community faucets which are monitored by a different, rotating female community member every month. Figure 2.10 is an image of the central community faucet located in Keur Samba. The faucets are open from sunrise until 9 or 10 am and again in the evenings, typically opening around 5 pm and closing around dusk. The water is frequently turned off early or faucets left off for days, and sometimes months, if there are problems with the water distribution system, such as a lack of fuel, the water tower manager is traveling, or late payments from water users, which also impacts fuel shortages.

Figure 2.10 *Image of water collection pans in line at the central community faucet in Keur Samba (photo by author)*

Figure 2.11 *Water collected from central community faucet in Keur Samba (photo by author)*

The water tower and water pump that supplies Keur Samba is located in Keur Lamine, a Mandinka village located 3 kilometers away. The water tower was installed in 2001 as part of the third phase of the Saudi well drilling and rural development program in the Sahelian countries of Africa. The water tower is managed by a respected member of the Keur Lamine community whose primary job is as a health care worker at the Koumbdia Catholic Health Post. Some issues with the Keur Lamine water system include the water pressure and color of the system, which vary widely from day to day and hour to hour. The water tower manager maintains that the water is red (Figure 2.11) from a lack of biannual cleaning. However, village members in Keur Samba believe the primarily Mandinka-populated village that controls the tower is purposefully funneling dirty water to Keur Samba. The intermittent use of the water distribution system most likely results in the reddish hue of the water. This can be attributed to sediment in the water being allowed to

settle during times of non-use and then getting flushed out when the system is running again.

When the manager of the water tower met with the author regarding water shortages in Keur Samba, he/she maintained the only reason water was not being supplied was due to missing payments from Keur Samba. As a follow up to this conversation, the author met with the Chief of Keur Samba, the author's host father's uncle, and heard a different story: that the problems with the water were because of mismanagement in Keur Lamine. After a little investigation, the author was able to conclude that both statements held some truth; however, if fuel was easier to come by it would largely solve many of the current supply issues in the Keur Samba water distribution system. When looking at ways to address this fuel supply issue, it came to the author's attention that a biofuel source, quickly gaining attention on the global scale, was already growing in all the villages tied into the current water system. *Jatropha curcas*, as previously discussed, shows great promise in reducing communities' dependency on diesel.

Jatropha curcas in Keur Samba

Jatropha is already cultivated in Keur Samba and is present in the surrounding villages and fields where it is commonly used as a live fence species. Figure 2.12 is an image of *Jatropha* being used as a windbreak and live fence in a home garden.

Figure 2.12 *Jatropha curcas being used as a live fence and a windbreak, Keur Samba (photo by author)*

Some farmers in and around Keur Samba have planted *Jatropha curcas* in their homes and fields already, typically as either a privacy barrier for their homes and as a means of containing household animals, or to delineate ownership of fields. There are several cultural beliefs associated with the tree that can make it difficult to get farmers to adopt the tree in their homes; the first is that *Jatropha curcas* attracts snakes, and the second is that if *Jatropha curcas* is used in the home, it will bring loneliness. However, there are many more positive beliefs surrounding the trees. One farmer, who heads up the World Vision experimental farm 3 kilometers from Keur Samba, uses *Jatropha curcas* in collaboration with a local women's group to produce and sell soap. This farmer also experimented with pressing *Jatropha curcas* seeds and using the oil to run a diesel engine. The World Vision experimental farm established in 2005 has been used recently to develop a *Jatropha curcas* seed source. In this farmer's personal experience in working with the seed, three kilograms

will make one liter of diesel. In 2013, the farmer was able to sell his *Jatropha curcas* shoots at 500 CFA per kilogram; he sold 133 kilograms in 2014, totaling 66,500 CFA or 133 USD. The presence of a market in the area for selling *Jatropha curcas* shoots is important to encourage farmers to adopt the plant.

Processing

Processing *Jatropha curcas* seeds can be done very simply, or when available, more advanced methods can be used such as mechanical pressing systems. *Jatropha curcas* seeds are processed using the same methods as groundnut processing, which include hand picking, dehulling by hand, drying in the sun, and using an antique groundnut press. Figure 2.13 depicts traditional methods used in Keur Samba to process peanuts: laying peanuts in the sun to dry followed by shelling the peanuts manually, a social pastime of the women in the village. *Jatropha curcas* seeds need to be dried in the sun for three weeks prior to processing (Eckart and Henshaw 2012). After *Jatropha curcas* seeds have been dried, they can be stored for 7-8 months. After 8 months seeds lose their viability for both oil extraction and planting (Jongh and van der Putten 2010). *Jatropha curcas* oil, once separated, can be used directly in older diesel engines or in new motors running at constant speeds like generators.

Figure 2.13 *Photos of peanut processing in Keur Samba. In the photo on the left, peanuts are being dried in the sun, and the photo on the right shows women shelling peanuts (photo by author)*

Feasibility of using *Jatropha curcas*

The potential of *Jatropha curcas* for use in developing communities as an affordable, sustainable source for fuel production has been highly recommended for many reasons: it is easily propagated, drought resistant, grows rapidly, has non-edible, high oil content seeds and multiple potential medicinal and economic uses (Divakara et al. 2010, Achten et al. 2008). However, the existing research and knowledge regarding yield-potential of the tree varies widely. For this reason, the least optimistic values were always selected when choosing values to use in forecasting the economic feasibility in Keur Samba.

Throughout Keur Samba and the surrounding villages, *Jatropha curcas* can be found used in hedgerows as a living fence or surrounding home compounds. While irrigation is not required for tree survival, it does increase and improve the yields (Cynthia and Teong 2011). For these reasons, this case study will include both seed production from rainfed *Jatropha curcas* trees intercropped with groundnuts, and also an irrigation planting scheme

where irrigation requirements for the trees are incorporated back into the existing water demand for consumers to provide the optimal amount of water to the trees for seed yield. Some case studies have irrigated *Jatropha curcas* trees in order to provide two harvests per year. This study focuses on providing enough irrigation to maximize an annual seed oil production. A second harvest would require much more nutrient input into the system to maintain quality seed production and is an additional labor and financial burden that, especially initially, local farmers would be hesitant to undertake.

Nutrient Requirements

One of the factors making *Jatropha curcas* so attractive for use in arid, semi-arid environments is the low nutrient requirements of the crop. Studies have shown an increase in seed oil content and production when fertilizer is applied to high density planting schemes of *Jatropha curcas* plantations (>2500 plants ha^{-1}). Another method is allowing pruned plant material to be incorporated back into the soil at the base of the trees. This has been shown to provide available nutrients for *Jatropha curcas* uptake (Jongschaap et al. 2007). This study will assume *Jatropha curcas* home cultivation will be fertilized the traditional way of local home gardens with horse, goat, and cow manure. Animals from each respective household will be kept in the compound overnight, and manure removed in the morning and disposed of in the family garden plots.

Harvesting

Jatropha curcas fully matures in 4-5 years (Nahar and Ozores-Hampton 2014). In a Senegal case study taking place in Nder (a region in the north of Senegal), *Jatropha curcas* trees produced fruits at 14 months with no irrigation and no weeding to reduce competition for resources (Simpson 2009).

Disease Susceptibility

Jatropha curcas is a highly adaptable species but is susceptible to damage form light frost and low temperatures. Since *Jatropha curcas* thrives in low rainfall and high temperature regions, one of the biggest threats can come from over-watering the trees. Collar rot from

temporarily overwatering, termites and millipedes have been known to damage trees in Senegal (Simpson 2009).

Seed Yield

To achieve the best oil yields, seeds should be harvested when mature or 90 days after flowering. The seeds will turn from a green to yellow-brown (Achten et al. 2008) when ready to be harvested.

Seed availability

The presence of Trees for the Future, a non-profit organization that focuses on planting trees in rural communities in the developing world by training communities in the latest agroforestry techniques, along with a Peace Corps agroforestry extension agent ensure a sufficient supply of *Jatropha curcas* seeds for the region. When the author left her village as a result of completing her service in November of 2014, seed saving techniques were being adopted by the farmers with seed-producing *Jatropha curcas* trees. The agroforestry extension agent who replaced the author in Keur Samba will also be able to supply the village with as many *Jatropha curcas* seeds as needed to supplement those locally available. The Ministry of Agriculture's Jatropha Program, set up a research program with ISRA to produce one billion Jatropha plants to be disseminated to farmers throughout the country.

Figure 2.14 *Farmer Yaaya Bâ indicating his ripening* Jatropha curcas *seeds (photo by author)*

Chapter 3 - Methodology

Hydraulic Model: Introduction to EPANET

The water distribution system in Keur Samba was modeled using EPANET 2.0 software, a program developed by the U.S. Environmental Protection Agency to simulate hydraulic flow and water quality behavior within a pressurized pipe network (Rossman 2000). The water distribution system of Keur Samba was modeled in EPANET using a system of pipes, nodes (pipe junctions), a pump, storage tank, reservoir, and time demand patterns to control the flow from the pump and end nodes. When creating a hydraulic model in EPANET the following steps can be used to represent any water distribution system (Rossman 2000):

1. Draw a representation of the distribution system using EPANET objects: pipes, nodes, pump, and tanks
2. Edit the object properties using site specific elevations, lengths and diameters
3. Describe how the system is operating with controls and patterns
4. Select the hydraulic analysis options
5. Run the hydraulic analysis
6. View results

Preliminary data was gathered in Keur Samba over the course of the author's two-year Peace Corps Service. GPS technology was used to calculate distance and elevation for the water tower and the three connecting villages. Informal interviews were conducted with the manager of the water tower and the supervisors at the various communities' faucet outlets. Village census data was gathered from the Chief of Keur Samba. The author was also reliant on the water system for two years and kept records of water outages and time spent to gather water at the main community faucet in Keur Samba.

EPANET has been used to model water distribution system in large urban centers, as well as smaller scale systems in well-developed, and developing countries all over the world (Abbott, O'Neill, and Barkdoll 2014). Because EPANET is a demand-driven model, when used on systems with low-pressure or intermittent supply, it is especially important that the

user recognizes any deficiencies in the model's ability to accurately reflect conditions in the real system (Trifunović et al. 2008). For this reason, the author validated the model results with the pumping time, fuel use, and supply as experienced in the author's two years of relying on the system.

Keur Samba, like most rural villages in Senegal, is incorporated into a multiple-village water distribution system. The central water tower is located in Keur Lamine, and this tower provides water for Keur Lamine, as well as Keur Aly Lobe and Keur Samba. The distances between Keur Lamine and Keur Samba and Keur Aly Lobe are 2480 meters (1.54 miles) and 1600 meters (0.99 miles), respectively. There are three, four, and two community faucets in Keur Lamine, Keur Samba, and Keur Aly Lobé, respectively.

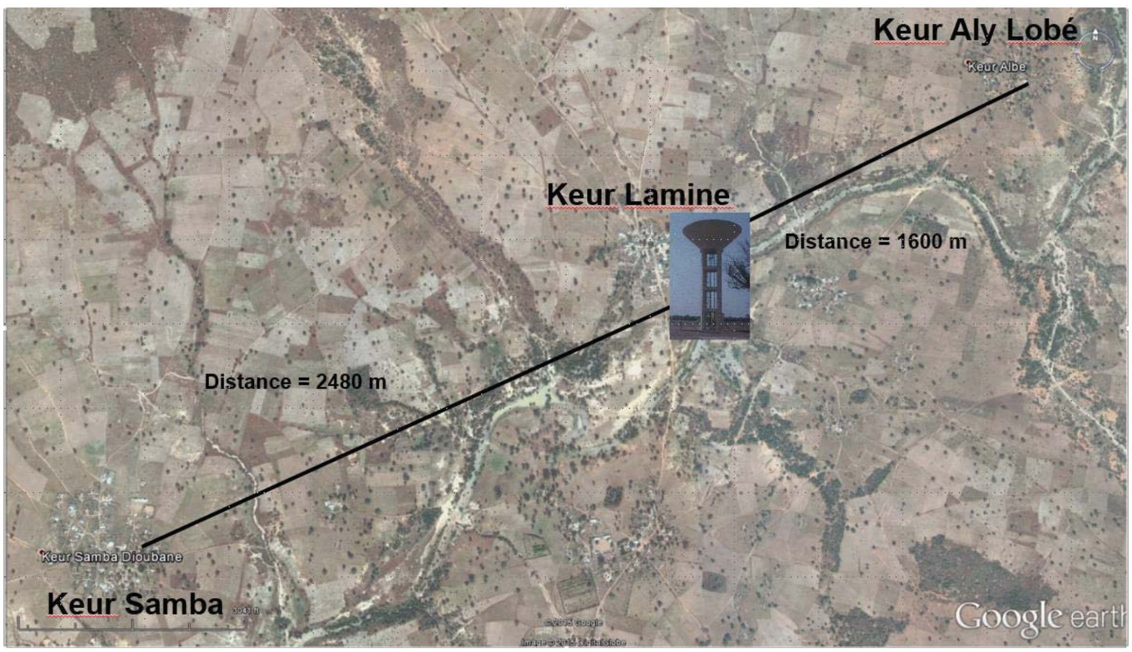

Figure 3.1 *Layout of water distribution system spanning from central water tower in Keur Lamine to Keur Samba and Keur Aly Lobe, superimposed on aerial photo (Image source: Google Earth)*

Calculating Water Demand

EPANET uses the demands entered at each node to determine flow rate. The pressure values at each node can be used to evaluate if the model is meeting the desired flow rate at each outlet.

Node Properties

The demand input for EPANET was calculated based on values provided by the World Health Organization and Water Engineering Development Centre guidelines for improved access. Table 3.1 includes the amounts required for survival per person in units of liters per capita per day. Demand values for mosques and community gardens was estimated differently depending on their use patterns (Howard and Bartram 2003) (Batteson, Davey, and Shaw 1998, Reed et al. 2013)

Table 3.1 *Guidelines for water quantities (WHO/UNICEF 2012)*

Basic Access	Water assured for consumption but only meets basic hygiene needs (hand washing, food preparation)	20 l/c/d
Intermediate Access	Water assured for consumption and hygiene with laundry likely to occur within confines of the household	50 l/c/d
Optimal Access	All consumption and hygiene needs met	100 l/c/d
Mosque/Religious Activities	Washing and drinking	2-5 l/c/d
Vegetable Garden	Based on a square meter for 1 day	3-6 liters
Water Consumption for Faucet, current use	Communally located	15.5 l/c/d

Base Demand

$$\boldsymbol{Base\ Demand_{Individual\ Use} = \frac{Water\ Demand\ \times Total\ Population}{Number\ of\ Water\ Outlets}}$$

3-1

The calculated base demands were the same for each node in a community. Using the village census data which was gathered from the village chief or provided by the official water tower report, Table 3.2, the total population for each village was multiplied by the demand, which differed depending on the scenario being tested, and this value was divided by the total number of outlets/faucets in the village (four, three, or two). Using the author's knowledge of the village and an average value found for family compounds in Senegal, ten individuals was the average household size used in the demand calculations.

A household value was important to incorporate into these calculations because the *Jatropha curcas* irrigation requirements are most reasonably calculated on a household by household basis. As part of this study, the responsibility falling to each household for irrigation and supplying land for cultivating the *Jatropha curcas* trees was investigated. Small home gardens are a common practice in these communities, mostly dedicated to cash crops like hot peppers, or fruit tree production like mangos, papayas, and bananas, and so is a culturally appropriate way to cultivate the *Jatropha curcas* trees.

To determine the households reliant per faucet the following calculations were made:

Using the total population of 1,963 people served by the study site water distribution system and an average of ten individuals per family compound, a total of 196 households are reliant on the water system which has only nine community faucets. Using this information, at each faucet there are approximately 22 households dependent on a single outlet for all their water needs.

Table 3.2 *Village population, number of households, and number of community faucets*

Village	Population	Households	Community Faucets
Keur Aly Lobe[1]	409	38	2
Keur Lamine[2]	457	39	3
Keur Samba[3]	1100	119	4

[1] République du Sénégal (2015)
[2] Appendix C - Forage Report
[3] Gathered by author

Different equations were used for the faucets located at the mosque and community garden, Equations 3-2 and 3-3. There is a mosque in each community, three total for the overall system, and one community garden located in Keur Samba.

$$\boldsymbol{Base\ Demand_{Mosques} = Recommended\ Amount\ \times Population\ at\ Mosque} \tag{3-2}$$

$$\boldsymbol{Base\ Demand_{Irrigation} = Irrigation\ Requirement\ \times Watering\ Time} \tag{3-3}$$

For Equation 3-2, the recommended amount was based on the minimum amount, 2 liters per person per day, indicated in the Technical Notes provided by the World Health Organization (Reed et al. 2013). The minimum amount was used because an overestimate of the population attending the mosque was predicted by assuming one individual from each household would attend the mosque at each of the five prayer times, every day. Number of people per community was obtained from the Forage Report and census data provided by the village chief. An average irrigation requirement of 4.5 liters per square meter was chosen and then applied to the 50 square meters currently being cultivated and irrigated in the community garden at Keur Samba at the time of the author's departure due to end of Peace Corps service.

Creating EPANET Model for Current System

Two scenarios were used in the initial development of the EPANET model for this study. The initial model, Scenario A, was created to simulate the current water availability in Keur Samba. A value of 15 liters per person per day was used and a time pattern was applied that reflected water availability of only five hours a day. A value of 15 liters per person was chosen because this best mimicked the actual pumping time when simulated in the EPANET model. When this model reflected what the author felt was an accurate representation of the current water distribution system based on diesel requirement and corresponding pumping time, meaning based on the author's experience and information from the water tower operator that currently only an hour of pumping time and 3 liters of fuel a day was used, Scenario B was created to scale up the system to what ideally would be supplied if water met basic needs and was continuously available. To meet these needs, a Scenario B model was created using an increased base demand of 20 liters per person and a time pattern that allowed for continuous access throughout the day. The mosque and community garden demands remained the same for both scenarios. Using the results from EPANET for Scenario B, an idea of what fuel would be needed was estimated and applied to the feasibility analysis of *Jatropha curcas* production to meet these increased fuel needs.

Table 3.3 *Description of each scenario used in EPANET model to determine fuel self-sufficiency of water distribution system*

Scenario	Description
I1	Iteration 1: Scenario B plus *Jatropha* irrigation
I2	Iteration 2
I3	Iteration 3
I4	Iteration 4
I5	Iteration 5
A	15 liters/person/day and intermittent access
B	20 liters/person/day and continuous access
C	Greywater without irrigation
D	Greywater
E	Mechanical expeller
F	Mechanical expeller combined with greywater

Table 3.4 *Nodal Demand Calculations used in Scenarios A & B for EPANET*

	Water Demand liters/person/day	Population	Nodes in community	BASE DEMAND
Scenario A: 15 liters and Intermittent Supply				Liters/ second
Keur Lamine	15	457	3	0.026
Keur Aly Lobe	15	406	2	0.035
Keur Samba	15	1,100	4	0.048
Scenario B: 20 liters and Continuous Supply				
Keur Lamine	20	457	3	0.035
Keur Aly Lobe	20	406	2	0.047
Keur Samba	20	1,100	4	0.064
Mosque Demands			**Households**	
Keur Lamine	2	457	45	0.001
Keur Aly Lobe	2	406	38	0.001
Keur Samba	2	1,100	119	0.003
Community Garden				
	liter/m^2	**m^2**	**Watering (liters/day)**	**Base Demand**
Keur Samba	3 - 6	50	225	0.003

Demand Pattern

EPANET will assume a constant demand unless the user specifies differently. To reflect demands that fluctuate throughout the day, such is the case in water distribution systems where either water is only available intermittently or the population frequents faucets more in the mornings and evenings, a demand pattern can be assigned to the base demands entered at the nodes in the model.

When creating a model of the current system in Keur Samba, a demand pattern was created to reflect the actual hours of operation of the water system. A demand pattern uses multipliers for a given time period and applies them to the base demand value for that node to determine the actual demand value at the time period in question. The first demand pattern created uses a multiplier of 4.8 for the five hours of operation. The current system

of Keur Samba can usually be expected to run from 5:00 A.M. to 8:00 A.M. and 4:00 P.M. to 6:00 P.M. For these five hours, the base demand is 4.8 times higher than the flow then the hours it is off. The value 4.8 comes from 24 hours of flow being supplied in just five hours (24 divided by 5) giving the multiplier 4.8.

For these hours, 4.8 times the average demand is used so that over the course of 24 hours, the multiplier is still an average of one. The left axis in Figure 3.2, Figure 3.3, Figure 3.4 and Figure 3.5 must average to a value of one in order to meet the base demand entered into EPANET in liters per person per day.

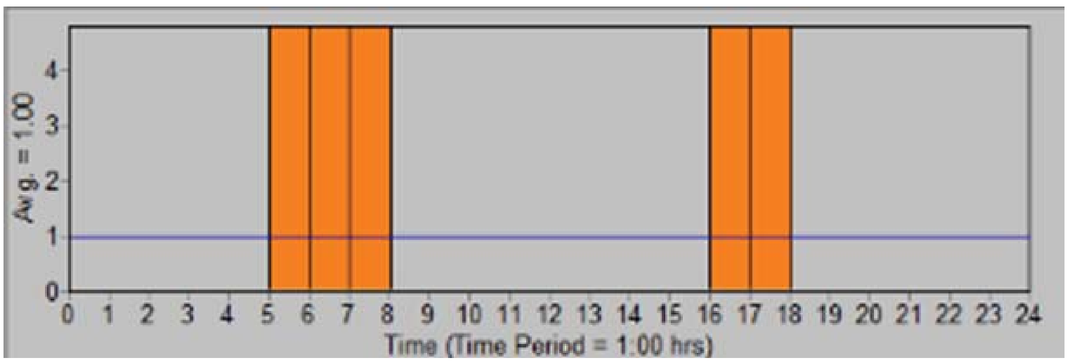

Figure 3.2 *EPANET screen capture of the demand pattern for the current system. The left axis is an average of the multiplier values.*

To simulate continuous supply of the water system, a second demand pattern was created based on the author's observations while living in the village. Figure 3.3 depicts the demand pattern where water is supplied from 5:00 A.M. to 8:00 P.M., with peak demand times in the morning and early evening. The author observed the majority of water collection and laundry activities happened in the morning hours leading up to lunch time. This mid-morning period was when women generally gathered water for drinking and cooking for the rest of the day. This also allowed women to be naturally heated by the sun throughout the day for evening bathing. After lunch time, families rested until water was once again gathered for evening bathing, meal preparation, and to allow water to cool overnight for drinking.

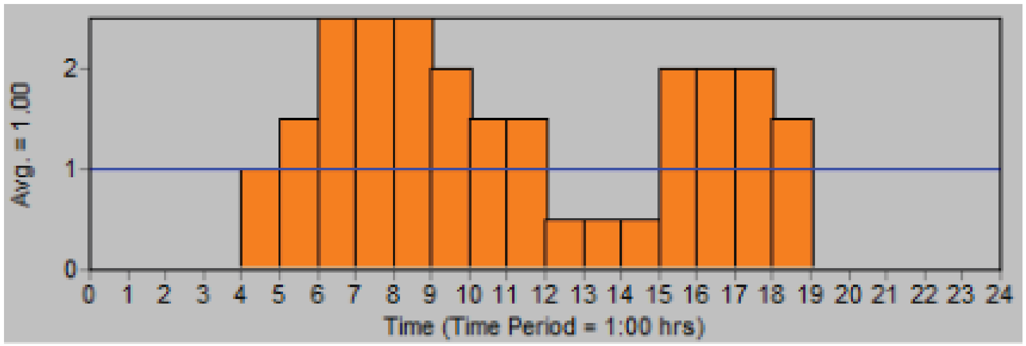

Figure 3.3 *EPANET screen capture of the hourly demand pattern for simulating continuous supply*

A demand pattern for both the current and continuous system models included a separate demand category for the faucets located at the mosque and community garden. A demand category can be used for a single node to assign different base demands and time patterns. For the faucets located closest to the mosque, two demand categories were assigned. The first based on community drinking demands and the second for the five prayer times and associated water demands. For the mosque, a multiplier of 4.8 was used for the five hours of prayer time: 4:00 A.M., Noon, 3:00 P.M., 6:00 P.M., and 8:00 P.M. These hours vary slightly throughout the year based on the timing of sunset and sunrise.

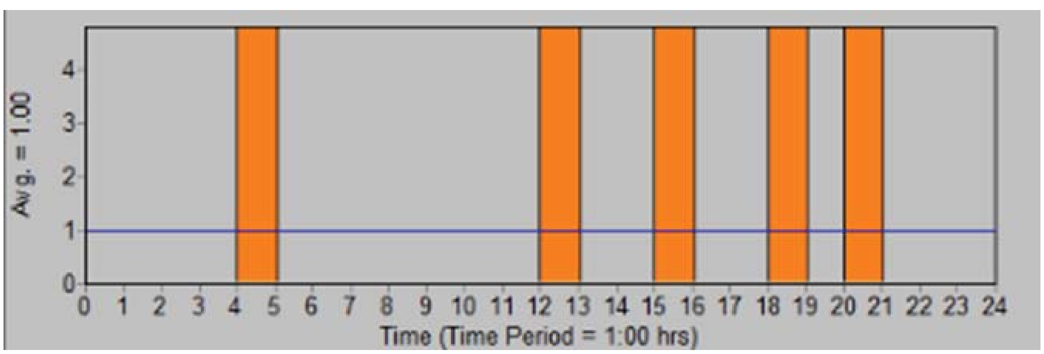

Figure 3.4 *EPANET screen capture of the demand pattern for Mosque use*

A fourth, and final, time pattern was assigned for the Keur Samba community garden. The garden only demands water twice a day for irrigating: approximately 5:00 A.M. to 9:00 A.M. and 4:00 P.M to 8:00 P.M. For these hours a multiplier of 3 was applied to the base demand values.

Figure 3.5 *EPANET screen capture of the hourly demand for community garden irrigation*

Reservoir and Tank Properties

The information for the tank, pump, and reservoir was assembled using a report prepared for the Ministry of Mines, Energy, and Water, *Ministere des Mines, de l'energie et de l'hydraulique,* regarding the technical aspects of the water tower installed in Keur Lamine. An abridged copy of the report is included in Appendix D.

EPANET requires a tank elevation, initial water level, minimum and maximum water level, and a diameter.

Table 3.5 is a summary of the tank properties. The size of the tank was calculated using the total capacity and solving for the values of the radii (Eq. 3-4) and height. Given the tank volume of 100 m^3 and a height of 6 meters, a bottom and top radii of 1.5 meters and 3 meters were chosen as the best fit values for this tank.

Volume of a circular truncated cone:

$$V = \frac{1}{3}\pi\left(r_1^2 + r_1 r_2 + r_2^2\right)h \quad \textbf{3-4}$$

r_1 = lower radius, m
r_2 = upper radius, m
h = height, m

Table 3.5 *EPANET inputs for the tank at the study site*

Tank	(meters)
Elevation	30.0
Initial Level	4.0
Minimum Level	0.0
Maximum Level	6.0
Diameter	4.5

The reservoir in EPANET is representative of the groundwater aquifer and for this water system the reservoir equals the static water level minus the calculated drawdown value. Information provided in the technical report gave a static water level of 17.55 meters below ground level and provided drawdown levels for four different flow rates (
Table 3.6) (Senegal 2001). This information was applied using Jacob's method for equating values for the head-loss (B) and well-loss (C) coefficients to account for the overall head losses in the pumping well (Duffield and Rumbaugh 1991).

$$S_w = BQ + CQ^2 \qquad \textbf{3-5}$$

S_w = drawdown in pumped well
B = head-loss coefficient
Q = pumping rate
C = well-loss coefficient

Table 3.6 *Reservoir data calculated from technical report to compute Well-loss and Head-loss coefficients ((Senegal 2001)*

Flow, Q (m^3/hr)	Flow, Q (lps)	Drawdown, s (m)	s/Q
14.4	4.0	1.4	0.3547
29.9	8.4	3.5	0.4218
45.0	12.6	5.5	0.4365
60.0	16.8	7.8	0.4634

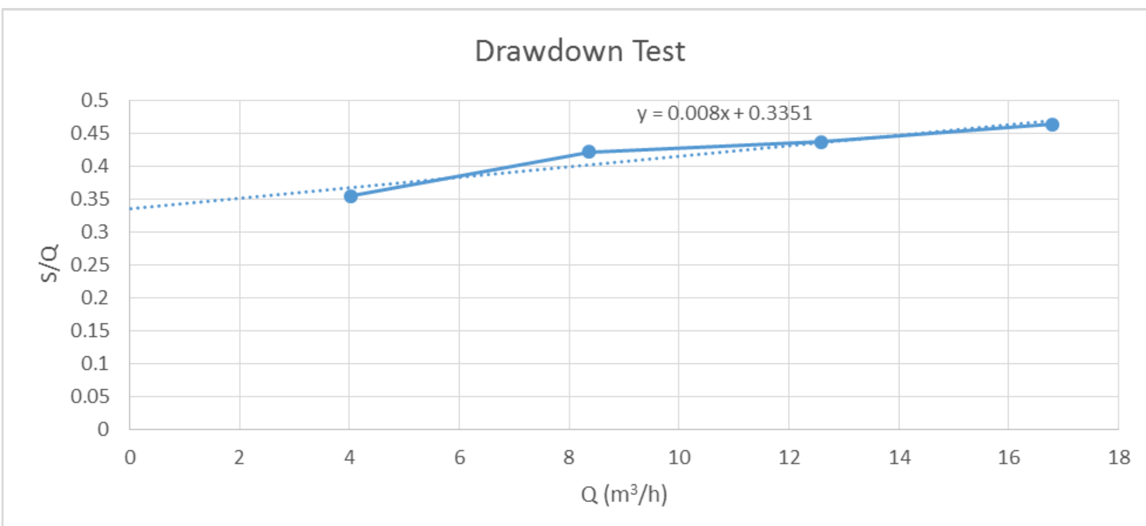

Figure 3.6 *Plotted drawdown and flow values with linear trend line*

The value, C is represented by the slope of the straight line and the value, B is where the line intercepts the vertical axis. When entering elevations into EPANET, 14 meters was

assumed to be the ground surface elevation and all other elevations were calculated relative to this value.

Table 3.7 *Summary of calculated drawdown values for reservoir in EPANET*

Variables	EPANET input
C	0.008
B	0.335
Q (liters/second)	8.130
Calculated Drawdown, S_w, (meters)	20.83

Pump Properties

A pump curve was assigned to the system's Grundfos submersible pump (model SP 30-7), as indicated in the technical report, along with the pump specifications (Grundfos 2015). Figure 3.7 is a snapshot of the pump curve in EPANET.

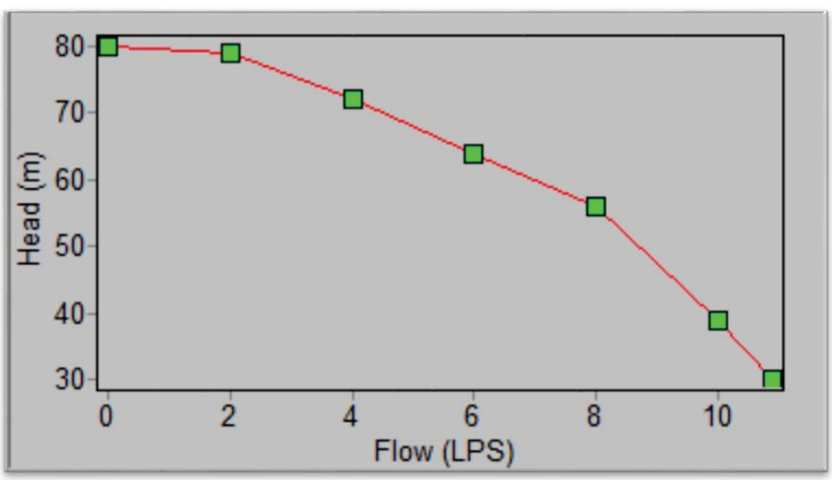

Figure 3.7 *EPANET screen capture of the Pump Curve*

Using the Control Editor in EPANET, the model was simulated to have the pump automatically turn on and off based on the water level in the tank. The pump turned on when the tank's capacity became less than half full and turned off when the tank was filled to capacity.

Pipe Properties

A handheld Garmin eTrex® 10 Global Positioning System was used to mark waypoints in the water distribution system, specifically, the water tower in Keur Lamine, and the four community faucets in Keur Samba. From these points, the lengths of pipes were determined by using the path tool in Google Earth to estimate elevations and distances between the waypoints. A pipe diameter of 63 mm, or 2.5 inches, was used for the whole system based on the pipe used when the author assisted installing a branch off of the existing system. Figure 3.8 provides a close-up of the PVC used in the system and the process of installing a branch to the community garden in Keur Samba.

Figure 3.8 *Pipe installed for community garden branch, March 2014 (photo by author)*

To create a representation of the system, the author chose best-fit branch lines based on village layout and from experience working with the system designer gathered when installing new branches. Figure 3.9 is a depiction of pipe layouts within the village of Keur Samba.

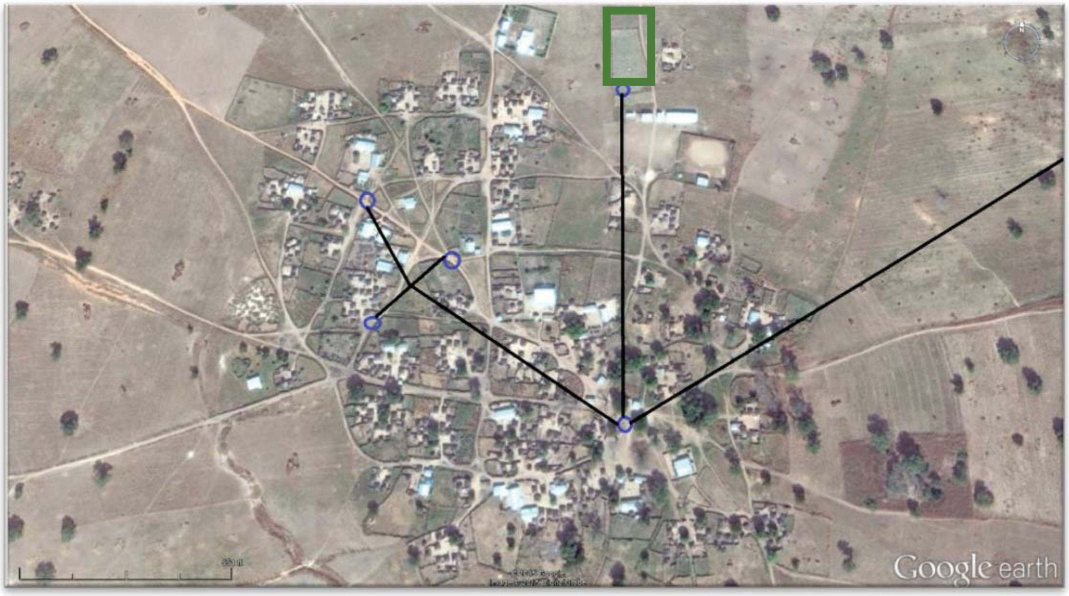

Figure 3.9 *Detailed image of water taps in Keur Samba superimposed on aerial photo. The community garden is enclosed in the green circle. (Image source: Google Earth)*

Pipe roughness coefficient is used for computing head loss for flow in the pipe. EPANET gives the option of three different formulas for computing the head lost by water in the pipe due to friction with the pipe walls: the Hazen-Williams formula, Darcy-Weisbach, or the Chezy-Manning formula. For this model, the Hazen-Williams, which is the most commonly used head-loss formula in the United States was used (Rossman 2000). The EPANET manual lists a value ranging from 140-150 for the Hazen-Williams C-factor as appropriate for plastic. To be conservative, a value of 150 was used for all the pipes in this study.

Project Analysis Units

System-wide pressures were desired to be at a minimum value of 20 psi (14 m of head) and a maximum value of 100 psi (70 m of head) for normal operations (Chase 2000). The resulting pressures, displayed in Figure 3.10 and Figure 3.11 below, validated that the EPANET model was an accurate representation of the current and scaled-up systems, and could be used in the feasibility analysis for *Jatropha curcas* oil substitution.

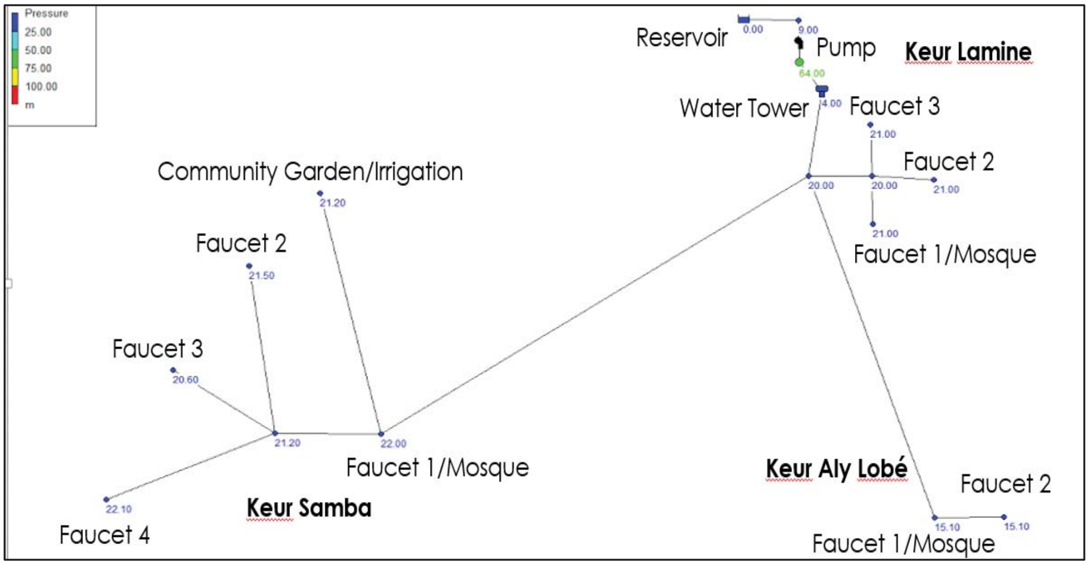

Figure 3.10 *EPANET Screen Capture for Current System providing 15 l/p/d and intermittent supply with individual nodal pressures displayed. Pressure units are in meters of head.*

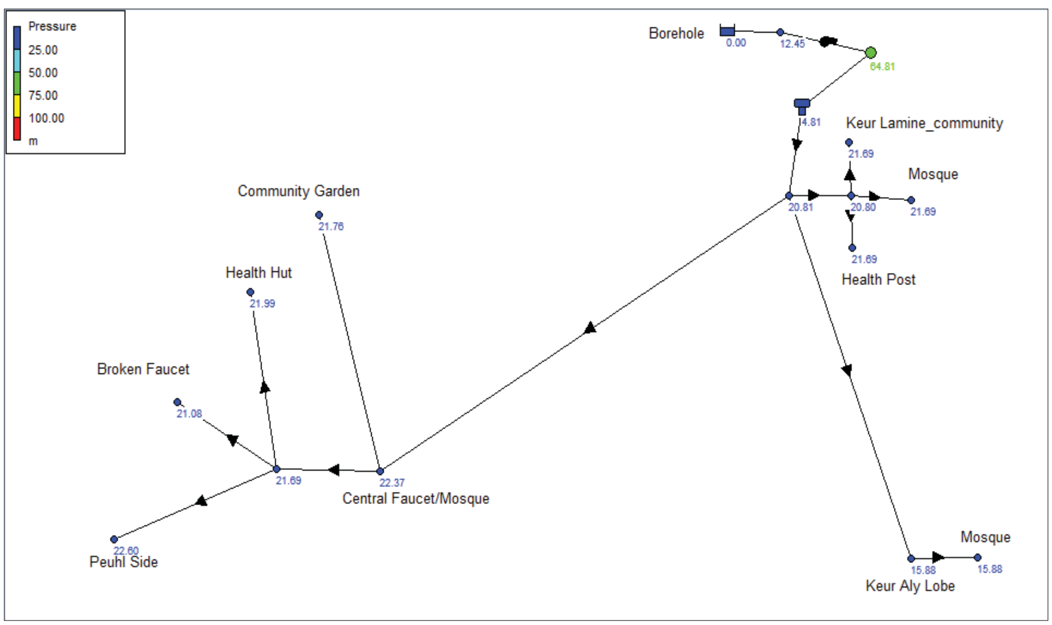

Figure 3.11 *EPANET Screen Capture for Current System providing 20 l/p/d and Continuous Supply with individual nodal pressures displayed*

Initially, both simulations received 'system unbalanced' warning messages from EPANET meaning the hydraulic results produced for the analysis were inaccurate. In order to

eliminate the unbalanced conditions, the convergence accuracy requirement was changed from 0.001 to 0.002 in the project's Hydraulic Options. This change allowed both models, and all future models, to run successfully. While the suggested default value in EPANET is 0.001, the EPANET manual recommends loosening the accuracy requirement value to allow the trials to run to completion, thereby producing accurate hydraulic results for the model (Rossman 2000).

Pump Fuel Properties

The pump in Keur Samba's water distribution system is powered by a diesel engine generator. The manager of the water tower is responsible for managing the fuel for the generator and running the pump. Based on reports from the manager for this system, the best case scenario for the current system, meaning payments had been received and diesel was available for purchase, the system requires 3 liters of diesel per day. Based on this amount, and the hydraulic model created in EPANET, required pumping time is only an hour a day to provide intermittent flow for the current system. When the system was scaled-up to provide 20 liters of water per person per day and continuous flow, the pump needed to run for two hours a day. This increases the diesel required to run the system to 6 liters per day. Diesel engines are at a minimum 2.5 kW (3.35 HP) in order to be suitable for pumping system application (Ghoneim 2006). In Table 3.8 an engine power of 6.7 kW was selected as the closest representative of the Keur Samba system generator which also consumes diesel oil at a rate of 3.0 liters per hour.

Using the new pumping time as modeled in EPANET to meet basic access and continuous flow for all users, an annual amount of 2190 liters of diesel is required to fuel the water distribution system.

Table 3.8 *Theoretical fuel consumption of well-maintained motorized pumps data (Awulachew, Lemperiere, and Tulu 2009)*

Engine power KW	Consumption of diesel oil (l/hr)
1.5	0.7
3.7	1.7
5.2	2.4
6.7	3.0

Jatropha curcas *Planting Establishment*

Two different planting schemes will be analyzed in this report: first, the use of *Jatropha curcas* as an intercropping species incorporated into farmers' groundnut fields, and second, an irrigated plantation of *Jatropha curcas* to be established in the community garden. These two areas are highlighted in the image below. A planting density of 15-25 cm between trees was chosen as ideal for groundnut intercropping based on a trial study completed at the *Institut Sénégalais de Recherches Agricoles* (ISRA) station in Fanaye, Senegal (Simpson 2009). A planting density of 2 m x 2 m was chosen for the irrigated *Jatropha curcas* to be cultivated in the community garden. This planting scheme produces 2500 plants per hectare and is a common planting scheme for oil productions (Achten et al. 2008). The community garden encloses a space of 5400 m^2 (0.54 ha) and the highlighted green lines total 960 meters.

Figure 3.12 *Rainfed* Jatropha curcas *(black lines) intercropped with groundnuts (brown ovals) and millet or corn (yellow circles) (Image source: Google Earth)*

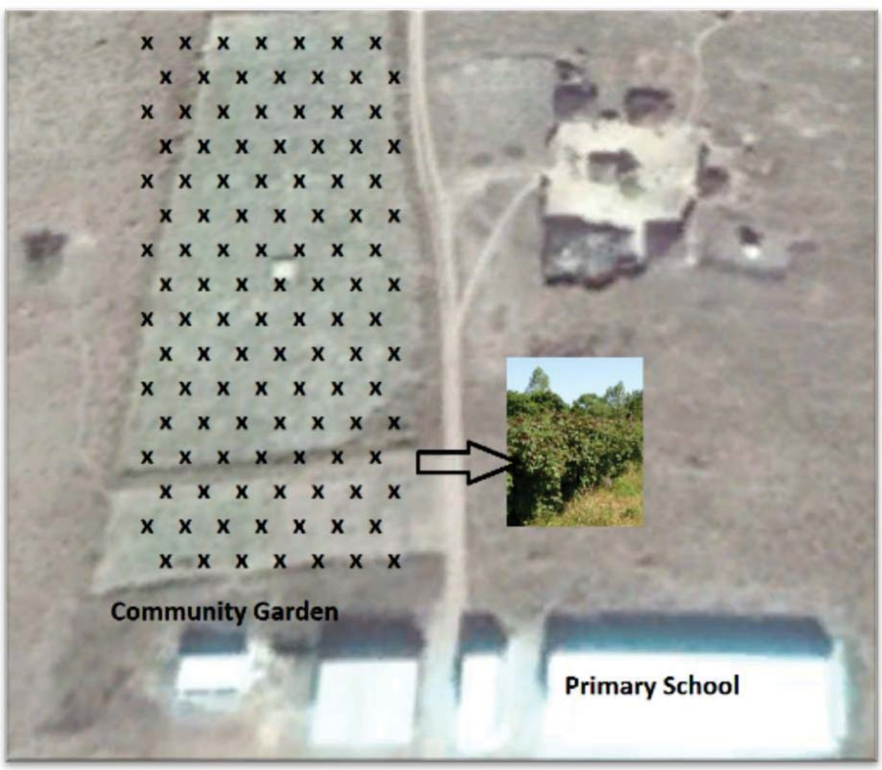

Figure 3.13 *Irrigated* Jatropha curcas *indicated by black X planted in Keur Samba's community garden at 2 m hexagonal spacing (Image source: Google Earth)*

The yield prediction of *Jatropha curcas* seeds per hectare varies widely from case to case and is the least consistent variable according to research available for predicting yields from *Jatropha curcas* plantations. A study in Mali found that using *Jatropha curcas* in a hedgerow produced 0.9 kg of dry seed per meter of hedge (Jongschaap et al. 2007). This value will be used when calculating yield for the rainfed, groundnut intercropped *Jatropha curcas* planting schemes. For the irrigated plantation, a yield of 2.5 tons $ha^{-1}yr^{-1}$ was recommended as achievable for semi-arid areas (Achten et al. 2008). This value seems practical, and even conservative, when compared to other reported yields ranging from 0.5 – 12 tons ha^{-1} and 5 tons ha^{-1}(Jongschaap et al. 2007).

Calculations:

Rainfed

0.9 kg of seed per meter of hedge × 960 meters = 864 kg of dry seeds

Irrigated

2.5 tons (2500 kg per ha^{-1}) × 0.54 ha = 1350 kg of dry seeds

Oil Extraction

To extract the oil in this case study, the traditional technology of an antique groundnut oil press was used when calculating process time and total oil production. This technology already exists in Keur Samba and the village is experienced in the processes of de-hulling, grinding, steaming, and pressing as it is similar to the process for groundnut production. The following data was taken from a case study conducted in Senegal and will be used when calculating equivalent times for the case of Keur Samba. Using an antique groundnut press, 25% of oil was recovered from the seeds and only 25 kg of seeds were processed every four hours (Simpson 2009). Based on this study, a ratio of 4.375 kg of *Jatropha curcas* seeds to produce 1 liter of oil was found, compared to the more favorable ratio of 4 kg of seeds to 1 liter of oil more commonly used in oil extraction calculations (Adhikari and Wegstein 2011).

Calculations:

Rainfed

$$864 \text{ kg of dry seeds} \times \frac{1 \text{ liter of } Jcurcas \text{ oil}}{4.375 \text{ kg of dry seeds}} = \quad 198 \text{ liters of } \textit{Jatropha curcas} \text{ oil}$$

Community Garden Irrigated

$$1350 \text{ kg of dry seeds} \times \frac{1 \text{ liter of } Jcurcas \text{ oil}}{4.375 \text{ kg of dry seeds}} = \quad 309 \text{ liters of } \textit{Jatropha curcas} \text{ oil}$$

Rainfed and community garden *Jatropha curcas* production only supplies 507 liters of oil annually. This is not enough to meet the current needs of the water distribution system, approximately 1600 liters short to achieve Scenario B. Based on the success of individual households producing *Jatropha curcas* for oil in Nepal (Karlsson and Banda 2009, Adhikari and Wegstein 2011) the required production, per household, in all three communities was calculated. Using the census data from Appendix D, a total of 196 households was used for the communities in the calculations.

Oil Requirement for Scenario A = 1095 liters per year

1095 liters – 507 liters = 588 liters

$$Land\ Requirement = 588\ l \times \frac{4.375\ kg\ of\ dry\ seeds}{1\ liter\ of\ Jcurcas\ oil} \times \frac{1\ hectare}{2500\ kg} = \quad 1.03 \text{ ha}$$

Per Household:

$$1.03 \text{ ha} * 10{,}000 \text{ m}^2 \text{ ha}^{-1} * (196 \text{ household})^{-1} = \quad 52.5 \text{ m}^2 \text{ per household}$$

Oil Requirement for Scenario B = 2190 liters

2190 liters – 507 liters = 1683 liters

$$Land\ Requirement = 1683\ l \times \frac{4.375\ kg\ of\ dry\ seeds}{1\ liter\ of\ Jcurcas\ oil} \times \frac{1\ hectare}{2500\ kg} = \quad 2.95\ \text{ha}$$

150 m^{2}per household

Seed Processing

A case study was found that provided time requirements using an antique groundnut press. These values were applied to the current study as the community of Keur Samba already has the materials and experience from processing groundnuts, and so could likely apply these to processing *Jatropha curcas* seeds (Simpson 2009). The town of Keur Samba has three groundnut presses, in addition to two in Keur Lamine and one in Keur Aly Lobe for a total of six groundnut presses to process the seeds.

$$Process\ Time = \frac{4\ hours}{25\ kg\ of\ seed} \times\ total\ dry\ seed\ production\ (kg)$$

Table 3.9 *Calculated Processing times for Scenario I1: supplying Scenario B with* Jatropha curcas *oil*

Scenario I1	Dry seeds (kg)	Processing Time (days)
Rainfed	864	
Community Garden	1350	
Households	7375	
Total	**9589**	**10.65**

Irrigation Requirement

Total rainfall for the Koungheul Region of Senegal averaged 487 mm from 1990 to 2009 (TheWorldBankGroup 2015). The ideal, recommended irrigation amounts vary widely for *Jatropha curcas*. An optimal growth rate of the trees was found when 1200 mm was

available for the plants throughout the year (Jongschaap et al. 2007, Beerens 2007). Using this value, an additional 712.66 mm of water must be applied to meet the optimal water availability. The dry season for Keur Samba lasts approximately 300 days. To apply 712.66 mm over the dry season, the plants must receive 2.6 mm per day or 9.50 liters per plant per day.

Calculations:

$$Irr_{Req} = (712.66\ \frac{liters}{m^2} \times \frac{10000\ m^2}{ha} \times \frac{ha}{2500\ plants}) \div 300\ days$$

$$Irr_{Req} = 9.50\ liters/plant/day$$

Increased water use:

Community Garden

0.54 ha * 2500 plants ha^{-1} * 9.50 liters/plants/day = 12825.00 liters/day

Scenario B; supplying 20 l/p/d and continuous access to community users

2.95 ha * 2500 plants ha^{-1} * 9.50 liters/plants/day = 24462.5 liters/day

Incorporating Irrigation into EPANET model

To investigate the feasibility of using *Jatropha curcas* trees to fuel the existing water distribution system, irrigation demands were added to the user demands in the EPANET model by adding a second demand to each node. In EPANET, each node can have multiple demands associated with one outlet, allowing for a faucet to be given multiple demands that correspond to specific time patterns.

Table 3.10 *Demands for Junction 11, central faucet and Mosque outlet in Keur Samba as seen in EPANET model for Scenario I1*

Demand Category	Base Demand (lps)	Time Demand Pattern*	Category
1	0.064	2	Basic Access, Users
2	0.0028	5	Mosque
3	0.0909	6	*Jatropha curcas* Irrigation

*As depicted in Figures 3.2, 3.3, 3.4 & 3.5

The household consumption demands remained constant for all case studies, based on the value calculated to provide 20 L/p/day and continuous access. To determine if *Jatropha curcas* cultivation for oil production was feasible, a second irrigation demand was associated with each node. This irrigation demand was partitioned using the same number of households assigned to each node determined previously, and according to the number of trees each households could be expected to cultivate.

It was previously calculated, based on the pumping times from the EPANET model, that to provide fuel for Scenario B in EPANET, an increased fuel use of 6 liters per day would be required to run the pump long enough to supply 20 liters per person per day, with continuous access, throughout the daytime hours. A second demand for irrigating enough *Jatropha curcas* trees to provide 6 liters of oil a day was added to each community node in the EPANET model. This was accomplished by using the demand categories option which allows for each node to be assigned a separate base demand and time pattern associated with both household and irrigation requirements.

When the new irrigation base demands were entered into EPANET, the system produced pressures below 14 meters. To correct for this head loss in the distribution system, the threshold water height in the tank, below which the pump was set to turn on, was increased, in order to increase the elevation differences between the tank and the nodes. Because the

tank is now supplying more water and must remain at a higher level to maintain adequate pressure throughout the system, the pump must be on for a longer period of time, resulting in more fuel required to meet the system needs of both consumer and irrigation demands.

When the model produced system pressures that remained above 14 meters, the pump time was then analyzed over the course of a week, 168 hours, to determine the fuel requirement. This was done by selecting the time analysis for the pump and counting how many hours it was running for the week, and then averaging to get a daily pumping time. In Scenario I1 the pump would need to be on for an additional 4.29 hours per day. This pumping value was then used to re-calculate the diesel required to run the system for this amount of time each day in order to supply water for the village and for irrigating *Jatropha curcas* trees. The calculated value was 12.86 liters of diesel per day. This value was then used in calculating the next required irrigation amount to produce enough trees to provide 12.86 liters of *Jatropha curcas* oil. The following proposed analysis procedure describes the methods used in determining the feasibility of using *Jatropha curcas*-derived oil for powering any given water distribution system.

SYSTEM SUSTAINABILITY ANALYSIS PROCEDURE

The following general procedure allows project managers to decide if *Jatropha curcas* is a viable substitute for fueling the current water distribution system.

1. Model current water distribution system in EPANET

2. Increase user demands for continuous sufficient amounts to meet optimal water needs (optional)

3. Inspect results and time period analysis for pump

4. Based on number of hours pump is running, estimate fuel needs

5. Calculate *Jatropha curcas* irrigation requirements to meet these fuel needs

6. Add an additional base demand for irrigation needs (can partition based on community or household)
7. Re-run model
8. Look at results for pump hours of operation
9. If pumping time is increased, repeat Steps 6-8
10. Procedure is finished when pumping time remains stable or use of *Jatropha curcas* cultivation as a fuel replacement is determined to be not feasible (land or water requirement)

Anticipated yields from *Jatropha curcas* cultivation

For the irrigated plantations, a yield of 2.5 tons (2500 kg) $ha^{-1}yr^{-1}$ was recommended as achievable for semi-arid areas. Yield predictions for *Jatropha curcas* plantation vary widely from 0.4 to 12 tons per hectare per year (Achten et al. 2008). Depending on how the trees are originally propagated, *Jatropha curcas* trees can produce seeds after 9-12 months and after 4-5 years are considered established and will produce to their full capacity (Simpson 2009, Nahar and Ozores-Hampton 2014).

Figure 3.14 shows a projected timeline over 8 years of seed production from establishment to an eight year old *Jatropha curcas* plantation. The irrigated *Jatropha curcas* trees reach full capacity at 5 years of age, while the rainfed trees continue to increase slightly in production. The values used in this case study were chosen based on conservative estimates of an established *Jatropha curcas* production.

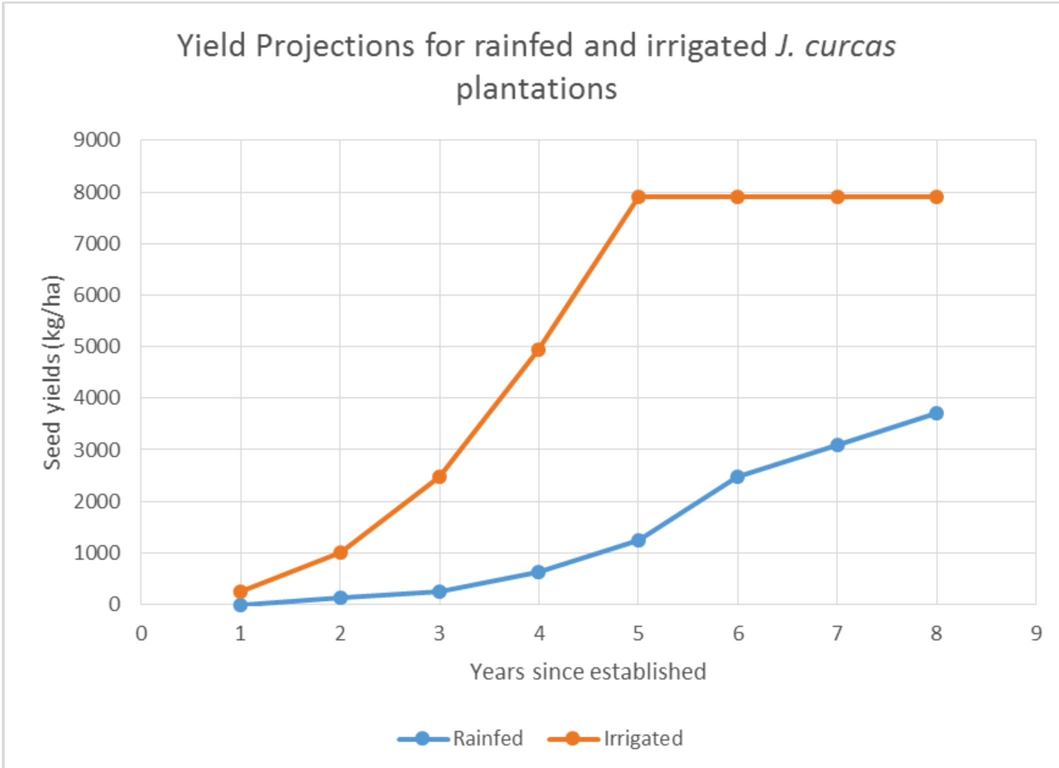

Figure 3.14 *Seed yield in kilograms per hectare of rainfed and irrigated Jatropha curcas seeds from establishment to 8 years of age (Eckart and Henshaw 2012)*

Jatropha curcas can be irrigated with the goal of achieving two harvests per season. However, an irrigation amount of 1200 mm was chosen as the optimal amount to produce a high number of seeds per tree in combination with a high oil content (Jongschaap et al. 2007). An increased irrigation and fertilization application could be considered if a community was interested and it was feasible for the given environmental, social, and economic constraints present in a community to attain two harvests. In this case study, the marginal soils and traditional farming practices of the study population are such that one, good harvest, is a far more suitable goal than increasing irrigation and fertilizer application in the hopes of achieving a second harvest.

Chapter 4 - Results

After running seven different models (Scenarios A, B and I1 through I5) in EPANET with each scenario irrigating enough trees to produce fuel for the previous scenario, it was determined that Keur Samba's current water distribution system could not support the increased demand from irrigating *Jatropha curcas* trees to provide enough seeds to meet all the diesel needed to run the pump. Table 4.1 displays the daily oil required to run the pump for each system, the corresponding irrigation required, the land required to cultivate the trees, and the time requirement to process the seeds.

Rows 1 and 2 indicate the rainfed, intercropping *Jatropha curcas* and irrigated community garden planting schemes, respectively. Additionally, Scenario A is the current system operating at 15 L/p/d and intermittent access; Scenario B is the WHO-recommended 20 L/p/d continuous access; and Scenarios I1-I5 attempt to iteratively balance the needs of sufficient water to irrigate seed-producing trees, and the rising fuel demands to accommodate the increasing pump run times needed for irrigation. This is summarized in Table 4.1.

Table 4.1 *Calculated Jatropha curcas oil produced from each scenario used in EPANET, along with the corresponding land for cultivation, required irrigation and process time for each scenario*

	Oil Required (liters/day)	Land Requirement (hectares)	Irrigation Required (liters/day)	*Jatropha* oil produced (liters/year)	Process Time (hours)
Rainfed	0	960 meters of hedge	0	197	6.40
Community Garden	0	0.54	12,800	309	36.0
A	3.00	0	0	0	0
B	6.00	0	0	0	0
I1	12.9	2.95	69,970	1,680	196
I2	23.1	7.78	187,000	4,497	525
I3	37.3	14.2	336,600	8,097	945
I4	72	23.5	557,700	13,400	1,570
I5	100	45.1	1,650,000	25,800	3,010

Table 4.2 shows the calculated daily requirements for each scenario to meet oil and irrigation needs of the water distribution system and *Jatropha curcas* plantations. The water required, column 3, combines user demands and irrigation demands for each day. Figure 4.1 displays the increasing requirements.

Table 4.2 *Summary of Oil and Irrigation Requirements*

	Diesel Required (liters/day)	Water Required (liters/day)	*Jatropha* oil produced (liters/day)
A	3.00	30,070	0
B	6.00	39,890	0
1.1	12.86	122,660	4.60
1.2	23.14	239,630	12.30
1.3	37.29	389,230	22.18
1.4	72.00	610,280	36.75
1.5	100.00	1,548,700	70.60

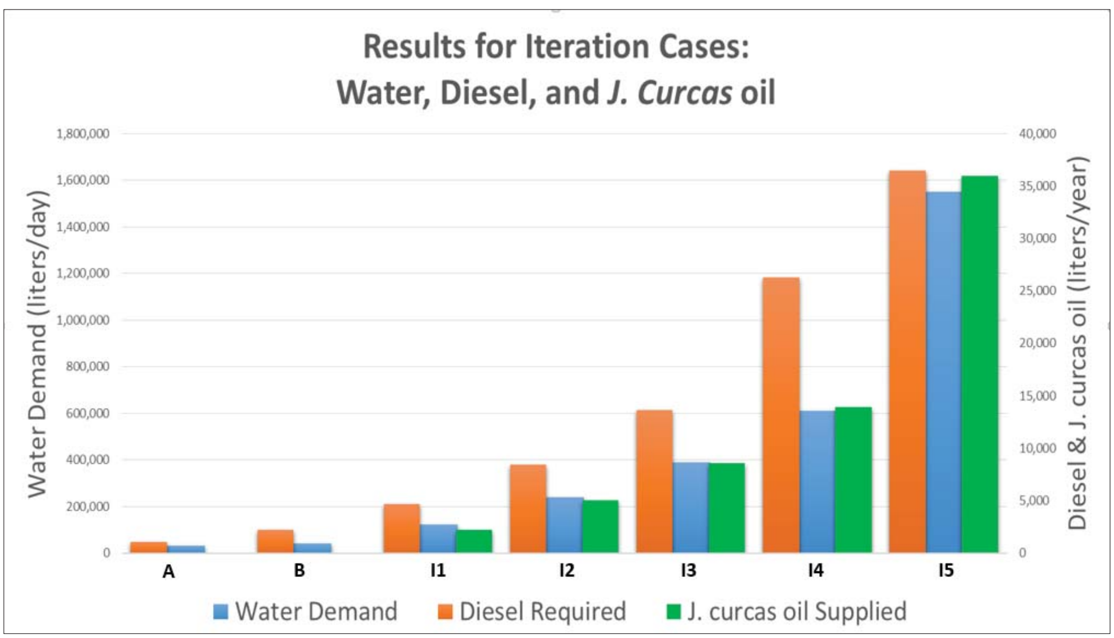

Figure 4.1 *Results for the seven scenarios modelled in EPANET displaying increasing water, diesel, and supplied Jatropha curcas oil.*

There are two values that were assumed in the *Jatropha curcas* calculations for this study that, if different initial values were chosen, would significantly change the results. These are the values for the recommended ideal irrigation amount of 1200 mm and the percent of oil recovered from each seed (1 liter of *Jatropha curcas* oil produced from 4.375 kg of dry seeds) (Simpson 2009). In order to make a recommendation that is cost-effective for the users of the water distribution system, two optional solutions are further investigated: (1) the use of greywater to irrigate the trees and (2) the incorporation of a multi-functional platform to increase the percent of usable oil recovered from each tree from 23% to 55%. Both of these solutions would decrease the demand of water from the water distribution system, therefore decreasing the amount of diesel/*Jatropha curcas* oil required to run the system.

Greywater Reuse

One solution to reducing the water demand of the system, while still supplying irrigation to the *Jatropha curcas* trees, is through the use of greywater. Greywater is untreated household wastewater that has not come into contact with sewage. In arid and semi-arid countries, like the region of Senegal in which this case study resides, it is especially important to consider alternative water sources like greywater for use in agricultural irrigation. A case study in the country of Oman researched the use of recycling ablution water, or water used for ritual self-cleansing before prayer, collected at mosques for irrigation. This study estimated that 80% of household water is greywater (Prathapar 2006). Harare, the capitol city and urban center of Zimbabwe, estimated only 60% of household water usage could be re-used as greywater (Madungwe 2007). In a study investigating rural, semi-arid areas of India, greywater represented 70% of domestic water use (Godfrey 2010).

Some risks associated with re-using greywater are the microorganisms and chemical contaminants that can be recycled with the water including harsh washing detergents or soaps, bacteria from dirty laundry, including fecal bacteria, and occasionally enteric pathogenic bacteria, like *Salmonella* (Godfrey 2010).

For 6 liters of oil a day, or 2190 liters of diesel a year, the current water distribution system that supplies the communities of Keur Samba, Keur Lamine, and Keur Aly Lobe can provide 20 liters of water per person a day with continuous access, in contrast to the intermittent access presently available. The objective of this section is to determine if the use of recycled greywater from households can meet the irrigation needs of *Jatropha curcas* trees planted in individual households for oil production to provide fuel for the water system.

Greywater Calculations

Using a value of 70% to represent water available to be applied as greywater for irrigation (Godfrey 2010), an average household can apply 140 liters a day (14 l/p/d with 10 people on average per household) to *Jatropha curcas* tree seed production. Using the irrigation requirement previously calculated of 9.5 liters/plant/day, each house would be able to irrigate 14.7 trees. Combining tree productions for all three communities, the overall oil produced by the 2881 trees is 659 liters annually. This could run the pump for 170.8 days.

Table 4.3 *Using recycled greywater requires an area of 1.15 ha and yields 658.56 liters of* Jatropha curcas *oil annually*

	Total Area (hectare)	Plants ha^{-1}	Yield (kg dry seed/ha)	Seed yield (kg)	*Jatropha curcas* Oil Production (liters)
Greywater	1.15	2,500	2,500	2,880	659

Combining Greywater with Irrigation Iterations

Incorporating recycled greywater into the required irrigation calculations for meeting the diesel needs of Scenario B, reduces the diesel requirement from 2190 liters to 1025 liters.

Calculations:

Greywater + Community Garden + Rainfed = (659 + 309 + 197) = 1165 liters

2190 liters required diesel – 1165 liters *Jatropha curcas* oil = 1025 liters

Table 4.4 *Combining recycled greywater with irrigation to meet diesel requirements for basic, continuous access water supply to communities*

Total Area (hectare)	Plants ha^{-1}	Yield (kg dry seed/ha)	Seed yield (kg)	*Jatropha curcas* Oil Production (liters)
1.79	2,500	2,500	4,475	1,025

When the new irrigation demands were modeled in EPANET, the daily diesel requirement remained similar to irrigation only demands, 12 liters per day or 4380 liters annually. The incorporation of recycled greywater would save users less than a liter of oil a day (Table 4.5).

Table 4.5 *Comparison of irrigation to a combination of greywater and irrigation diesel requirements*

	Irrigation	Greywater + Irrigation
Pumping Time (hour)	4.29	4
Diesel Required (liter)	12.86	12
Annual Diesel Required (liter)	4,693	4,380

Another alternative would be to incorporate a mechanical oil expeller to increase the percentage of oil extracted from each seed.

Mechanical Expeller

A multi-functional platform (MFP) consists of a simple diesel engine which is used to produce electricity and power agricultural processing equipment such as an oil expeller for *Jatropha curcas* seeds (Grimsby, Aune, and Johnsen 2012). Using an engine driven screw press, which can be powered by an MFP, 70 to 80% of the oil present in the seeds can be recovered (Eckart and Henshaw 2012). MFPs have had remarkable success in Mali. *Jatropha curcas* oil can be used directly to fuel the simple diesel engine used in MFPSs (Eckart and Henshaw 2012). A community group can create a formal organization to

request and purchase a MFP which is then subsidized 40-50% by international organizations, private investors, or various non-governmental organizations. Local skilled workers are in charge of installing, maintaining, and repairing the MFPs. A case study in Mali found the MFPs provided higher incomes, higher quality of life and social status, and allowed women to pursue educational opportunities and economic activities by freeing up two to six hours of a rural Malian woman's day (Simpson 2009).

The planned installation of Multi-Functional Platforms in Senegal as a part of the PREP (Program against Energy Poverty) has been on hold since the change of the program directorate from the Ministry of Energy to the Ministry of Agriculture (Simpson 2009).

Table 4.6 *Jatropha curcas oil extraction percentages, manual versus mechanical (Nahar and Ozores-Hampton 2014)*

	Dry seed (kg)	*Jatropha curcas* oil (liters)	Oil yield % (% of contained oil)
Hand-operated Expeller	4.4	1	20-30%[1]
Engine-driven Screw Press	1.8	1	77%[2] 68-80%[3]

[1](Simpson, 2009)
[2](Cynthia and Teong 2011)
[3](Achten et al. 2008)

For all previous calculations, it was assumed that an antique groundnut press would be used to process the seeds. However, this limits the amount of oil recovered from the seed to only 23%. Other studies use mechanical methods of extracting oil. Using the values from Table 4.6, an engine-driven screw press can produce 1 liter of *Jatropha curcas* oil from 1.8 kg of dry seeds (Nahar and Ozores-Hampton 2014).

The yield from the irrigated community garden and rainfed *Jatropha curcas* cultivation will remain the same as the previously calculated dry seed yields; however, the oil extraction efficiency increases. Therefore, the total *Jatropha curcas* oil produced was

recalculated. The water distribution system requires 2190 liters of *Jatropha curcas* oil annually to provide 20 liters of continuous water supply to each person per day.

It was previously calculated that the community garden will produce 1350 kg of dry seed. Using the ratio of 1 liter of *Jatropha curcas* oil for every 1.8 kg of dry seed (Table 4.6) the community garden can produce 750 liters of *Jatropha curcas* oil. The rainfed *Jatropha curcas* produces 864 kg of dry seed, yielding 480 liters of *Jatropha curcas* oil. These combine for a total of 1230 liters from the community garden and rainfed hedgerows. Home garden production will have to account for 960 liters of *Jatropha curcas* oil to make up the difference.

$$Planting\ space\ for\ home\ gardens = \frac{960\ liters\ of\ oil\ \times \frac{1.8\ kg\ of\ dry\ seed}{1.0\ liter\ of\ oil}}{2500\ kg\ ha^{-1}}$$

$$= 0.69\ ha$$

The whole community must cultivate 0.69 hectares, which amounts to 35 m^2 per home compound.

When processing seeds with a manual groundnut press, 2.95 ha of irrigated *Jatropha curcas* plantations was required with an increased pumping time of 4.29 hours a day to meet these irrigation demands plus basic user demands for household consumption. When new irrigation demands were entered into EPANET for *Jatropha curcas* production with a mechanical oil extractor, pumping time increased only slightly, from 2 to 2.7 hours to meet irrigation and basic use water demands. However, there was still an increase of 782 liters of diesel required to run the system, meaning the system is close, but not quite self-sufficient. The water distribution system is self-sufficient when the irrigation demands do not force an increase in pumping time so that the irrigated trees can produce enough oil to run the system's pump without requiring additional diesel for irrigation. A final scenario will be considered, combining greywater with a mechanical expeller.

Combining Greywater with a mechanical expeller

Combining MFP extraction with recycled greywater would provide 1599 liters of *Jatropha curcas* oil from the 1.15 ha of greywater irrigated home gardens. (Table 4.3).

Calculations

$$2881.2 \text{ kg of dry seeds}^{1} * \frac{1 \text{ ltr of } J.\,curcas \text{ oil}}{1.8 \text{ kg of dry seeds}}$$

$$= 1599 \text{ liters of } J.\,curcas \text{ oil}$$

This brings the total *Jatropha curcas* oil produced up to 2,827.84 liters annually. Table 4.7 summarizes fuel production.

Table 4.7 *Scenario F summary of oil produced from different planting schemes to achieve fuel self-sufficiency in the system*

Planting Scheme	*Jatropha curcas* oil produced (liters)
Rainfed	480
Community Garden	750
Recycled Greywater Home gardens	1600
Total	**2830**
Required Diesel	**2190**

The water distribution system requires 2,190 liters, leaving 637.84 liters to fuel the MFP. Using a case study conducted in Tanzania, a MFP, powered by a 10 HP lister engine, consumes 2.2 kg, or 1.7 liters, of Jatropha oil per hour (Grimsby, et al. 2012; Sanga and Meena 2008). The greywater irrigated Jatropha curcas trees could produce enough oil to run the MFP for approximately 375.2 hours or approximately an hour a day. Similar fuel

consumption values include 1.3 liters of Jatropha curcas oil per hour of MFP operation (Grothe and Uckert 2011). Using these values, *Jatropha curcas* trees could fuel the MFP for 490.6 hours or approximately 1.3 hours a day.

A case study in Mali found that for every one liter of fuel used in the crushing process, 21 liters of *Jatropha curcas* oil was produced (Weingart 2003). Using these values, the 638 liters of *Jatropha curcas* oil would provide enough fuel to process 13,395 liters of additional *Jatropha curcas* oil. Although further research would have to be conducted as to the fuel consumption of any new MFP, the *Jatropha curcas* oil produced in Scenario F appears sufficient to run the water distribution system pump, and fuel the MFP to process the seeds into oil.

Calculating Minimum Required Yield

One of the primary setbacks in the Senegalese biofuel initiative is the unrealistic yield expectations. As more research studies are produced on *Jatropha curcas* production, the expected versus actual seed yields are giving very different results. While the value chosen of 2500 kg per hectare seemed conservative for this region, new literature reports are reporting anywhere from 150 kg to, at the high end of the range, 2500 kg per hectare, see Appendix C for a collection of published *Jatropha curcas* yields. To provide farmers with a realistic expectation of seed yield needed for these communities to achieve fuel self-sufficiency, the required minimum yield of dry seeds per hectare was calculated.

It was necessary for the author to assume an initial tree cultivation scenario of 250 trees per household in the 2 m x 2 m, hexagonal spacing pattern with 2500 trees per hectare density in order to determine the minimum seed yield required for farmers to achieve fuel self-sufficiency for the system. This land requirement and number of trees was considered reasonable based on the author’s two years of working with the communities in tree extension and cultivation as a Peace Corps agroforestry extension agent. The following minimum seed yield was determined:

Calculations

0.1 ha * 2500 trees ha^{-1} = 250 trees

0.1 ha * 196 households in the water distribution system = 19.6 hectares

Seed Yield (kg of dry seed ha^{-1}) =

$$\frac{2800\ Required\ Diesel}{19.6\text{ ha } * \frac{1\ liter\ of\ \text{Jatropah curcas}\ oil}{1.8\ kg\ of\ dry\ seed}}$$

= 257.14 kg dry seed/ha

This value reflects a baseline yield that, based on actual and predicted literature reports, is reasonably achievable by Senegalese farmers. Appendix C - shows a summary of reported *Jatropha curcas* tree seed yields.

Figure 4.2 displays the results of the final scenarios incorporating greywater and a mechanical expeller. The final scenario, mechanical expeller and greywater, as displayed in Figure 4.2 is the only scenario where *Jatropha oil* was able to completely replace diesel in the system. This is displayed by the green column, *Jatropha curcas* oil, surpassing the orange column, diesel required to run the system, in the graph.

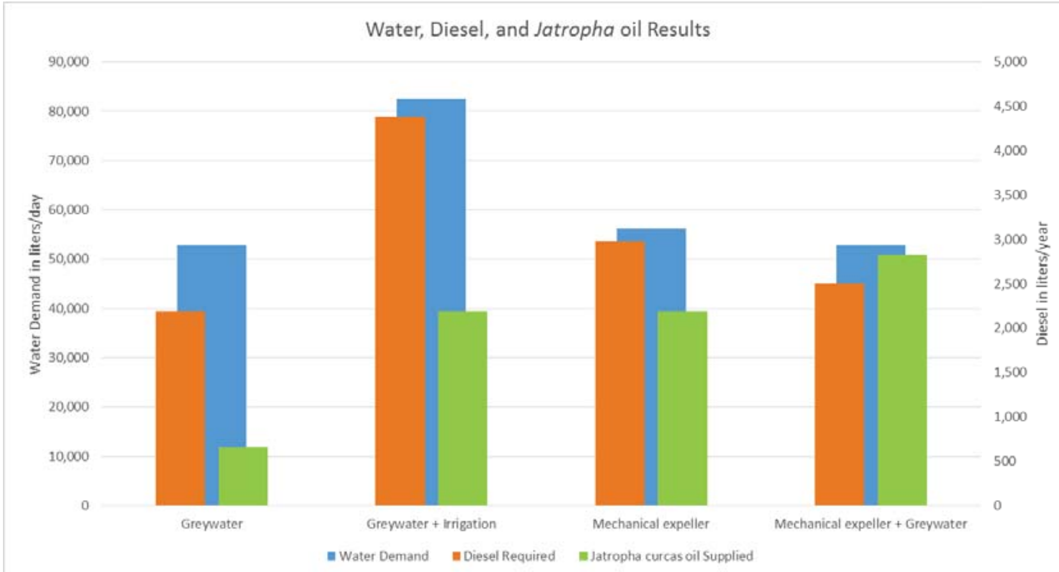

Figure 4.2 *Calculated water demand on water distribution system including user and irrigation requirements, the required diesel to fuel system, and Jatropha curcas oil produced by the different irrigation and oil extraction Scenarios*

Seed Yield over Time

All previous calculations used a seed yield value for *Jatropha curcas* trees based on a fully established tree (2500 kg per hectare at 2 m x 2 m hexagonal spacing). In order to determine the expected yields from tree establishment up until maturity, and therefore *Jatropha curcas* oil production over the first five years, seed yield values from an irrigated *Jatropha curcas* plantation over the course of eight years, was plotted in Figure 4.3 (Eckart and Henshaw 2012). Using Figure 4.3the initial five years of *Jatropha curcas* cultivation yields can be calculated for any scenario.

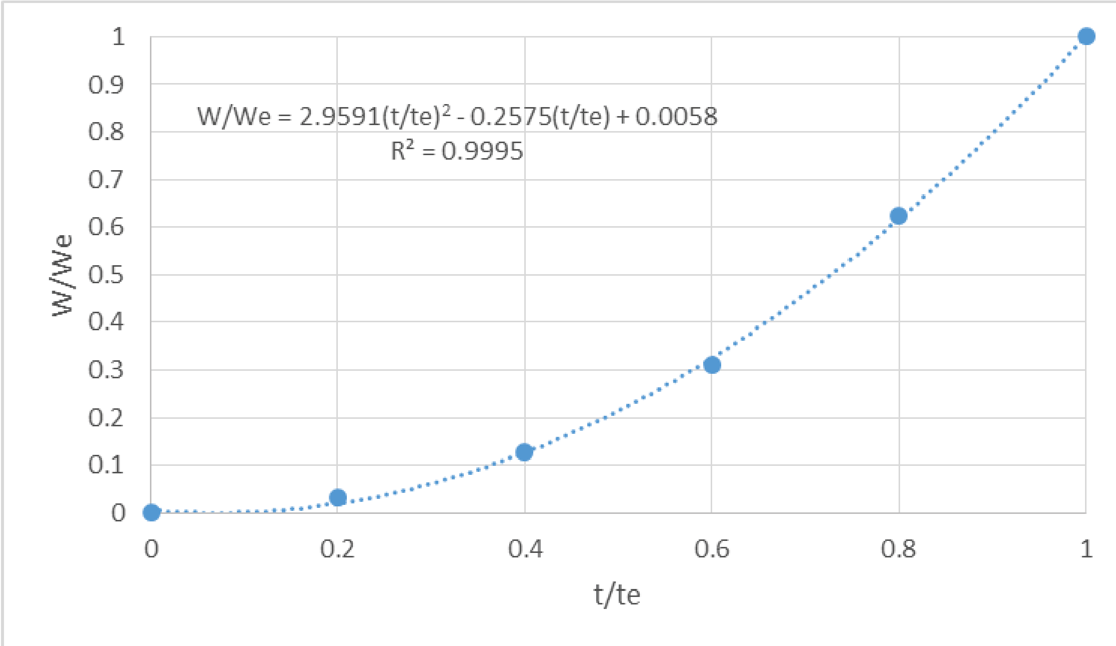

Figure 4.3 *Calculated Seed Yields for Jatropha curcas irrigated plantations (Eckart and Henshaw 2012)*

A best-fit line equation was generated, Equation 4-1. Using this equation, the five years can be calculated for the yields from *Jatropha curcas* plantations used in this case study.

$$W/W_e = 2.9591\,(t/t_e)^2 - 0.2575\left(t/t_e\right) + 0.0058 \qquad \textbf{4-1}$$

Where:
W = kg of seeds
W_e = kg of seeds from established plantations
t = time
t_e = time of tree establishment

The two types of oil expellers, mechanical and manual, used in the scenarios determined the total amount of land required to cultivate *Jatropha curcas* in order to provide enough seeds to fuel the water distribution system. For all mechanical scenarios, 0.69 hectares were required, and for manual processing (using a groundnut press), 2.95 hectares were required

to provide basic, continuous access to the communities. Figure 4.4 compares the calculated yield increases over time for the two different cases.

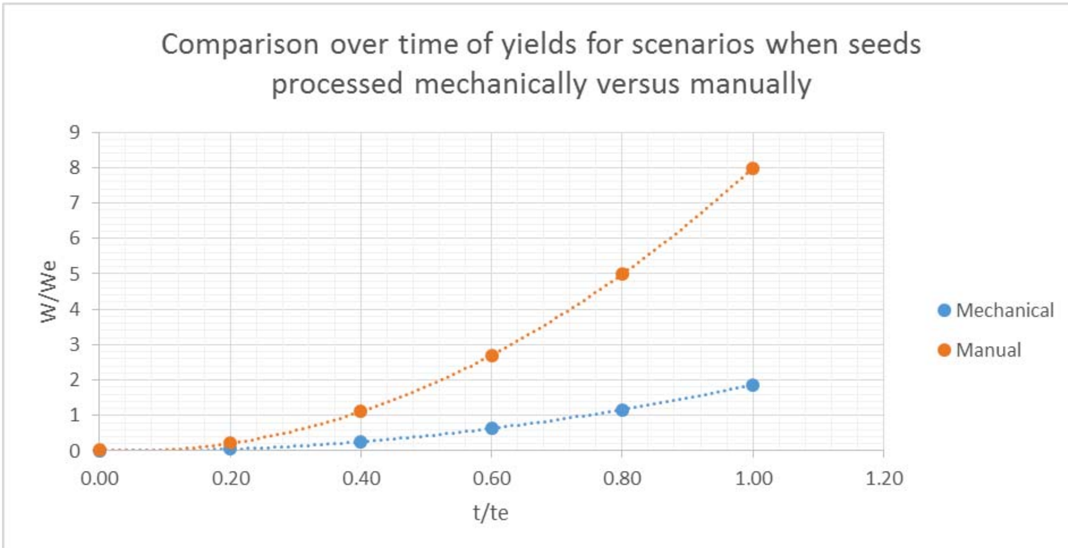

Figure 4.4 *Mechanical versus manual yield progression showing that manual pressing needs more seeds and water for the same amount of oil extraction*

The use of a manual oil expeller decreases the efficiency of oil retrieved from the seeds; therefore, more trees must be cultivated to provide the same amount of oil that a mechanical oil expeller can provide. Figure 4.4 can be used to estimate the rate at which a village can expect to receive oil returns from a newly established plantation.

Payback Period

What is of even more interest are the financial gains a community can expect from a specific scenario. Table 4.8 calculates the financial costs or savings a community would accrue once the *Jatropha curcas* trees are fully established after five years.

Table 4.8 *Calculated financial benefits of different scenarios as compared to the current system. Red numbers indicate an increase in overall annual spending on diesel.*

Scenario	Diesel Required	Annual Diesel Cost	Current System	Annual Cost
	Liters/year	USD $1.53[1]	Intermittent Access	USD
Mechanical, Greywater	0.00	$0.00	$1,675.35	$1,675.35
Mechanical, No Greywater	782.14	$1,196.68	$1,675.35	$478.67
Manual, Greywater	1,533.00	$2,345.49	$1,675.35	$670.14
Manual, No Greywater	2,502.86	$3,829.38	$1,675.35	$2,154.03

[1] Using a value of $1.53 for the current price of a liter of diesel in Senegal (The World Bank, 2015).

The current system uses the fuel requirements for intermittent access, only 3 liters a day, or 1095 liters a year as a comparison. Compared to current community annual spending on diesel, both cases involving mechanical extraction are financially beneficial to the community after five years; however, both cases using manual extraction of the seeds result in additional diesel costs to the community. An increase in cost reflects the added pumping time and associated fuel costs of providing irrigation from the water distribution system to cultivate *Jatropha curcas* trees.

Figure 4.5 displays the four scenarios: mechanical-greywater, mechanical-no greywater, manual-greywater, and manual-no greywater and the percent of total current costs each case would amount to annually after five years.

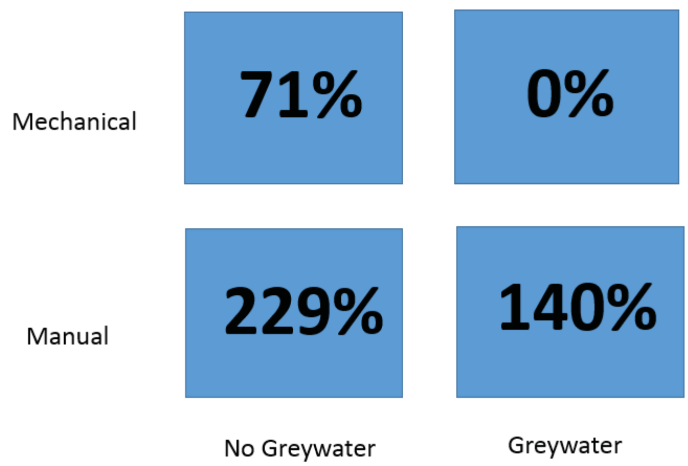

Figure 4.5 *After 5 years, the percent community must spend on diesel as compared to current system of intermittent access and 15 liters of water per person per day.*

Note: Current diesel costs were calculated based on the intermittent system the author was most familiar with, although cost, as well as availability of diesel to purchase, were limiting factors to powering the water distribution system.

It is also of interest to compare each case to an improved, continuous access water distribution system. To provide continuous, basic access to all community members, $3,350.70 would need to be spent annually on diesel. The percent of spending on diesel is favorable when adopting three of the four cases when compared to an improved water distribution system.

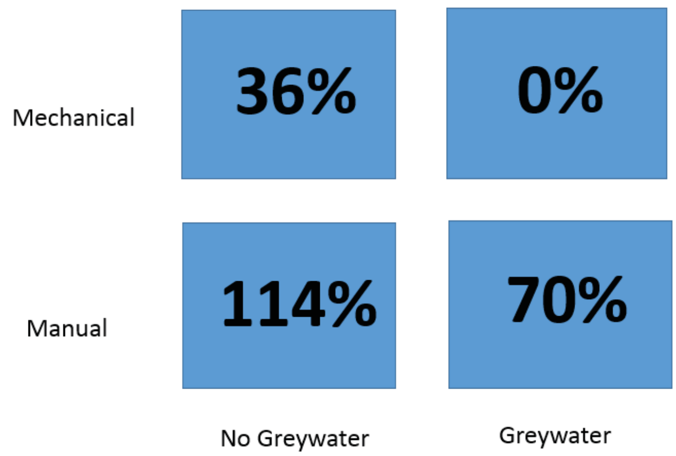

Figure 4.6 *After five years, the percent community must spend on diesel as compared to an improved, continuous access system (continuous supply at WHO-recommended supply amount).*

Since the use of a mechanical expeller provides the best financial returns to a community, it important to investigate how the initial purchase of a MFP would impact the community financially. The Senegalese government and outside donors are willing to subsidize this cost to help communities that show interest and are willing to financially commit to the project. If a community purchased a Multi-Functional Platform, they are expected to pay anywhere from 20-50% of the total cost, approximately $4,000, which includes the engine, battery charger, platform housing, rice de-huller, and mill. (Weingart 2003). According to an article by the United Nations Development Program (UNDP), Senegal's plan to establish more MFPs includes a feasibility study carried out by the UNDP to determine a community's eligibility. This investigation occurs over a three month period and communities must meet multiple criteria, including falling into a population range between 500 and 2000 (Treister 2007). For this study, an initial investment of $1000.00 on the communities' part will be considered (Cynthia and Teong 2011).

For the initial two years, the communities can expect to have to purchase 100% of the diesel required to run the water distribution system. However, using the yield prediction calculations from Figure 4.4, the communities can expect an increasing production of

Jatropha curcas oil with which they can begin to replace diesel to run the MFP and water distribution system generator. Table 4.9 shows a timeline calculating the payback period that a community can expect if an initial investment of $1000 to purchase a MFP is made in the first year of adopting this *Jatropha curcas* cultivation scheme.

Table 4.9 *Timeline for the communities of Keur Samba, Keur Lamine, and Keur Aly Lobe if a MFP is purchased and the case of combining MFP with recycled greywater is adopted in the community.*

	Seed Yield	Expenses			Savings		Annual	Cumulative
Year	**kg**	**Purchase Price**	**Annual Diesel[1]**	**MFP Fuel Cost**	**Diesel**	**Surplus Oil Production**	**NET**	
0	0	-$1,000.00	$0.00	$0.00	$0.00	$0.00	-$1,000.00	-$1,000.00
1	10.00	$0.00	-$3,828.06	-$0.73	$0.00	$0.00	-$3,828.06	-$4,828.06
2	125.35	$0.00	-$3,721.52	-$9.13	$106.54	$0.00	-$3,624.11	-$8,452.17
3	649.04	$0.00	-$3,276.37	-$47.29	$551.69	$0.00	-$2,771.98	-$11,224.14
4	1,581.09	$0.00	-$2,484.13	-$115.19	$1,343.93	$0.00	-$1,255.39	-$12,479.54
5	2,921.50	$0.00	-$1,344.78	-$212.85	$2,483.28	$0.00	$925.64	-$11,553.90
6	4,670.27	$0.00	$0.00	-$340.26	$3,828.06	$141.67	$3,629.46	-$7,924.43
7	4,670.27	$0.00	$0.00	-$340.26	$3,828.06	$141.67	$3,629.46	-$4,294.97
8	4,670.27	$0.00	$0.00	-$340.26	$3,828.06	$141.67	$3,629.46	-$665.51
9	4,670.27	$0.00	$0.00	-$340.26	$3,828.06	$141.67	$3,629.46	**$2,963.96**
10	4,670.27	$0.00	$0.00	-$340.26	$3,828.06	$141.67	$3,629.46	$6,593.42

Table 4.10 *Timeline for the communities of Keur Samba, Keur Lamine, and Keur Aly Lobe if a MFP is donated and no initial purchase price is included*

	Seed Yield	Expenses			Savings		Annual	Cumulative
Year	**kg**	**Purchase Price**	**Annual Diesel**	**MFP Fuel Cost**	**Diesel**	**Surplus Oil Production**	**NET**	
0	0	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
1	10.00	$0.00	-$3,828.06	-$0.73	$0.00	$0.00	-$3,828.79	-$3,828.79
2	125.35	$0.00	-$3,721.52	-$9.13	$106.54	$0.00	-$3,624.11	-$7,452.89
3	649.04	$0.00	-$3,276.37	-$47.29	$551.69	$0.00	-$2,771.98	-$10,224.87
4	1,581.09	$0.00	-$2,484.13	-$115.19	$1,343.93	$0.00	-$1,255.39	-$11,480.27
5	2,921.50	$0.00	-$1,344.78	-$212.85	$2,483.28	$0.00	$925.64	-$10,554.63
6	4,670.27	$0.00	$0.00	-$340.26	$3,828.06	$141.67	$3,629.46	-$6,925.16
7	4,670.27	$0.00	$0.00	-$340.26	$3,828.06	$141.67	$3,629.46	-$3,295.70
8	4,670.27	$0.00	$0.00	-$340.26	$3,828.06	$141.67	$3,629.46	**$333.76**
9	4,670.27	$0.00	$0.00	-$340.26	$3,828.06	$141.67	$3,629.46	$3,963.23
10	4,670.27	$0.00	$0.00	-$340.26	$3,828.06	$141.67	$3,629.46	$7,592.69

Payback Period, or the period of time required for a project to recover the money invested in it, is calculated with Equation 4-2 (AccountingExplained 2013). The formula is used when cash inflows are uneven from year to year, such is the case in this research study when diesel prices are ideally lessening annually based on the increasing seed yields and resulting amount of *Jatropha curcas* oil produced in a given year.

$$Payback\ Period = A + \frac{B}{C} \tag{4-2}$$

Where:
A = last period with negative cumulative cash flow;
B = absolute value of cumulative cash flow at end of Period A;
C = total cash flow during the period after A

Using this Equation, the following payback period was calculated for this case study:

$$Payback\ Period = 8 + \frac{|-665.51|}{2{,}963.96}$$

$$Payback\ Period = 10.2\ years$$

After 10.2 years, the communities involved will fully recover the initial cost of investing in a MFP, as well as investing in improving water access and supply by cultivating *Jatropha curcas* in the community.

Previously in the Water Development in Senegal section it was briefly mentioned that ASUFORs, the water users' associations, were required to open a bank account. Each rural water distribution system in Senegal is managed by an ASUFOR and therefore should be able to manage the net flow of cash associated with water system costs.

Chapter 5 - Summary of Results

The first improvement made to the system was to use EPANET to determine the changes needed in the current water distribution system in order to provide 20 liters of water per person per day and continuous access throughout the day to the communities of Keur Samba, Keur Lamine, and Keur Aly Lobe. This improvement required that diesel be increased from 3 liters per day to 6 liters per day in order to run the diesel-generator powered pump for a sufficiently long time to supply the required water.

1. The first objective was to determine if by simply increasing water demand in the current water distribution system; could enough *Jatropha curcas* trees be irrigated to produce oil to operate the diesel generator long enough to power the water system. This was not feasible using the current water system. This objective assumed an antique groundnut press would only be used to process the seeds which restricts oil recovery per seed to 23% (1 liter of *Jatropha curcas* oil for every 4.375 kg of dry seed). This objective also assumed ideal irrigation amounts of 9.5 liters/tree/day. These restrictions forced the water demand to increase more than the diesel generator pump could provide water to the system, using only *Jatropha curcas* oil.

2. The second objective was to determine the amount of *Jatropha curcas* oil that could be produced by just irrigating with recycled greywater. The result was 659 liters of *Jatropha curcas* oil could be produced annually. This could provide fuel for the current system for 171 days. Recycled greywater was then combined with Scenario 3 irrigation water demands to see if supplementing irrigation from the water distribution system with recycled greywater would substantially reduce pumping time. As Figure 4.2 depicts, required diesel does not substantially decrease, only 313 liters, with the introduction of greywater.

3. The third objective was to incorporate a Multi-Functional Platform into the system to improve the production efficiency of expelling oil from the seeds. MFP's have been used throughout Mali in gender empowerment and fuel self-sufficiency

schemes, and were due to be introduced into Senegal in the 2000's. A MFP would allow for an increase in oil extraction efficiency from the seeds to be achieved. This lowered the amount of trees needed to produce the 2190 liters of oil required to fuel the water distribution system to provide basic, continuous access to the communities. However, pumping time was still increased from 2 hours a day, to approximately 2.7 hours a day, resulting in an increase from 2190 to 2972 liters of required *Jatropha curcas* oil.

4. The final objective was to explore the possibility of combining greywater irrigation with a MFP. This combination allowed for the amount of oil produced by cultivating *Jatropha curcas* trees to surpass the required oil to run the system, thus allowing the community to achieve fuel self-sufficiency. Figure 4.2 illustrates the ability of Scenario 6 to provide more *Jatropha curcas* oil than required diesel to run the system.

Table 5.1 provides a summary of the combinations of irrigation, greywater recycling, and the use of a mechanical expeller for all scenarios and the resulting ability of each scenario to achieve fuel self-sufficiency (column highlighted in blue).

Table 5.1 *The ability of scenarios to meet fuel self-sufficiency with the required additions of irrigation, greywater, and/or mechanical expeller indicated.*

Scenario	Irrigation	Greywater	Mechanical Expeller	Fuel Self-Sufficient
Iteration Scenarios (I1-I5)	X			
C		X		
D	X	X		
E	X		X	
F	X	X	X	X

Chapter 6 - Discussion

It was outside the scope of this project to look into transforming the seed oil into biodiesel. Pre-treatment is recommended before using crude *Jatropha curcas* oil in an engine to limit engine wear. This can be as simple as filtering the oil, heating crude oil, or by decanting/sedimentation methods (Eckart and Henshaw 2012). Simple diesel engines, including those in MFPs, have been shown to run without any difficulties with crude *Jatropha curcas* oil; however, problems created by using unrefined vegetable oil are most commonly addressed by converting the oil to biodiesel by transesterification. Transesterification is the process of transforming plant oil and methanol to fatty acid methyl ester and glycerol using a catalyzed reaction (Eckart and Henshaw 2012). For increased efficiency of diesel engines, including MFPs, it has been recommended to use *Jatropha curcas* biodiesel, as opposed to *Jatropha curcas* oil (Cynthia and Teong 2011).

Future work should also include further research on projected seed yields. The values used in this case study were based on values for semi-arid *Jatropha curcas* production (Achten et al. 2008). Values were chosen that reflected established, fully productive trees. Research is needed to help future project developers accurately predict seed yields from *Jatropha curcas* plantation.

Finally, while countries outside of Senegal have tried implementing *Jatropha curcas* plantations and installing MFPs to process the seeds and electrify rural communities, no such effort has been made in Senegal. While the government is supportive of a country-wide biofuel initiative, until they show support by disseminating trainings and materials, it may be difficult for farmers to gain from producing large-scale Jatropha without the support of private industries. Future work would ideally include the implementation of a *Jatropha curcas* plantation in the study area to gauge governmental support, market profitability, and actual production of trees in this region.

Social adoption discussion

The political and social landscape of Senegal raises challenges for implementing a system of *Jatropha curcas* production. It is essential to assess these concerns and understand how they might affect the success of large-scale production. In order to fully predict the sustainability of *Jatropha curcas* production, these cultural concerns must be accounted for and ultimately accommodated. Policies surrounding the implementation of a country-wide biofuel initiative, should aim to embrace the rich diversity of Senegalese culture while leveraging every communities' potential to produce Jatropha.

Jatropha co-operatives have been successful in various regions of the world; from Nepal to Mali.(Adhikari and Wegstein 2011, Simpson 2009). Community collaboration on agricultural projects is an often used system in the communities reliant on the Keur Lamine water distribution system. This next section looks at several of the social constructs that support and also inhibit the adoption of a multi-community, collaborative *Jatropha curcas* production scheme.

The large amount of labor required for non-mechanized agricultural production and the pooling of community resources to achieve better harvests, has instilled in the communities that the author is familiar with, the benefits of collaborative efforts. Keur Samba has a history of community projects centered on agriculture: a community vegetable garden, the processing of millet in the field, and the use of peanut oil presses to process peanut butter. The author has only two years of field experience working with this community, but feels the ability of the community to produce *Jatropha curcas* is possible if a new community group was organized, if a motivated and educated leader from the community took charge, and if support from the local Trees for the Future technician and Peace Corps volunteers was substantial in the beginning years of the project.

While the author was based out of Keur Samba, a primarily Wolof community, the village housing the actual pump tower and water tank was a Mandinka community. Mandinka's are well known for their highly productive home gardens. Each household has multiple garden plots tended by a female from that household. Some of these gardens are fenced by

Jatropha curcas trees which then received the benefit of sharing irrigation water with the vegetable plots. While Wolof communities would need to develop a community group to implement a village-wide *Jatropha curcas* production scheme, the author feels a Mandinka village would be able to function more individually (meaning home-by-home) and only collaborate in the processing of the seeds.

Chapter 7 - Conclusion

Communities in this region are planting *Jatropha curcas* trees as live fencing, hedgerows, and windbreaks through the help of Peace Corps agroforestry extension workers and other NGOs such as Trees for the Future and WorldVision. Even if cultivating *Jatropha curcas* trees to provide a renewable energy source does not fully meet the rural energy requirements for fueling water distribution systems throughout Senegal, it will contribute toward alleviating rural poverty, lessening a community's reliance on diesel, diversifying energy resources, and improve the resilience of rural communities by providing economic and environmental benefits. For these reasons, it is recommended that rural Senegalese farmers incorporate *Jatropha curcas* trees around their homes, intercropped in their fields, and as live fencing in home gardens.

There is never one solution to a problem, and *Jatropha curcas* is no exception. It is simply one tool that can be used toward sustainable development in rural, isolated, energy-scarce villages. Perhaps even more notable than the potential for the trees to produce oil, are the many other uses of the plant from soap production to protecting crop yields as a living fence, and even using seed cake as a fertilizer. This hardy tree with its variable uses represents the resiliency of the populations it could best serve. The three key elements in a successful, sustainable water distribution system are: the right technology, ownership by the communities involved, and local capacity to repair and maintain the system. The objective of this report was to research the potential for this tree to replace diesel fuel. It is up to the individual communities to adopt this system for obtaining fuel independence.

Based on the Scenarios researched in this report, it is in a community's best interest to invest in a mechanical oil expeller. Multi-Functional Platforms show great promise, have already been incorporated into self-sufficiency schemes in Mali, and provide multiple agricultural tools, not just an oil expeller. It is also recommended that communities develop a system of reusing greywater to supplement irrigation. A decrease in demand on the water distribution system will allow for the community to achieve a surplus of *Jatropha curcas*

oil that could be sold, or used with an MFP to generate electricity for charger cell phones and other agricultural or grain processing machines.

References

Abbott, Megan L, Jennifer O'Neill, and Brian D Barkdoll. 2014. "Adaptive Greedy-Heuristic Algorithm for Redundancy Augmentation by Loop Addition in Branched Water Distribution Systems." *Journal of Water Resources Planning and Management* 141 (6):06014005.

AccountingExplained. 2013. "Payback Period." Accessed June 9. http://accountingexplained.com/managerial/capital-budgeting/payback-period.

Achten, WMJ, Louis Verchot, Ywe Jan Franken, Erik Mathijs, Virendra Pal Singh, Raf Aerts, and Bart Muys. 2008. "Jatropha bio-diesel production and use." *Biomass and bioenergy* 32 (12):1063-1084.

Achterbosch, Thom; Meijerink, Gerdien; Slingerland, Maja; Smeets, Edward. 2013. "Combining bioenergy production and food security."78.

Adhikari, Narayan Prasad, and Michael Wegstein. 2011. "Financial analysis of Jatropha plantations in the context of Nepal." *Journal of the Institute of Engineering* 8 (1-2):143-148.

Agency, Central Intelligence. 2011. *The CIA World Factbook 2012*: Skyhorse Publishing Inc.

Awulachew, Seleshi Bekele, Philippe Lemperiere, and Taffa Tulu. 2009. Module 4 Pumps for small-scale irrigation. Addis Ababa, Ethiopia: International Livestock Research Institute.

Batteson, Helen, Key Davey, and Rod Shaw. 1998. "Guidance manual on water supply and sanitation programmes." *WEDC, Loughborough*.

Beerens, Peter. 2007. "Screw-pressing of Jatropha seeds for fuelling purposes in less developed countries." *Eindhoven University of Technology. Ministerio de Ambiente y Energía-MINAE-(2007).“Plan Nacional de Biocombustibles”. Costa Rica*.

Chase, Donald V. 2000. "Operation of water distribution systems." *Water Distribution Systems Handbook, L. W. Mays, ed., McGraw-Hill, Inc., Two Penn Plaza, New York*:15.1-15.16.

Church, RJ Harrison. 2002. "Senegal." *Africa South of the Sahara 2003*:428.

Cynthia, Ofori-Boateng, and Lee Keat Teong. 2011. "Feasibility of jatropha oil for biodiesel: economic analysis." World Renewable Energy Congress.

Divakara, BN, HD Upadhyaya, SP Wani, and CL Laxmipathi Gowda. 2010. "Biology and genetic improvement of Jatropha curcas L.: a review." *Applied Energy* 87 (3):732-742.

Duffield, GM, and JO Rumbaugh. 1991. "AQTESOLV." *Aquifer Test Solver Version* 1.

Eckart, K, and P Henshaw. 2012. "Jatropha curcas L. and multifunctional platforms for the development of rural sub-Saharan Africa." *Energy for Sustainable Development* 16 (3):303-311.

ENDA, Energy, Environment, Development Programme. 2007. "Biofuels in Senegal Jatropha Program 2007-2012."5.

FAO. 2008. "The State of Food and Agriculture: Biofuels: prospects, risks and opportunities."138.

Foidl, N, G Foidl, Mittelbach Sanchez, M Mittelbach, and S Hackel. 1996. "Jatropha curcas L. as a source for the production of biofuel in Nicaragua." *Bioresource Technology* 58 (1):77-82.

Ghoneim, AA. 2006. "Design optimization of photovoltaic powered water pumping systems." *Energy Conversion and Management* 47 (11):1449-1463.

Godfrey, S. 2010. "Safe greywater reuse to augment water supply and provide sanitation in semi-arid areas of rural India." *Water science and technology* 62 (6):1296-1303.

Grimsby, Lars Kåre, Jens Bernt Aune, and Fred Håkon Johnsen. 2012. "Human energy requirements in Jatropha oil production for rural electrification in Tanzania." *Energy for Sustainable Development* 16 (3):297-302.

Grundfos. 2015. "Grundfos SP Engineering Manual " Accessed February 1. www.grundfos.com.

Heller, Joachim. 1996. *Physic Nut, Jatropha Curcas L*. Vol. 1: Bioversity international.

Henning, Reinhard K. 2004. "The Jatropha System." *Integrated rural development by utilisation of Jatropha curcas L. as raw material and as renewable energy.*

Studientag Möglichkeiten und Grenzen erneuerbarer Energien in Tansania-Erfahrungen in der Partnerschaftsarbeit 24.

Hope, Rob, Tim Foster, and Patrick Thomson. 2012. "Reducing risks to rural water security in Africa." *Ambio* 41 (7):773-776.

Howard, Guy, and Jamie Bartram. 2003. *Domestic water quantity, service level, and health*: World Health Organization Geneva.

Iiyama, Miyuki, David Newman, Cristel Munster, Meshack Nyabenge, Gudeta W Sileshi, Violet Moraa, James Onchieku, Jeremias Gasper Mowo, and Ramni Jamnadass. 2013. "Productivity of Jatropha curcas under smallholder farm conditions in Kenya." *Agroforestry systems* 87 (4):729-746.

Jongh, JA, and Eric van der Putten. 2010. *The Jatropha Handbook: From Cultivation to Application*: FACT Foundation.

Jongschaap, REE, WJ Corré, PS Bindraban, and WA Brandenburg. 2007. "Claims and Facts on Jatropha curcas L."

Karlsson, Gail, and Khamarunga Banda. 2009. "Biofuels for sustainable rural development and empowerment of women: Case studies from Africa and Asia."

Madungwe, Emaculate. 2007. "Greywater reuse: A strategy for water demand management in Harare?" *Physics and chemistry of the earth* 32 (15):1231-1236.

Maes, WHA, Antonio Trabucco, Wouter MJ Achten, and Bart Muys. 2009. "Climatic growing conditions of Jatropha curcas L." *Biomass and bioenergy* 33 (10):1481-1485.

Nahar, Kamrun, and Monica Ozores-Hampton. 2014. "Jatropha: an alternative substitute to fossil fuel."

OxfamNovib. 2009. "Monitoring Report 2008."108.

Prathapar, S. A. 2006. "Design, construction and evaluation of an ablution water treatment unit in Oman: A case study." *The International journal of environmental studies* 63 (3):283-292.

Reed, RA, Sam Godfrey, Sam Kayaga, Brian Reed, Jonathan Rouse, Julie Fisher, Karen Vilholth, and Frank Odhiambo. 2013. "Technical notes on drinking-water, sanitation and hygiene in emergencies."

Rossman, Lewis A. 2000. "EPANET 2: users manual."

Senegal, Republique de. 2001. Rapport de Forage: Keur Lamine. edited by de l'Energie et de l'Hydraulique Ministere des Mines. Dakar

Sheehan, John, Vince Camobreco, James Duffield, H Shapouri, M Graboski, and KS Tyson. 2000. An overview of biodiesel and petroleum diesel life cycles. National Renewable Energy Lab., Golden, CO (US).

Simpson, Brent M. 2009. "Mission report regarding the potential use of Jatropha curcas as an additional source of fuel and income for farmers in the Senegal River Delta. ."35.

Skinner, Jamie. 2009. "Where every drop counts: tackling rural Africa's water crisis." *International Institute for Environment and Development (IIED): London, UK*.

Smith, Peter, A Mbaye, J Pickford, P Barker, A Coad, M Ince, R Shaw, B Skinner, and M Smith. 1994. "Pipeline extensions spread benefits." Water, sanitation, environment and development: selected papers of the 19th WEDC conference, Accra, Ghana, 1993.

TheWorldBankGroup. 2015. "Climate Change Knowledge Portal." Accessed February 23, 2015. http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Africa&ThisCCode=SEN.

Trabucco, Antonio, Wouter MJ Achten, Colm Bowe, RAF Aerts, JOS VAN ORSHOVEN, Lindsey Norgrove, and Bart Muys. 2010. "Global mapping of Jatropha curcas yield based on response of fitness to present and future climate." *GCB Bioenergy* 2 (3):139-151.

Treister, Negar Rachel. 2007. "Multi-Functional Platform in Senegal." Carnegie Council Accessed 5/1/2015. http://www.policyinnovations.org/ideas/innovations/data/senegal.

Trémolet, Sophie. 2006. "Case Study on Senegal's Water and Sanitation Sector Economic Regulation." *World Bank (mimeo)*.

Trifunović, N, K Vairavamoorthy, JE Van Zyl, AA Ilemobade, and HE Jacobs. 2008. "Use of demand-driven models for reliability assessment of distribution networks

in developing countries." Proc. 10th Annu. Water Distribution Systems Analysis Conf. WDSA2008.

Weingart, Jerome M. 2003. "Multi-function platforms: Enhancing economic productivity of rural communities." *Tech Monitor*.

WHO/UNICEF. 2012. "Joint monitoring programme for water supply and sanitation data tables."

Youm, I, J Sarr, M Sall, and MM Kane. 2000. "Renewable energy activities in Senegal: a review." *Renewable and Sustainable Energy Reviews* 4 (1):75-89.

Appendix A - **EPANET Nodal Inputs**

Table A.1 *Compilation of community base demands and total irrigation for each Scenario used in EPANET*

EPANET INPUTS		
Scenario	**Base Demands per community outlet node (liters/second)**	**Total Irrigation (liters per day)**
Iteration 1	0.0909	82,787.16
Iteration 2	0.2429	199,776.53
Iteration 3	0.4373	349,411.08
Iteration 4	0.7245	570,513.84
Iteration 5	1.3919	1,663,534.93
C*	0.0000	128,21.76
D	0.0554	55,432.89
E	0.0213	292,12.94
F*	0.0000	128,21.76

*Scenarios C & F do not include increased household irrigation. The total irrigation is from the community garden only.

Appendix B - **EPANET Irrigation and Water Supply Detailed Results**

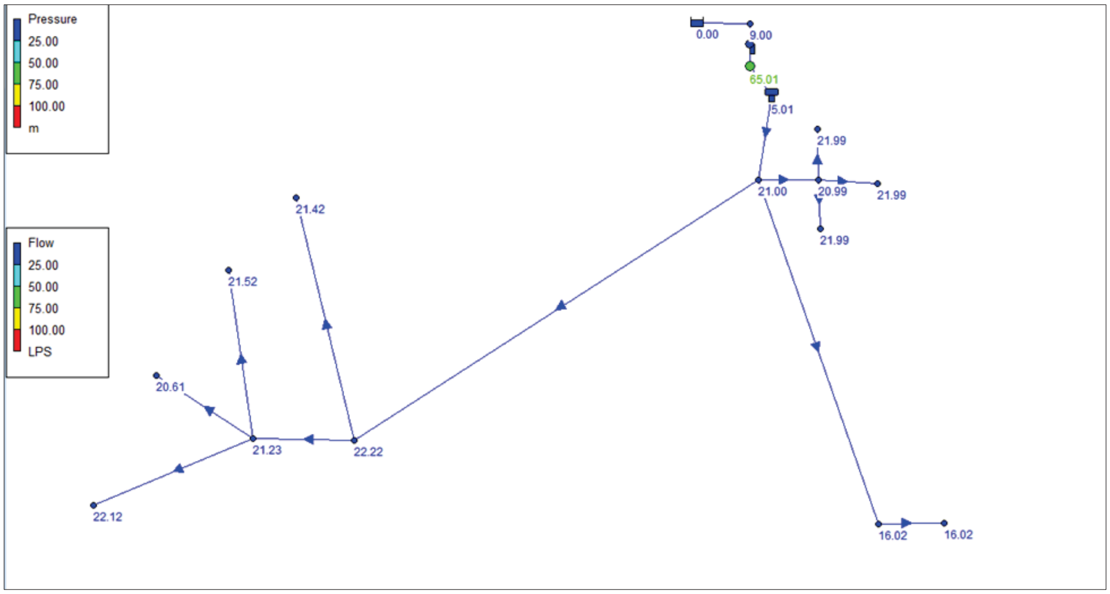

Figure B.1 *EPANET screen capture for Scenario A: water distribution system supplying less than basic access, intermittently*

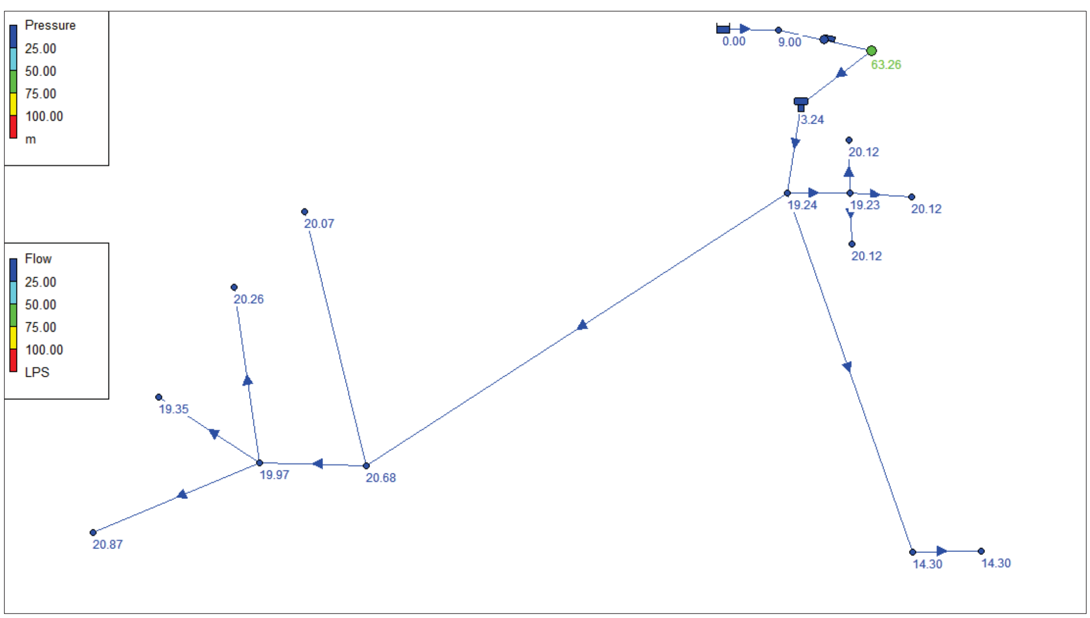

Figure B.2 *EPANET screen capture for Scenario B: basic access, continuous supply improved system*

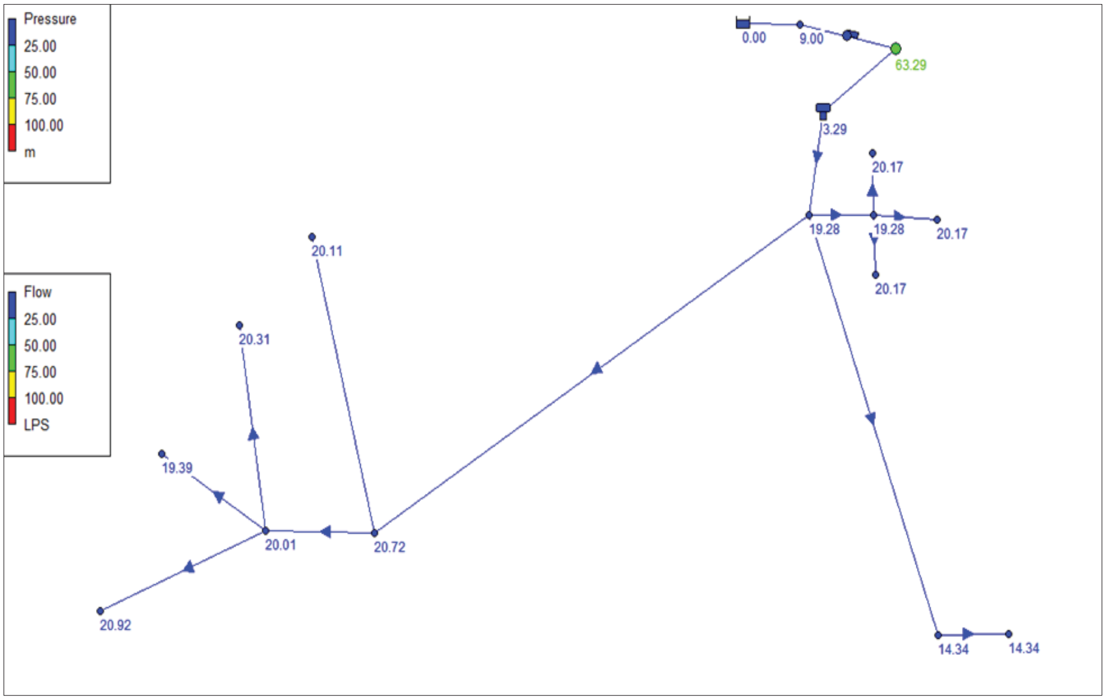

Figure B.3 *EPANET screen capture for Scenario I1: water distribution system supplying continuous, basic access plus meeting irrigation demands to run Scenario B diesel requirements*

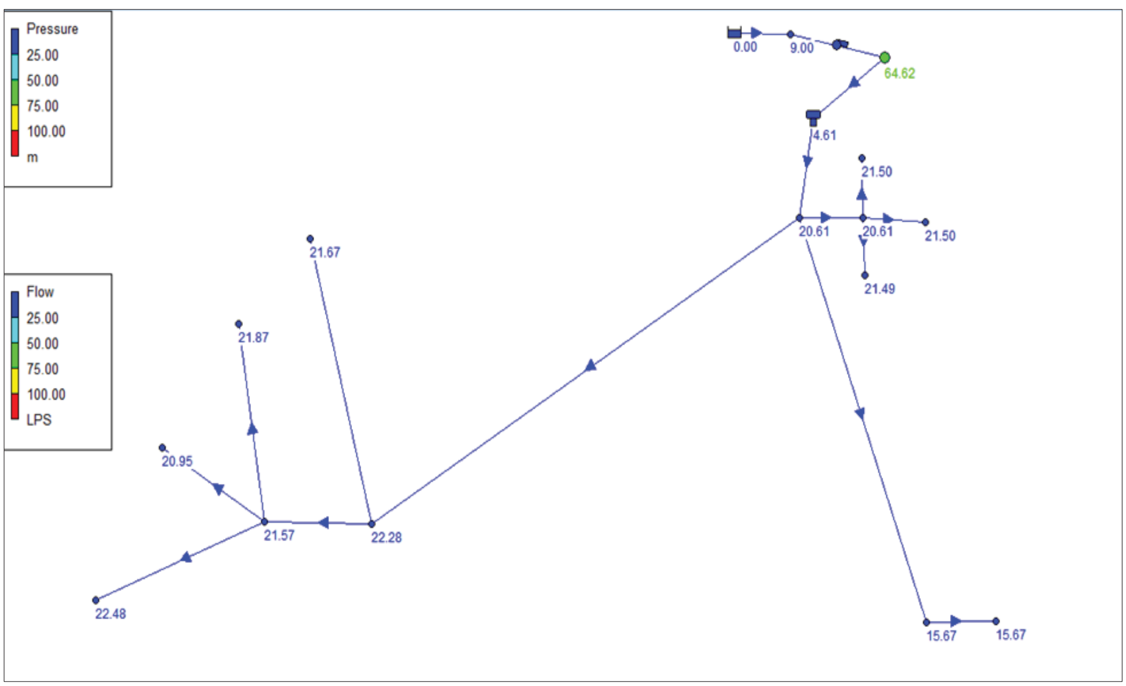

Figure B.4 *EPANET screen capture for Scenario I2: water distribution system supplying continuous, basic access plus meeting irrigation demands to run Scenario I1 diesel requirements*

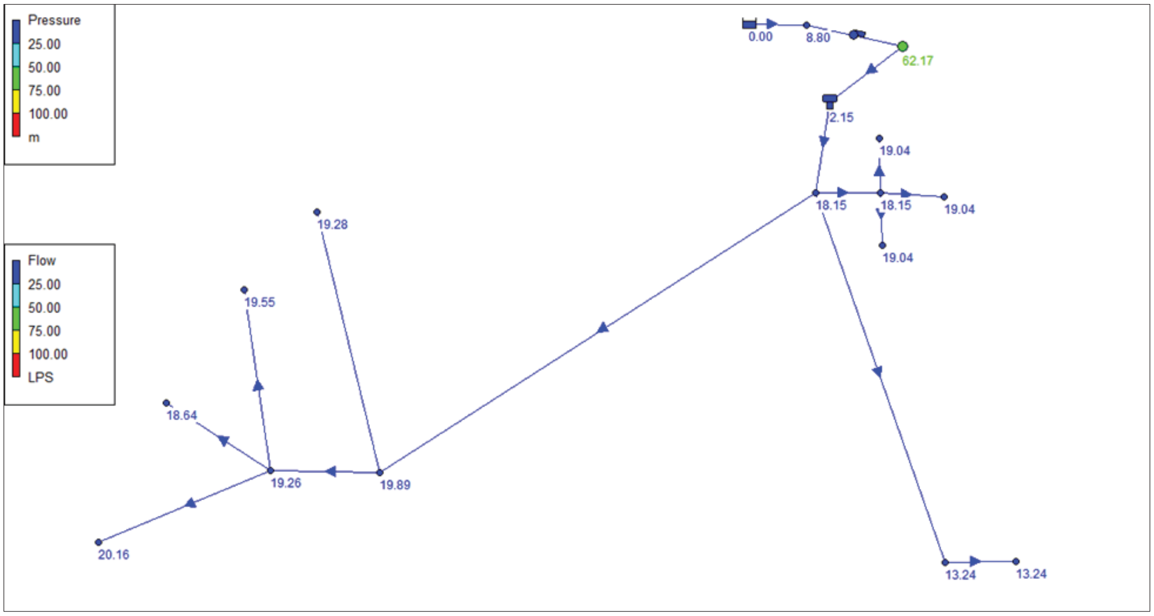

Figure B.5 *EPANET screen capture for Scenario I3: water distribution system supplying continuous, basic access plus meeting irrigation demands to run Scenario I2 diesel requirements*

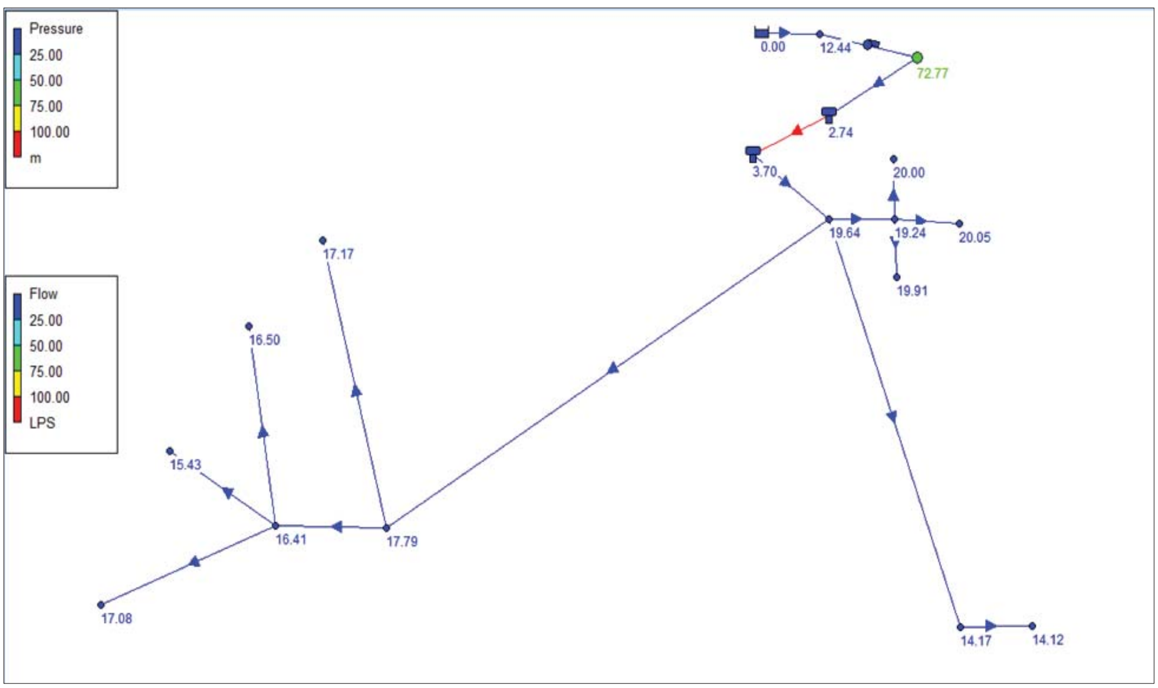

Figure B.6 *EPANET screen capture for Scenario I4: water distribution system supplying continuous, basic access plus meeting irrigation demands to run Scenario I3 diesel requirements*

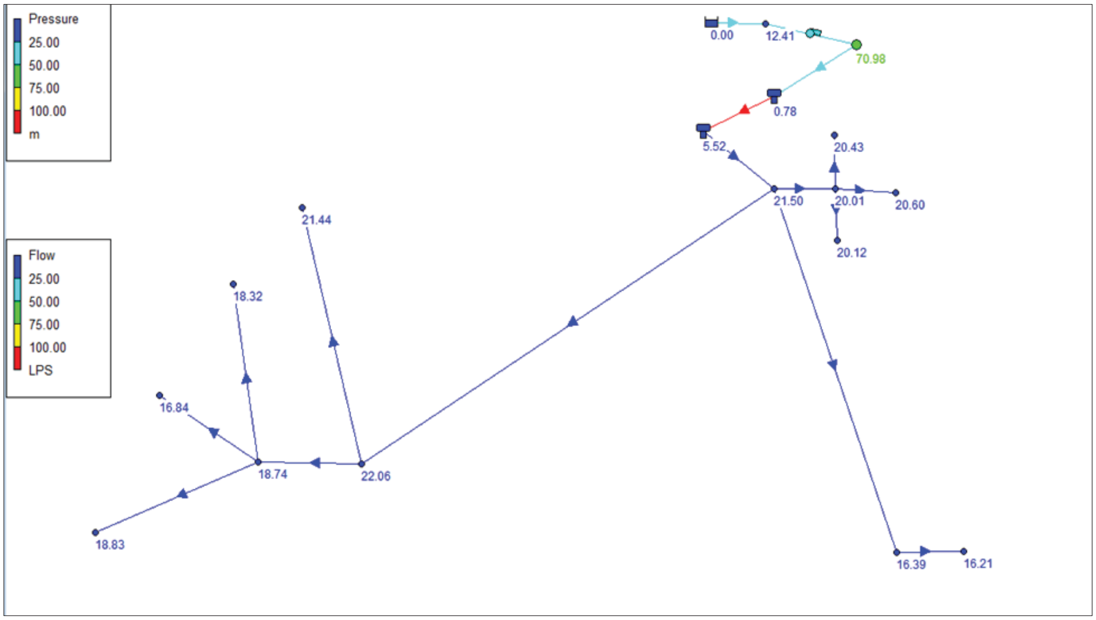

Figure B.7 *EPANET screen capture for Scenario I5: water distribution system supplying continuous, basic access plus irrigation demands to produce 100 liters of* Jatropha curcas *oil*

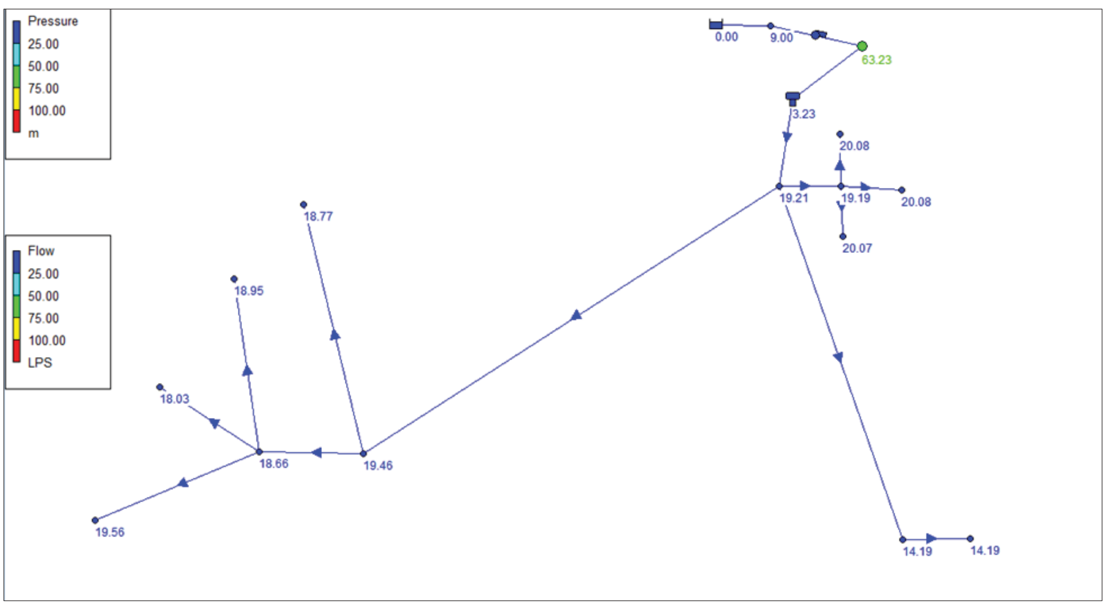

Figure B.8 *EPANET screen capture for Scenario D representing the reduced irrigation demands to provide* Jatropha curcas *oil for the reduced demands of a scheme combining recycled greywater with irrigation*

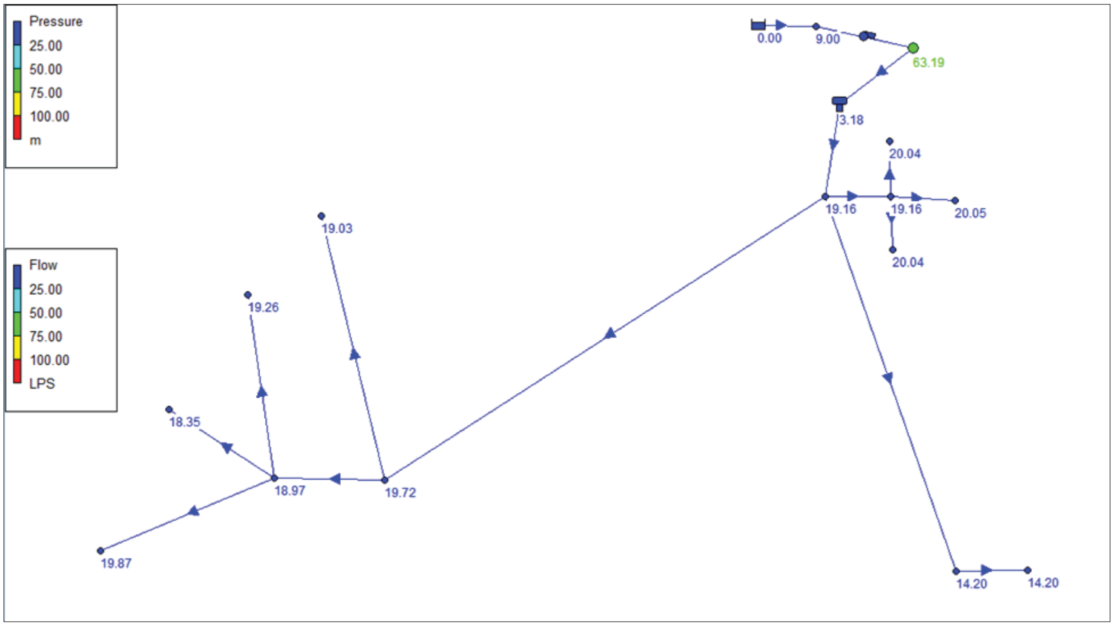

Figure B.9 *EPANET Screen Capture for Scenario F representing the reduced irrigation demands when a Multi-Functional Platform is used to process the seeds.*

Appendix C - **Collection of published *Jatropha curcas* dry seed yields**

Table C.1 *Collection of published dry seed yields for multiple J. curcas planting schemes and locations*

Location	Average Annual Rainfall	Age	Kg $tree^{-1}$ $year^{-1}$	Kg ha^{-1} $year^{-1}$
Cape Verde[1]	600		380	
Mali[1]	1020			2640
Paraguay[1]	1370	3		100
Paraguay[1]	1370	4		700
Paraguay[1]	1370	5		1000
Paraguay[1]	1370	6		2000
Paraguay[1]	1370	7		3000
Paraguay[1]	1370	8		4000
Paraguay[1]	1370	9		4000
Thailand[1]	1470		0.32	794
Nicaragua, Managua[2]	1200	2		2327
Nicaragua, Managua[2]	1200	3		2786
Nicaragua, Managua[2]	1200	4		3848
Indonesia[3]		2		1000
Zambia[3]		2-3		500
Kenya[4]		4-6		150

Sources:
[1](Heller 1996)
[2](Foidl et al. 1996)
[3](Trabucco et al. 2010)
[4](Iiyama et al. 2013)

Table C.2 *Table of dry seed yields comparing rainfed versus irrigated plantation of J. curcas trees over an eight year period (Eckart and Henshaw 2012)*

	Rainfed	**Irrigated**
Age	kg $tree^{-1}yr^{-1}$	kg $ha^{-1}yr^{-1}$
1	0	250
2	125	1,000
3	250	2,470
4	620	4,940
5	1,235	7,910
6	2,470	7,910
7	3,090	7,910
8+	3,710	7,910

Appendix D - **Community Census Data with reference to nodes in EPANET**

Table D.1 *Census data compiled for all three communities reliant on study site water distribution system.*

Village	Population	Households	Community Faucets	Node IDs
Keur Aly Lobe[1]	406	38	2	4,17
Keur Lamine[2]	457	45	3	8,9,10
Keur Samba[3]	1100	119	4	7,11,12,13,14

[1]PEPAM
[2]Forage Report
[3]Author

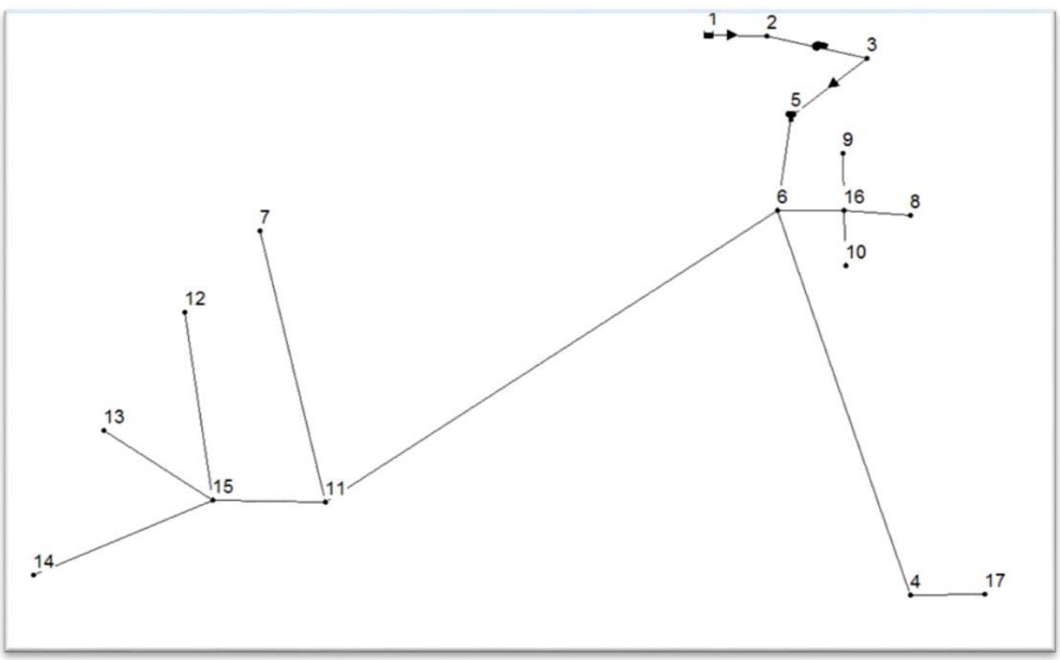

Figure D.1 *Layout of nodes in EPANET model. Numbered nodes assigned to community faucets as outlined in Table 8.3.*

Appendix E - Copyright permissions

Figure 2.1, Figure 2.4, Figure 3.1, Figure 3.9, Figure 3.12 and Figure 3.13 are compliant with the Google Earth End-user License Agreement (EULA) and fall under the category of fair use.