1-1-2012

Technical and Economic Assessment of Adobe as the Primary Building Material On the Water Yield of a Single Basin Solar Still

Nathan Daniel Manser
University of South Florida, N_Manser@msn.com

Technical and Economic Assessment of Adobe as the Primary Building Material On the Water Yield of a Single Basin Solar Still

by

Nathan Daniel Manser

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Environmental Engineering
Department of Civil & Environmental Engineering
College of Engineering
University of South Florida

Major Professor: James Mihelcic, Ph.D.
Jeff Cunningham, Ph.D.
Maya Trotz, Ph.D.

Date of Approval:
March 9, 2012

Keywords: Appropriate Technology, Local Material, Metal Removal, Sustainable Development, Mexico

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation, under grant number 0965743. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

It is estimated that only one percent of global freshwater is available to humans, with nearly three billion people living in water scarce conditions. Populations living in impoverished settings are particularly vulnerable to water related illnesses, with approximately 2.2 million people dying each year from to waterborne illnesses. This research uses modeling and field studies to assess the quantity, quality, and economics of distillate produced for drinking water from a brackish water source using two single-sloped, single-basin distillation reactors. The reactors were constructed from adobe and concrete in an arid rural community in San Luis Potosí, Mexico and tested from August to October. The cost of one adobe reactor with an evaporative area of 0.65 m^2 is 430 pesos, whereas the same size reactor made from concrete costs 630 pesos. Results show that desalination reactors made from adobe produce 848 mL/m^2-day and reactors made from concrete produce 979 mL/m^2-day of distillate, while similar reactors made from other materials are estimated to produce over 2,100 mL/m^2-day under similar meteorological conditions. These volumes represent approximately 10 percent of drinking water needs of a local family with typical water use habits. The concentrations of total dissolved solids in the source water decreased from 1,102 mg/L to 40.3 mg/L over the study's duration for a removal of 96% which is comparable to current desalination systems (97%). Results suggest that over 90% of a household's drinking water demand could be satisfied (91%) if a network of thirteen distillation reactors were constructed and maintained for ten years when compared to purchasing water from private water vendors.

CHAPTER 1: INTRODUCTION

More than two-third of the earth's surface is covered with water; however, most of the available water is present as either seawater or icebergs in the Polar Regions. The majority of Earth's water tends to be saline, as 97% of the total water is brackish. The remaining 3% is fresh water, mainly in the form of glaciers, ice caps and groundwater and only 1% of the total freshwater supply is readily available. Unfortunately, many people in the world, and especially those in developing countries, have access to water but still die because of its poor quality or the irregular quantity available to them. According to the United Nations, approximately 2.2 million people die each year due to water related illnesses and currently it is estimated that 884 million of the world's population lacks access to safe water (WHO/UNICEF, 2010).

Table 1.1 illustrates the proportion of the global population that has access to an improved drinking water source in both rural and urban settings. The indicators show favorable increases from 1990 to 2008 in both population groups as the Millennium Development project has brought attention to this issue. This has occurred especially in the rural population sectors which improved access by nearly 22% over the two decade period.

Table 1.1: The proportion of the global population with access to an improved drinking water source as measured in the Millennium Development Goals 2010 Report. Progress was made on improving access to drinking water in both rural and urban populations from 1990 to 2008; however there are still one out of four rural people that do not have access to an improved water source.

Global Population	1990	2008	Percent Increase
Total	77%	87%	13%
Urban	95%	96%	1%
Rural	64%	78%	22%

The impact of water supply and water quality can be measured by looking at the annual mortality rate of water related illnesses such as diarrhea. Table 1.2 displays the percentage of deaths that occurred in children in 2008 from diarrhea in selected countries and on a global scale, as children are more susceptible to illness they are useful indicators in determining the presence of lower quality water. This data suggests that under developed countries like Kenya, India and Mexico all lack access to high quality water when compared to a developed country like the United States, which places more stress on already water scarce populations.

Table 1.2: The percentage of deaths attributed to diarrhea in children in selected countries, as well as the global average. It can be seen that many undeveloped countries are impacted by this problem, emphasizing the need for improved access to drinking water in poverty stricken areas.

Location	Age: 0-1 Months	Age: 1-59 Months
Mexico	0.4%	9.0%
United States	0.0%	0.2%
Kenya	1.7%	27.3%
India	3.4%	24.0%
Global	**1.0%**	**12.0%**

Data provided by Visualization from Gapminder World, powered by Trend-analyzer from www.gapminder.org, accessed online April 2011.

Despite the progress demonstrated in Table 1.1 in providing access to an improved drinking water source water scarcity is becoming an increasing concern as population growth and water use habits are exceeding what can be provided by local water supplies. Table 1.3 lists some national water footprints and Figure 1.1 illustrates the varying levels of water scarcity on the planet.

Table 1.3: A list of water consumption rates per person per year for selected nations in the world. Developed from the United Nations 2nd Water Development Report (2006).

Nation	**Water Footprint (m^3/capita/year)**
United States	2,100 - 2,500
Mexico	1,300 - 1,500
China	600 – 800
Saudi Arabia	1,200 – 1,300
Madagascar	1,000 – 1,200
Iran	1,500 – 1,800

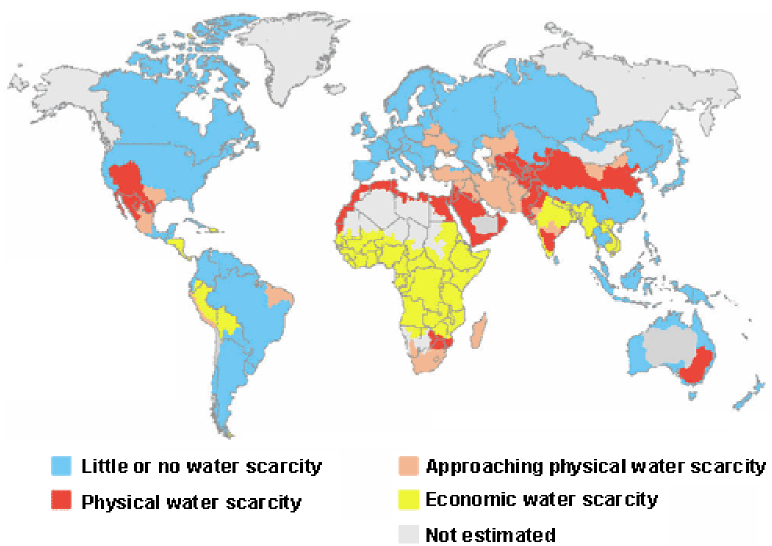

Figure 1.1: The varying levels of water security for all countries are indicated on this map. Reprinted with permission from the International Water Management Institute 2006-2007 Annual Report (IWMI, 2007).

As seen in Table 1.3 and Figure 1.1, many of the countries with water scarcity issues are located in arid or semi-arid regions and some with increased levels of water scarcity (e.g. Mexico, Australia, Saharan-Africa, and many Middle Eastern). These countries have relatively large water footprints as well, indicating an unsustainable use of water in those countries. In 1990, 335 million people living in about 28 countries experienced water stress or scarcity. Today, approximately 1.2 billion people live in water scarce regions (IWMI, 2007) and by 2025, it is estimated that 46 to 52 countries may fall into some level of water scarcity, and the total affected population could rise to 3 billion (Gleick, 1993).

As the global water crisis continues, arid countries are highly impacted as water tables keep falling and groundwater supplies are becoming brackish as extraction rates outpace recharge rates. Today at least 80 arid and semi-arid countries, where 40% of the global population lives, have been identified to have serious periodic droughts that increase the stress on the local water supply (Miller, 1991).

Groundwater is the major source of potable water supply in arid and semi-arid areas and its availability may be threatened not only by the introduction of contaminants by human activities but also by natural processes (Carillo-Rivera et al., 2002). Figure 1.3 shows the presence of arsenic in groundwater and soil samples taken across the Southwestern United States and Mexico. Heavy metals such as this will have long term impacts on the health of consumers who drink water contaminated with them, and furthermore, commonly utilized source and point-of-use water treatments are typically not suited for heavy metal removal making it difficult to utilize the contaminated water for human consumption.

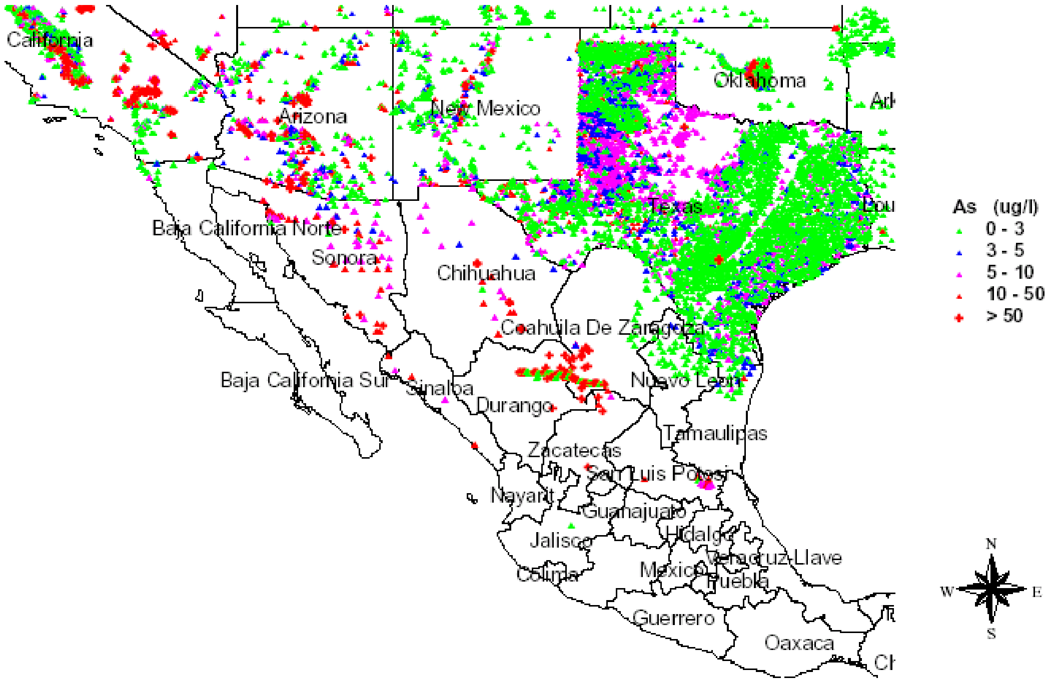

Figure 1.2: Concentrations of arsenic contamination in groundwater and soil samples across the Southwestern United States and Mexico. The red colored areas indicated the presence of arsenic at a concentration of greater than 50μg/L (Camacho et al., 2011). The World Health Organization (WHO) guideline for arsenic in drinking water is 10μg/L (WHO, 2011).

Nevertheless, as the quality and quantity of the water supply becomes more critical in arid and semi-arid regions, the potential use for solar energy as a means to desalinate or decontaminate a water source is typically great in these regions (Chaibi, 2000) as high amounts of solar energy are available for use.

1.1 Research Motivation

Motivation for this study stems from the author's experiences working with small rural communities located in North Central Mexico over a two-year period while serving as a Peace Corps volunteer as part of the Master's International Program (http://cee.eng.usf.edu/peacecorps/). In these communities, typically, the demand for potable water exceeds the supply, placing the populations at a higher risk levels for water-related illnesses and health problems associated with long-term dehydration as sufficient clean water is not available. In addition, the supply that is available is sometimes not suitable for human consumption as pollutant levels are too high.

However, despite the lack of an improved water source, the communities in this region do receive ample levels of solar radiation on a daily basis which can be used to desalinate the water that is present through the process of solar distillation. Solar distillation, a passive solar technology, is the process of using solar energy to produce purified water from an impure source.

There have been numerous studies pertaining to solar distillation, including the design (Elkader, 1998; Fath, 1998; Samee et al., 2005 Murugavel et al., 2008), optimization (Nafey et al., 2002; Abu-Hijleh et al., 2003; Tanaka et al., 2009), and development of mass transfer models to predict performance (Mathioulakis et al., 1999; Jubran et al.; 2000, Khalifa et al., 2009). Recent research has begun to develop performance equations that require only design parameters and local meteorological data as inputs (Samee et al., 2007; Khalifa et al., 2011); however, there have been few published studies that examine the accuracy of the models compared to physical results when applied to a specific test location and solar distillation unit.

In addition, no peer reviewed articles were identified by the author relevant to the use of adobe in the construction of a solar still. This is an important research topic to address because adobe is a commonly used material in many parts of the world and may reduce the construction costs of a solar distillation unit as other more expensive construction materials may not be needed.

1.2 Objective and Hypotheses

This study examines the quantity and water quality of distillate produced in a single-slope single-basin solar distillation reactor constructed from adobe. Results are then used to determine how this kind of distillation system satisfies the demand for drinking water required for a typical family in the study location through an analysis of technical and economic parameters. The objective of this study is to determine the rate of water production and associated water quality of the solar still distillate when adobe is used as the primary construction material. This study will test four hypotheses:

1. The quantity of distillate produced (L/m^2-day) in a single basin passive solar still constructed from adobe will be similar to published performance models using other materials for construction;
2. The distillate produced from the adobe distillation reactor in this study will be sufficient to provide 75% of the daily water consumption required for drinking for a typical family in the study location;
3. The water quality of the distillate will satisfy the World Health Organization (WHO) drinking water guidelines for total dissolved solids concentration; and
4. The economic cost of the distillate (pesos/L) produced by the adobe distillation unit will be less than the cost of purchasing drinking water from a water vendor at the study location (0.875 pesos/L).

CHAPTER 2: PREVIOUS RESEARCH

2.1 Defining Domestic Water Supply

The domestic water supply is defined as the total amount of water needed to perform all household activities (WHO, 2000). The amount of water required on a daily basis, as defined by Howard and Bartram (2003), can range from 5 liters to 100 liters depending upon the level of access to the water source available to the user and the expected sanitation and hygiene benefits. Figure 2.1 (Cairncross et al., 1993) illustrates the relationship between the distance to the water source and the amount of water collected, where the amount of water consumed decreases when the amount of time required collecting the water increases. Other studies (Kennedy, 2006) do contend that the amount of water collected will plateau, indicating that there is some minimum quantity of water needed regardless of the distance needed to travel.

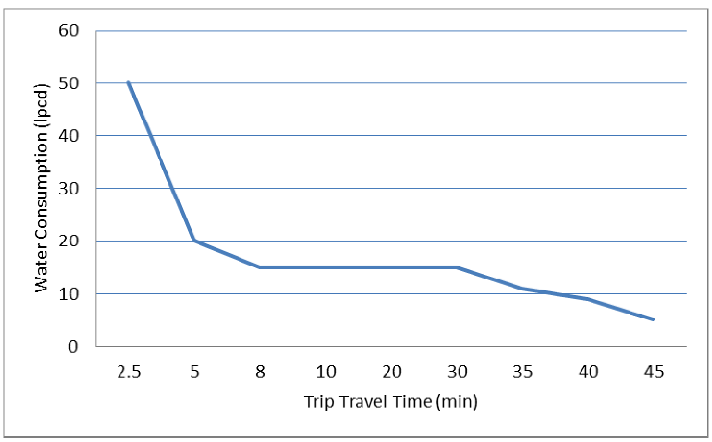

Figure 2.1: Typical relationship between water collection time and domestic consumption (adapted from Cairncross et al., 1993).

While the total volume of water required is important to consider when assessing a communities water situation, more detail is needed regarding how the water is specifically used. Table 2.1 demonstrates how the domestic water supply can be organized into four categories based on water use to provide a better understanding of water utilization.

Table 2.1: Categories of water use and examples of each use. These categories can help define the types of water sources needed in a household, which is important when demonstrating to end-users that the highest quality water should be saved for consumption uses only (Mihelcic et al., 2009).

Water Use Category	Examples
Consumption	Drinking and Cooking
Hygiene	Personal and domestic cleanliness (e.g., bathing laundry, washing floors, dust suppression).
Productive	Gardening, brewing, animal watering, construction (e.g., manufacturing concrete or adobe).
Amenity	Washing a vehicle or motor scooter, lawn watering.

Applying these categories, a study done with a community in Kenya shows that total village water use to be 17 L/capita-day: consumption accounted for 21%, hygiene for 51%, and productive uses for 28% (Kennedy, 2006). In the context of applying a solar distillation technology, this research is concerned with the amount of water needed for consumption, or more specifically the amount for water required by a household for drinking and cooking.

2.2 Water Quantity Related to Consumption

There are numerous published studies that analyze the amount of water required for drinking, and as shown in Table 2.2 the human demand for drinking water ranges between 2 and 3 L/capita-day. However, Table 2.2 also indicates that there are exceptions to this estimation in situations where the working or environmental conditions are extreme, such as arid or tropical locations or manual labor based jobs, which can require up to 4.5 L/capita-day.

Table 2.2: Recommendations of the daily amount of water required by humans for drinking. Note that humans working or living in extreme conditions require twice as much water per day as consumers in normal conditions would. Adult females with infant children can require up 5.5 liters of water per day in any environment.

Study	Adult Male (L/day)	Adult Female (L/day)	Child (L/day)	Extreme Conditions (L/day)
IPCS (1994)	2	1.4	1	2.8-3.7
IRC (1981)	3	3	-	-
White et al. (1972)	2-3	2-3	1	-
Howard et al. (2003)	2.9	2.2 (5.5)	1	4.5

The other exception noted in Table 2.2 is the increase in water demand for adult females when they are lactating. Women in this category can require up to 5.5 L/capita-day for drinking purposes. These exceptions emphasize the importance of a detailed community profile when estimating the total demand for drinking water.

The other component of total water required for consumption is the quantity of water used during the preparation of food. This value can vary due to the type of food prepared and how it is prepared. In most cases, 2 L/capita-day is a sufficient estimation; however there are instances when an additional 4 L/capita-day are required (Howard et al., 2003). Considering the quantity of water required for cooking and the data provided in Table 2.2 relating to the quantity required for drinking, the commonly accepted range of water use ranges from 6 to 8 L/capita-day.

2.3 Solar Energy Principles

Solar energy reaches the atmosphere of earth in the form of radiant light and heat with energy of insolation equivalent to 1661 W/m^2 (Gueymard, 2004). After being partially reflected and absorbed by the earth's atmosphere, the maximum available solar irradiation reaching the surface of the earth ranges between 700 and 750 W/m^2 (Coskun et al., 2011). Figure 2.2 provides the annual mean net surface solar radiation for Earth for different latitudes.

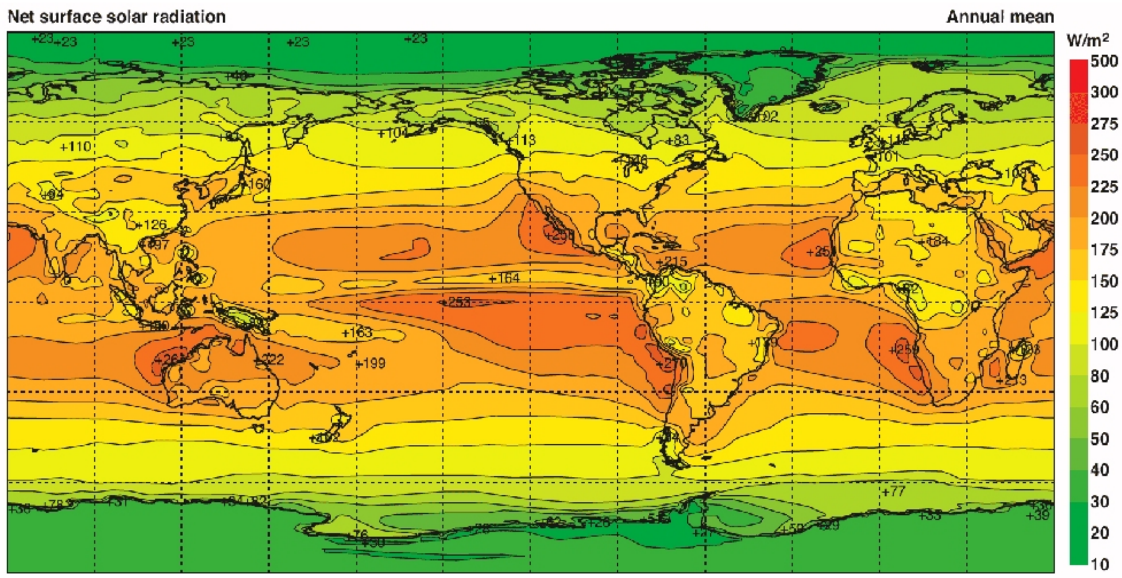

Figure 2.2: The annual mean of net surface solar radiation (W/m^2) on Earth (http://realneo.us/image/insolation-maps).

Examination of Figure 2.2 reveals that, except near the poles, most of the landmasses on earth receive an average between 100 and 300 W/m^2 of available solar energy. This range compares to the accepted averaged continuous amount of solar energy on Earth of about 235 W/m^2 (Philibert, 2005), and represents between 6% and 18% of the total solar energy reaching the earth.

Despite the fact that only 18% of total solar energy is available for use and the difficulty that can be associated with its utilization, solar energy can be harnessed at different levels around the world through various solar technologies. Solar technologies are broadly characterized as either passive or active depending on the way they capture, convert and distribute sunlight. Active solar techniques use photovoltaic panels, pumps, and fans to convert sunlight into useful outputs. Passive solar techniques include selecting materials with favorable thermal properties to absorb the sun's energy, designing spaces that naturally circulate air, and referencing the position of a building or other technology to maximize the exposure to the sun (Coskun et al., 2011).

The drawbacks associated with the utilization of solar radiation for energy are well documented as this energy is: 1) very dilute at only about 1 kWh per square meter (Philibert, 2005), 2) intermittent being available only during day-time, and 3) unequally distributed over the surface of the earth - mostly between 30° north and 30° south latitude (Abbott, 1944).

2.4 Solar Distillation

Solar distillation is a passive solar technology and is the process of using solar energy to produce purified water from an impure source. The basic solar distillation process is described by Torchia-Nuñez (2007):

1. The basin of a solar still (Figure 2.3) is partially filled with brine, where the inside of the basin is typically covered by a black material (basin liner or collector plate) that absorbs incoming radiation after it passes through the glass cover and the brine.
2. The basin liner undergoes an increase in its temperature as it absorbs incoming solar radiation and transfers the heat into the brine in the basin.
3. In time clean distillate evaporates from the free surface of the brine, and a natural convection flow of humid air circulating between the free surface of the brine and the bottom of the glass cover takes place due to the temperature difference between the free surface of the heated brine and the cooler upper cover.
4. The inclined glass cover then serves as a condensing plate where the distillate condenses on the bottom surface and runs by gravity along the incline to a small collector channel in the shortest sidewall of the solar still.

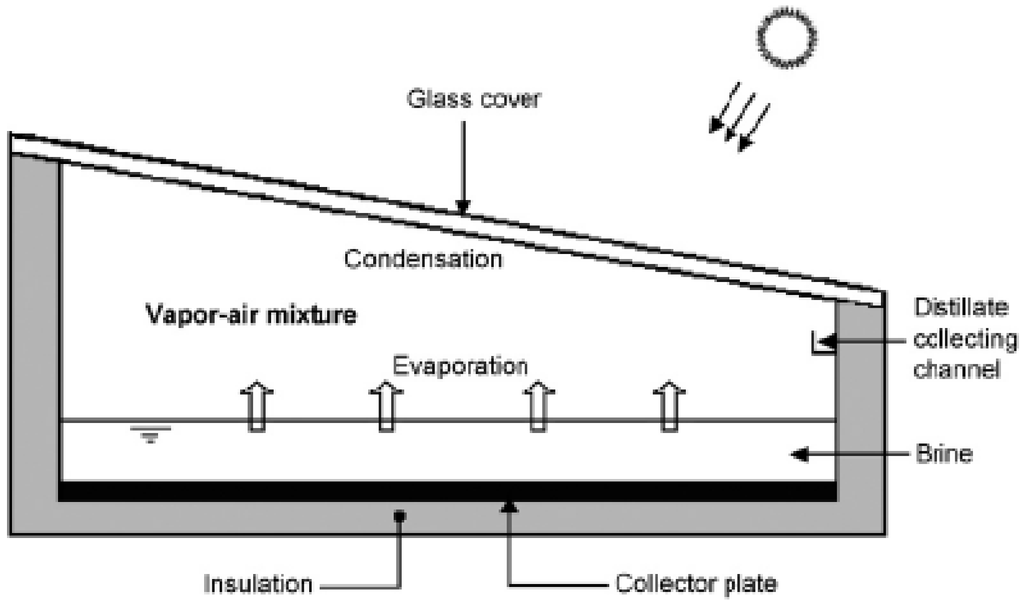

Figure 2.3: Schematic view of a solar still used to describe the basic process of solar distillation. Reprinted from Renewable Energy, Volume 33, J.C. Torchia-Núñez,M.A. Porta-Gándara and J.G. Cervantes-de Gortari, Exergy analysis of a passive solar still, Pages No. 608-616, Copyright (2008), with permission from Elsevier.

The first documented use of solar stills to purify water dates back to 1551 when it was used by Arab alchemists. Other scientists and naturalists used solar distillation over the coming centuries, including Della Porta (1589), Lavoisier (1862), and Mauchot (1869) (Tiwari et al., 2003). Talbert et al. (1970) provide a thorough historical review of solar distillation in a report for the US Department of the Interior. Fath (1998) reviewed various designs of solar stills and studied the suitability of solar stills for providing potable water in developing countries and Foster et al. (2005) performed a review of the advancements during the last ten years in solar distillation technologies.

Based upon the reviewed literature, the current status of solar distillation can be summarized as follows:

1. Fath (1998) concluded that producing fresh water by solar distillation can support community living activities, particularly in water scarce rural areas when the demand is less than 200 m^3 per day,

2. Barrera (1992) stated that distilled water production for potable use might be 3.5 times more economical than common water treatment processes, and
3. Foster et al. (2005) reports that solar distillation systems are easy to build, inexpensive, and extremely effective in distilling water with a high total dissolved salt content and in killing pathogenic bacteria such as cholera and *E. coli*.

2.5 Classification of a Solar Still

Solar distillation systems are typically classified as either a passive solar still or an active solar still. In a passive solar still, the solar radiation is received directly by the basin water providing the source of energy needed for driving the evaporation process. In the case of active solar stills, in addition to solar radiation, an external form of energy is fed into the basin to accelerate the evaporation process.

Malik et al. (1982) provides a detailed review of early passive solar still designs. Their work was updated by Tiwari (1992) and by Tiwari et al. (2003), who discuss the present status of solar distillation and include a review of active solar stills. Further work relevant to active solar stills is available in detail from Sampathkumar et al. (2010), while Kaushal (2010) offers a study comparing the geometry, property, advantages, disadvantages and performance of seven different still types, both active and passive. Tiwari et al. (2003) recommends that only passive solar stills can be economical to provide potable water as they require no extra energy input like active solar stills do. Table 2.3 provides a list of passive solar still types discussed in the current literature.

Table 2.3: Common types of passive solar stills reviewed in the literature. The basin type still is the simplest system to construct, but the production potential of the other systems is usually higher.

Passive Solar Still Type	Source
Basin (Single-sloped, Double-sloped)	Tiwari et al. (1997); Fath (1998); Murugavel et al. (2008); Kaushal (2010).
Double Condensing Chamber	Tiwari et al., (1997).
Vertical	Coffey (1975); Kiatsiriroat et al. (1987); Kiatsiriroat (1989).
Conical	Tleimat and Howe (1967).
Inverted Absorber	Suneja and Tiwari (1999).
Wick (Tilted, Multiple)	Frick and Sommerfeld (1973); Sodha et al. (1981); Tiwari 1984; Fath (1998); Kaushal (2010).
Multiple-effect (Diffusion)	Barrera (1993); Franco and Saravia (1994); Adhikari et al., (1995); Fath (1996); Tanaka et al. (2000a, b); Mahdi et al. (2011).
Inclined Weir	Sadineni (2008).
Hybrid Combinations	Hou and Zhang (2008);

The most commonly used solar distillation technology is a single effect, single-basin still (Figure 2.3) characterized by a relatively large thermal mass, i.e., the water basin (Aboabboud et al., 1996). The basin type solar still is the only field proven solar distillation technology that provides isolated communities with an efficient way to convert brackish water into potable water (Fath, 1998; Tiwari et al., 2003; Samee et al., 2007, Kaushal, 2010).

2.6 Basin Type Solar Still Design Parameters

The considerations for the design of a basin type solar distillation technology are primarily based upon the following design parameters: 1) the depth of the brine in the basin, 2) the evaporative area of the basin, 3) the angle of the condenser plate, 4) the insulation properties of the basin material, and 5) the type of material used as the basin liner. Table 2.4 summarizes some of the current research related to this topic. Each design parameter provided in Table 2.4 is discussed in further detail in the remainder of this section.

Table 2.4: This table lists a summary of some research pertaining to the optimization of a single basin passive solar distillation unit categorized by the design parameter.

Design Parameter	Study Topic	Sources
Cover Tilt Angle	Condenser angle optimization	Harris et al. (1985); Al-Hinai et al. (2002); Badran (2007); Tanaka (2010).
Brine Depth	Depth of brine optimization	Al-Hinai et al. (2002); Badran (2007); Samee et al. (2007).
Insolation Properties of the Basin	Reducing bottom loss coefficients	Cooper (1969); Tiwari et al. (1987).
	Multiple basin materials	Murugavel et al. (2008a); Akash et al. (1998).
Basin Liner Material	Asphalt	Badran (2007).
	Sponge cubes	Bassam et al. (2003).
	Multiple absorber types	Murugavel et al. (2008b); Velmurugan et al. (2010).
	Perforated black plate	Nafey et al. (2002).
	Black rubber and black gravel	Nafey et al. (2001).
	Black dye	Rajvanshi et al. (1979)
Other	Internal reflectors	Badran (2007); Madhlopa et al. (2009).
	External reflectors	Malik et al. (1982); Kumar et al. (2008); Shanmugan et al. (2008).

2.6.1 Cover Tilt Angle

The effect of the cover tilt angle on the productivity of a solar still can be significant because the variation in the tilt angle results in a number of physical changes in the still (Khalifa, 2011). Some of the major impacts are:

1. The volume available for water evaporation above the water surface; larger volumes as a result of larger tilt angles need longer time to become saturated which delays the start of productivity.
2. The heat transfer area of the cover; the increase of the tilt angle results in increased thermal losses from the cover which can limit overall productivity.
3. The speed at which the droplets travel along the interior surface of the cover towards the collecting tray; some droplets will fall into the basin if the angle is too low.

The general rule of thumb used to determine the glass cover tilt angle is that the angle should be 10 degrees higher than the latitude in the winter and 10 degrees lower that the latitude in the summer for a particular location (Harris et al., 1985). Figure 2.4 shows the results from a study conducted in Oman (Al-Hinai et al., 2002) that analyzed the effects of cover tilt angle on the productivity of the still.

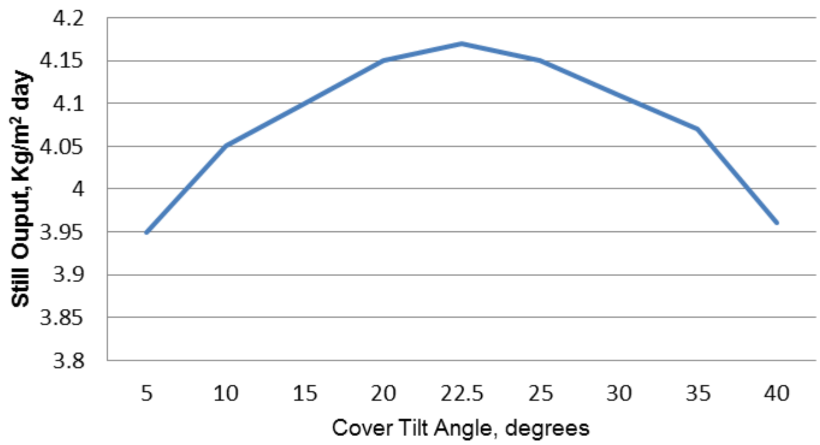

Figure 2.4: The average single basin solar distillation system output for different angles of slope for the cover. Reprinted from Energy Conversion and Management, Vol. 43, H. Al-Hinai, M.S. Al-Nassri, and B.A. Jubran, Effect of climatic, design and operational parameters on the yield of a simple solar still, pp. 1639-1650, Copyright (2002), with permission from Elsevier.

Figure 2.4 shows there is an optimized angle of the cover tilt of approximately 22 degrees that provided the best average productivity for a basin type solar still for this particular location. The latitude ranges from 18 degrees to 22 degrees in Oman, which follows the rule of thumb for estimating the appropriate cover tilt angle.

Khalifa (2011) provides a detailed review and summary of all of the pertinent literature regarding the optimization of the cover angle on a basin-type solar still. In this review a correlation is developed that defines the relation between the cover tilt angle and the latitude angle. This dependency is illustrated in Figure 2.5 and it can be seen that the cover tilt angle and the latitude angle are within close agreement.

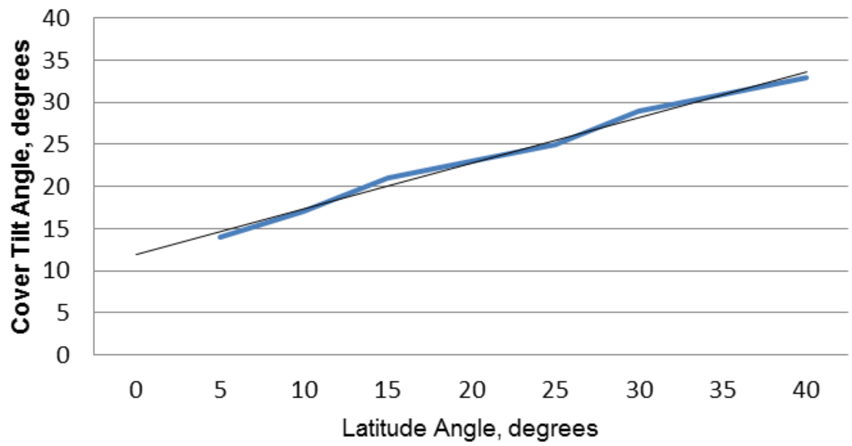

Figure 2.5: The trend of the relation between the cover tilt angle and the latitude angle. Reprinted from Energy Conversion and Management, Vol. 52, A.J. Khalifa, On the effect of cover tilt angle of the simple solar still on its productivity in different seasons and latitudes, pp. 430-436, Copyright (2011), with permission from Elsevier.

It is clear from Figure 2.5 that the tilt angle should be increased as the latitude increases, or as location moves north or south away from the equator. Furthermore, the figure suggests an optimum cover tilt angle that is close to the latitude angle of the test location which validates the rule of thumb.

2.6.2 Brine Depth

The depth of the brine in a basin-type solar still is considered to be the design variable with the largest influence on overall still productivity, and despite the variability in the literature about the quantitative impacts of brine depth, the overall consensus is that as brine depth increases productivity will decrease.

In a study by Khalifa et al. (2011), a linear regression using the least squares method was fitted to data from numerous investigations that reported the relationship between brine depth and productivity. From this analysis the following power regression was developed where y is the productivity, L/m^2-day, d is the brine depth, cm, and R^2 is the correlation coefficient:

(Equation 2.1)

Based upon Equation 2.1 the following conclusions can be made about the relationship between brine depth and productivity:

1. The relationship is inversely proportional, defined by the negative exponent, as brine depth increases the productivity decreases;
2. There is much variability in the investigation data, as demonstrated by the low value of the regression coefficient.

The low regression coefficient in Equation 2.1 indicates that the equation may not be suitable for use as a performance prediction model. Some of the variability in this model can be explained by the extreme diversity of the study locations used by the authors. Figure 2.6 illustrates the correlation between water depth and productivity, where the inverse relationship is also visible.

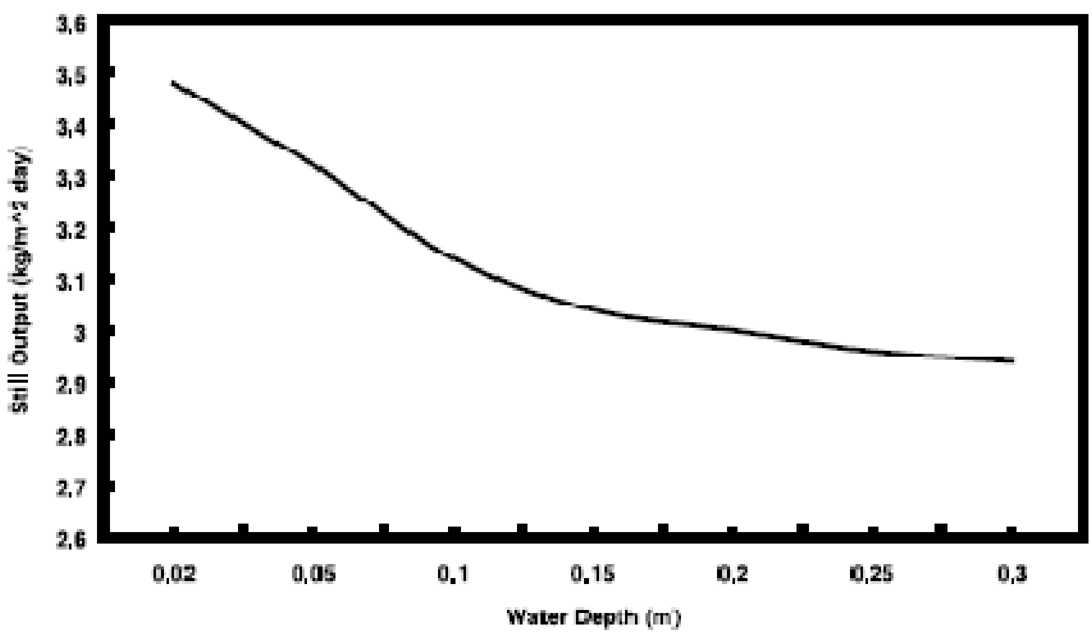

Figure 2.6: The effect of brine depth on distillate production is that shallower brine produces more because it requires less energy to reach evaporation temperature which will allow for more productive hours. Reprinted from Energy Conversion and Management, Vol. 43, H. Al-Hinai, M.S. Al-Nassri, and B.A. Jubran, Effect of climatic, design and operational parameters on the yield of a simple solar still, pp. 1639-1650, Copyright (2002), with permission from Elsevier.

This inverse relationship is due to the increase of the heat capacity of the brine in the basin, as the volume of brine available for evaporation is proportional to the brine depth. So as depth and volume increase, so does the amount of energy that it takes to heat the brine to a sufficient temperature to promote evaporation. Studies (Al-Hinai et al., 2002) have demonstrated that even though more distillate is produced during daylight hours when shallow brine depths are used, nocturnal distillate production is proportional to brine depth.

This increased productivity is a result of the larger volume of brine that absorbs solar radiation throughout the day, effectively storing the heat to drive evaporation during the nocturnal hours. In effect, it was concluded that despite the fact that deeper brine depths will take longer to start producing distillate each day; there may be favorable increases in overall productivity during the day (Aboul-Enein et al., 1998). Figure 2.7 shows the daily and nocturnal output expected for different brine depths.

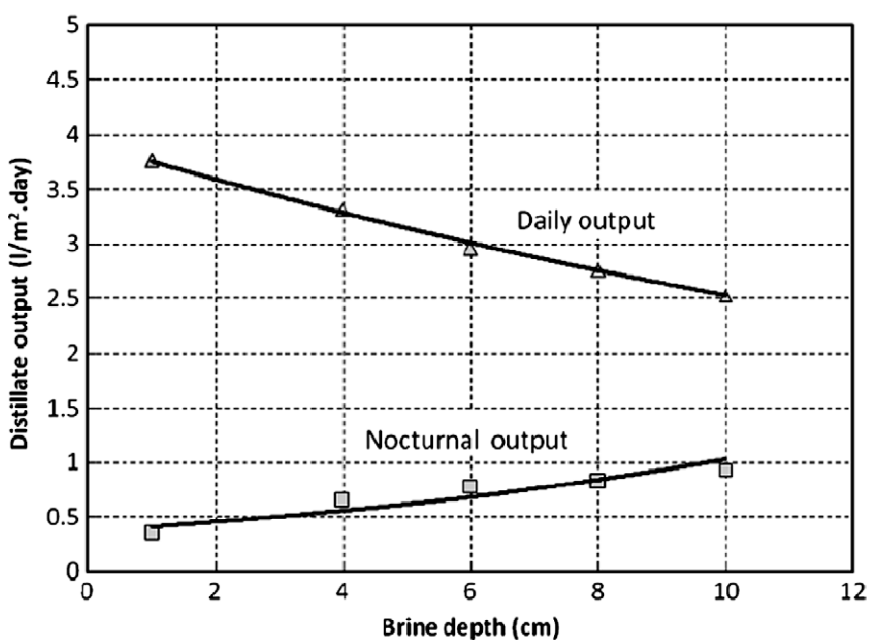

Figure 2.7: The daily and nocturnal output for different brine depths. Reprinted from Desalination, Vol. 249, A.J. Khalifa and AM Hamood , Performance correlations for basin type solar stills, pp. 24-28, Copyright (2009), with permission from Elsevier.

Analyzing Figure 2.7 for an optimized depth it appears that 2-3 cm of water will provide the greatest productivity during the daylight hours. Conversely, for nocturnal output, it appears that 10 cm of water provides the most production. Table 2.5 summarizes Figure 2.7 into a total daily production value and there does not appear to be a significant advantage to increasing the maximum brine depth past 4 or 5 cm despite the added nocturnal production at deeper depths.

Table 2.5: Numerical analysis of the total (daylight and nocturnal hours) water output of a solar distiller for the model presented in Figure 2.7.

Brine Depth (cm)	Nocturnal Output (L/m^2-day)	Daily Output (L/m^2-day)	Total Output (L/m^2-day)
1	0.4	3.7	4.1
4	0.7	3.4	4.1
6	0.8	3.0	3.8
8	0.9	2.8	3.7
10	1.0	2.5	3.5

The only firm design rule in terms of brine depth is provided by Samee et al. (2007). They recommend that the minimum quantity of brine in the basin should be equivalent to twice the fresh water produced daily. This volume can be translated into a depth if site specific details are known. Murugavel et al. (2008a) however recommends that for lower sun radiation intensity, use of a shallow basin still (1-5 cm) is preferable and for higher sun radiation intensity a deep basin still (greater than 5 cm) is preferable to take advantage of nocturnal production. However, the authors do not provide detail regarding the ranges for defining between low and high radiation intensity locations.

2.6.3 Basin Thickness

The primary purpose of the basin is to store brine; the secondary function of the basin is the insulation that it provides to the brine waiting to be evaporated. Generally the structural materials used in a solar still are wood, galvanized iron, aluminum, asbestos cement, masonry bricks and concrete (Phadatare et al., 2007). Studies that compare materials directly in a controlled experiment are not prominent and could be a potential for future research.

However, as shown by Figure 2.8, one study (Al-Hinai et al., 2002) did inquire about the effect of varying the thickness of the basin wall on productivity. This figure shows that productivity will increase with the thickness of the basin wall. In this particular case it appears that increasing the basin wall thickness from 2 to 5 cm provides the greatest return in productivity with a plateau effect occurring after 10 cm of thickness. However, these values most likely vary for different types of materials as insulation properties vary.

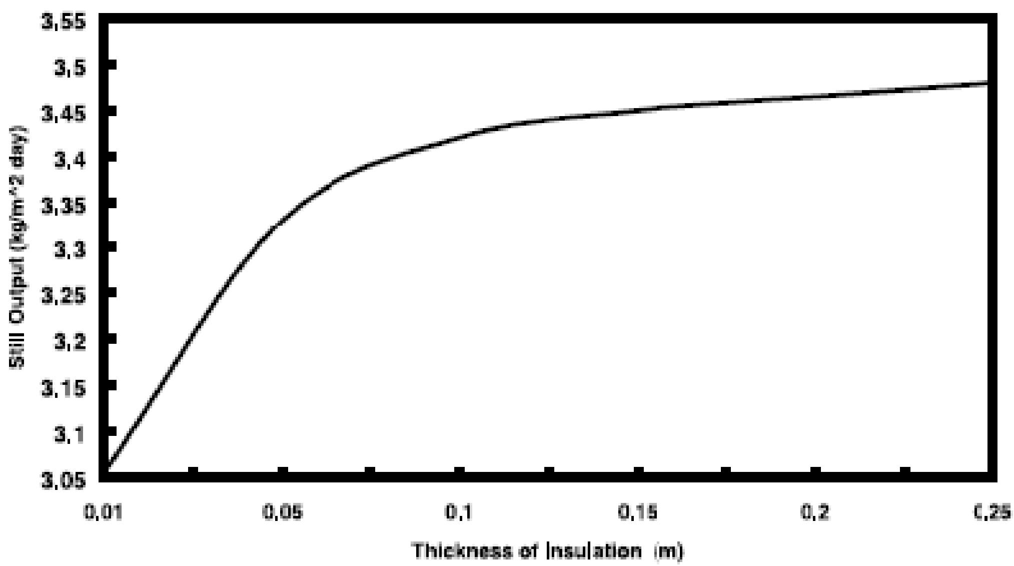

Figure 2.8: The insulation thickness effect on the still output for simple solar still. Reprinted from Energy Conversion and Management, Vol. 43, H. Al-Hinai, M.S. Al-Nassri, and B.A. Jubran, Effect of climatic, design and operational parameters on the yield of a simple solar still, pp. 1639-1650, Copyright (2002), with permission from Elsevier.

2.6.4 Basin Liner Material

While the basin holds the brine and retains the solar energy stored in the solution, the basin liner serves as the conduit between the solar radiation and the brine. The purpose of the basin liner is to absorb the incident radiation that is transmitted through the glass cover and transfer the energy in the form of heat into the brine.

Typically these materials are black to enhance their ability to capture solar radiation. The basin liner should be resistant to hot saline water, have a high absorbance to solar radiation, good resistance to accidental puncturing and in the case of damage (possibly by broken glass), and it should be easily repaired (Badran, 2007).

As shown in Table 2.4, several studies have investigated the optimization of the basin liner material. Figure 2.9 details the findings Al-Hinai et al. (2002) where multiple materials were examined for their impact on productivity. From this study and others (e.g., Velmurugan et al., 2010), materials like asphalt and rubber were found to provide the best improvement in productivity this may be due to the high absorbency of the asphalt compared to the black paint, and also the possibility that the asphalt liner will act as an insulator at the same time due to its higher heat capacity. Murugavel et al. (2008a) concludes that rubber is the best basin material to improve absorption, storage and evaporation effects.

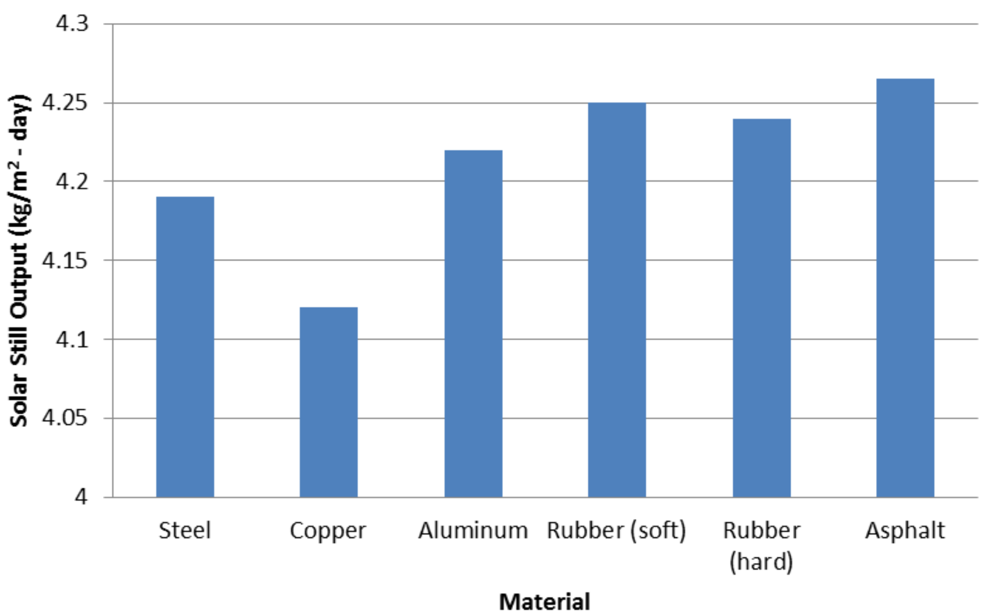

Figure 2.9: Effect of basin liner materials on distillate output in a single basin solar distillation unit. Reprinted from Energy Conversion and Management, Vol. 43, H. Al-Hinai, M.S. Al-Nassri, and B.A. Jubran, Effect of climatic, design and operational parameters on the yield of a simple solar still, pp. 1639-1650, Copyright (2002), with permission from Elsevier.

Nafey et al. (2001) also performed a detailed study into the use of rubber as a basin liner, and it was concluded that increases in the thickness of the basin liner also had favorable impacts on overall still productivity. These results are shown in Table 2.6 and it can be seen that the thickest rubber used provided between a 10% and 20% increase in solar still productivity depending on the depth of the brine.

Table 2.6: The increasing percentage in solar still productivity due to the use of black rubber is demonstrated in this table. Reprinted from Energy Conversion and Management, Vol. 42, A.S. Nafey, M. Abdelkader, A. Abdelmotalip and A.A. Mabrouk, Solar still productivity enhancement, pp. 1401-1408, Copyright (2001), with permission from Elsevier.

Experiment Date	**Brine Volume (L/m^2)**	**Rubber Thickness**		
		2 mm	**6 mm**	**10 mm**
6-9-1998	20	5.2%	5.4%	10%
8-9-1998	30	6.3%	9.0%	15%
10-9-1988	40	6%	9.7%	15%
14-9-1988	50	7.8%	10%	19%
16-9-1998	60	8%	11%	20%

Typically paint, silicone, or dye is used as a common basin liner to get this benefit (Nafey et al., 2003; Badran, 2007); however, a custom-cut sheet of black rubber of any thickness may be an effective upgrade to the simple still without adding too much cost. There has been little published information regarding the impact on taste that the various basin liners may have, or if volatile organic compounds are transferred to the distillate.

2.7 Basin Type Solar Still Performance

Like the design parameters that can control productivity, there are other operational parameters that essentially determine how a basin-type solar distillation unit will perform. The meteorological parameters of wind velocity, solar radiation, and ambient temperature are important variables in overall still productivity (Nafey et al., 2000; Mathioulakis et al., 2003; Tiwari, 2003). Unlike the design parameters, however, these operational parameters cannot be controlled or optimized. Table 2.7 lists the meteorological parameters and the typical unit of measurement.

Table 2.7: The various meteorological parameters that affect solar still performance are listed. Values for these variables can be measured or estimated using meteorological databases such as the one available from NASA.

Parameter	Variable	Units
Solar Irradiation	*H*	kW h/m^2
Wind Velocity	*V*	m/s
Ambient Temperature	*t*	C

2.7.1 Solar Irradiation

The effect of the solar irradiation (*H*) on productivity has been investigated by several groups (Malik et al., 1982; Mowla et al., 1995; Al-Hanai et al., 2002; Badran, 2007). It is found that the solar radiation is the most important parameter influencing still productivity. This relationship is demonstrated in Figure 2.10 where still output increases as the daily solar insolation values increase and vice versa.

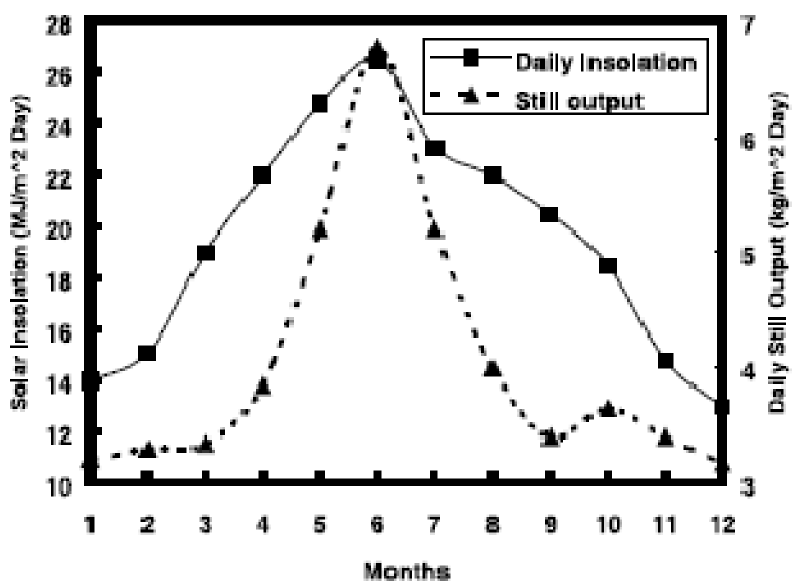

Figure 2.10: The variation of an average solar intensity and single still output in 12 months. Reprinted from Energy Conversion and Management, Vol. 43, H. Al-Hinai, M.S. Al-Nassri, and B.A. Jubran, Effect of climatic, design and operational parameters on the yield of a simple solar still, pp. 1639-1650, Copyright (2002), with permission from Elsevier.

2.7.2 Ambient Temperature

Several researchers (Al-Hanai et al., 2002; Tiwari et al., 2003; Badran, 2007; Velmurugan et al., 2010) have performed recent investigations into the effects of climatic, operational and design parameters on the performance of basin-type single slope passive solar stills. It has been concluded from these studies that the productivity of the solar stills increases with the increase of ambient air temperatures.

The effect of ambient temperature variations on solar still productivity is examined theoretically by Nafey et al. (2000) using the model of Malik et al. (1982). The numerical results showed that a slight increase of 3% in the solar still productivity is obtained by increasing the ambient temperature by 5°C. Figure 2.11 shows the effect of changes in ambient temperature on the productivity of a basin-type single slope passive still in a 2002 study. Results from this study show that increasing the ambient air temperature from 23°C to 33°C increases the distillate yield by 8.2%.

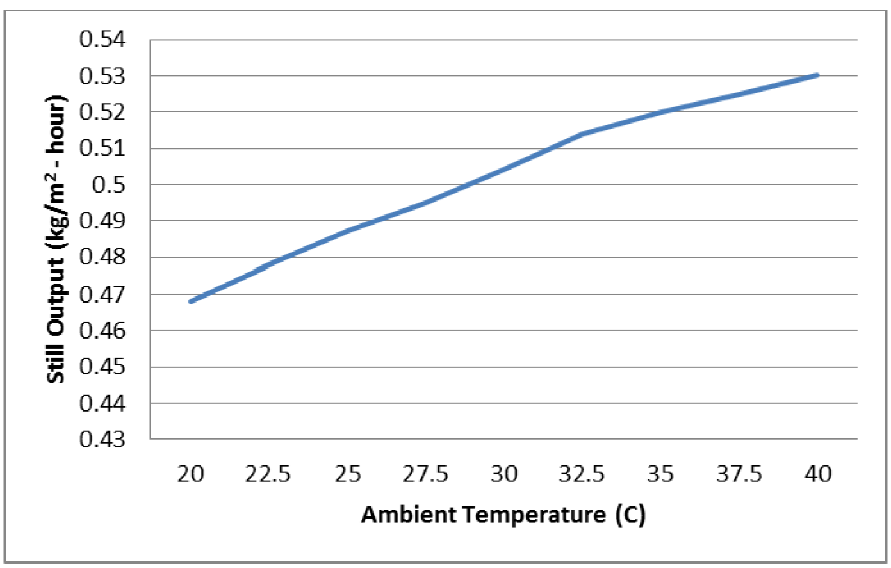

Figure 2.11: Effect of ambient conditions on single still output and temperature. Reprinted from Energy Conversion and Management, Vol. 43, H. Al-Hinai, M.S. Al-Nassri, and B.A. Jubran, Effect of climatic, design and operational parameters on the yield of a simple solar still, pp. 1639-1650, Copyright (2002), with permission from Elsevier.

2.7.3 Wind Velocity

Similar to the effects of solar radiation and ambient temperatures, the effects of wind speed on solar still productivity are well documented. However, there is conflicting information pertaining to the effect that is occurring. Table 2.8 organizes the literature into three categories:

1. studies that find increases in productivity with increases in wind speed,
2. studies that find decreases in productivity with increases in wind speed, and
3. studies that find that there are no significant impacts on still output with changes in wind speed.

Table 2.8: A summary of current research regarding the effects of wind speed on the productivity of a solar distillation unit.

Productivity Increase	Productivity Decrease	No Significant Change
Cooper (1969)	Hollands (1963)	Morse et al. (1968)
Soliman (1972)	Eibling et al. (1971)	
Malik et al. (1973)	Yeh et al. (1986)	
Nafey et al. (2000)		
Al-Hinai et al. (2002)		

Figure 2.12 shows the variation found in daily productivity in a basin-type solar still with varying wind speeds and volumes of water. The relationships in Figure 2.12 provide support to the idea that it is possible that all of the scenarios mentioned in Table 2.8 could occur in a given still depending upon the amount of water in the still and the variation of wind speed.

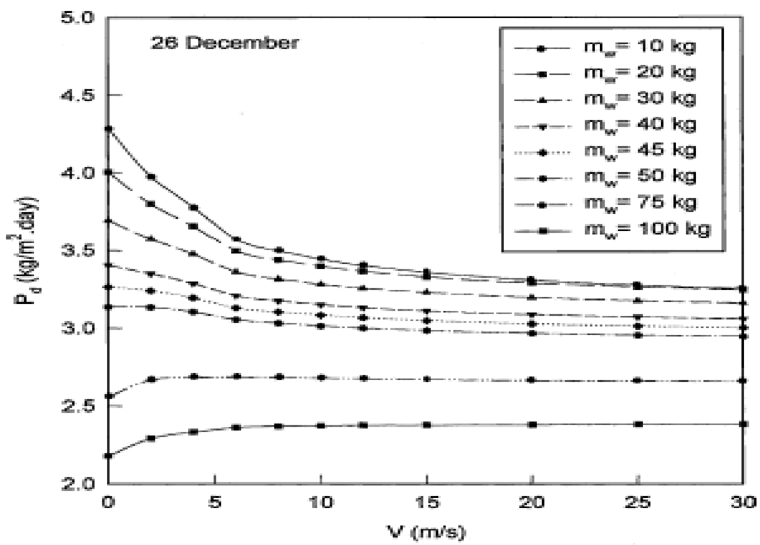

Figure 2.12: Variations of daily productivity with wind speed for different masses of basin water. Reprinted from Energy Conversion and Management, Vol. 45, A.A. El Sebaii, Effect of wind speed on active and passive solar stills, pp. 1187-1204, Copyright (2004), with permission from Elsevier.

For the passive single effect basin type stills, it is found that there is a critical mass (depth) of basin water beyond which the overall productivity (P_d) increases as wind speed (V) increases. For shallow depths less than the critical depth, productivity (P_d) decreases as wind speed (V) increases. The value of the critical mass (depth) for the investigated single effect passive stills is found to be 45 kg (4.5 cm) (El-Sebaii, 2004). This critical mass can be used to help with the brine depth design parameter calculation if productivity increases due to increased wind speed are desired.

2.7.4 Predicting Performance: Standard Operating Equation(s)

Many of the productivity calculation methods that have been suggested over the past five decades are based on an analytical dynamic modeling of the heat and mass transfers in each discrete part of the still (Dunkel, 1961; Hongfei et al., 2002; Tsilingiris, 2009; Feilizadeh et al., 2010). Murugavel (2008a) has a good illustration and description of the principal energy exchange mechanisms that occur within a basin type solar still. These mechanisms are detailed in Figure 2.13.

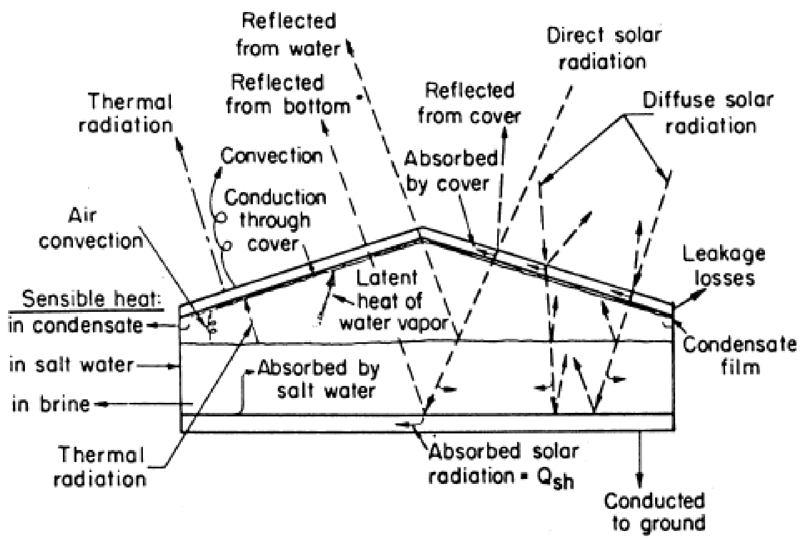

Figure 2.13: A diagram of the main energy exchange mechanisms that occur within a solar distillation unit. Reprinted from Desalination, Volume 220, K.K. Murugavel and K.S. Chockalingam, Progresses in improving the effectiveness of the single basin passive solar still, Pages No. 677-686, Copyright (2008), with permission from Elsevier.

This approach introduces several drawbacks related to the difficulty to determine in practice the actual characteristics of the installation, the first is missing or unreliable meteorological data, and the second is the complexity of the equations describing transport phenomena inside the still (Mathioulakis et al., 2003). Because of this several authors (Khalifa, 2009; Nafey et al., 2000; Mathioulakis et al., 1999) have developed simplified expressions to predict the productivity of a solar still in the field.

Khalifa et al. (2009) published a set of performance equations (Equations 2.2 - 2.4) that were based upon various design and operating parameters, namely brine depth (δ), solar insolation (H), and cover tilt angle (θ).

$$y = 3.884e^{-0.0458\delta}; R^2 = 0.832 \quad \text{(Equation 2.2)}$$

$$y = 0.0036H^2 + 0.0701H + 0.2475; R^2 = 0.762 \quad \text{(Equation 2.3)}$$

$$y = -0.0025\theta^2 + 0.1562\theta + 0.843; R^2 = 0.734 \quad \text{(Equation 2.4)}$$

Equations 2.2 - 2.4 are applicable under the following conditions:

- Passive basin type solar still under solar radiation between 8 and 30 MJ/m^2 day.
- Galvanized iron body.
- Insulation thickness between 5 and 10 cm of polystyrene or any other insulation with equivalent conductivity.
- Glass cover with tilt angle between 5° and 45℃.
- Brine depth ranging from 1 to 10 cm.
- Latitude angles between 20° and 35° N.

Updating their 2009 work, Khalifa (2011) reworked Equation 2.2 so that still productivity could be determined based upon the depth (δ) of brine in the still. The new relationship, equation 2.1, was discussed earlier during the review of the impacts of brine depth on distillate production.

$$y = 3.259\delta^{-0.19},\ R^2 = 0.129 \quad \text{(Equation 2.1)}$$

Because Equation 2.1 has a low correlation coefficient (r^2 = 0.1229), it may be used for a crude estimate of the productivity at different brine depths under the following wide range conditions:

- Single and double slope basin-type solar still with cover tilt angle between 10 degrees and 35 degrees, and brine depth between 0.5 and 30 cm;
- Latitude angles between 20 degrees and 35 degrees;
- Solar radiation between 8 and 30 MJ/m^2-day (Khalifa, 2011).

Mathioulakis et al. (1999) investigated a simplified method for the evaluation of the performance of a typical solar still and the prediction of long-term water production. Equations 2.5 and 2.6 are taken from the results of this study.

$$M_{w,d} = a_1 H_d + a_2 H_d + a_3 T_{a,d} + a_4 T_{a,n-1} + a_5 T_{a,d-1} + a_6 \quad \text{(Equation 2.5)}$$

$$M_{w,n} = b_1 T_{a,n} + b_2 H_d + b_3 T_{a,d} + b_4 T_{a,n-1} + b_5 \quad \text{(Equation 2.6)}$$

In Equations 2.5 and 2.6; $M_{w,\,d}$ is the productivity of the solar still during the day (kg), $M_{w,\,n}$ is the productivity of the solar still during the night (kg), H_d is the average daily solar insolation (MJ/m^2), $T_{a,\,d}$ is the day time average ambient temperature (C), $T_{a,\,n-1}$ is the previous nights average ambient temperature(C), $T_{a,\,d-1}$ is the previous days average ambient temperature(C), $T_{a,\,n}$ is the night time average ambient temperature(C), and $a_1 ... a_6$ and $b_1 \ldots b_5$ coefficients for the linear regression model.

It is concluded from the results that the suggested model satisfactorily predicted the long-term output of the solar still using standard meteorological data sets, such as the average values of air temperature and solar radiation. However, it is necessary to conduct site specific field tests to determine the coefficients $a_1 ... a_6$ and $b_1 \ldots b_5$ before the model can be applied to a particular study, making the model difficult to apply.

In a recent study (Nafey et al., 2000) an effort was made to create an expression that can be used to predict the productivity of a basin-type solar distillation unit with data that is readily available. This expression, Equation 2.7, differs from a majority of the research in the area of modeling solar still performance in that it is a function of the design and operating parameters of the solar still instead of the complicated thermodynamic relationships that are occurring throughout the still.

$$P_d = -1.39 + 0.894H + 0.033t - 0.017V - 0.008\theta - 1.2\left({}^{\delta}/_{l}\right) \quad \text{(Equation 2.7)}$$

Table 2.9 summarizes the variables for the expression that is shown in Equation 2.7. All of these variables are measurable in the field or can be estimated from meteorological databases if available for the particular study location.

Table 2.9: Design and operational parameters used to determine solar still productivity with Equation 2.7.

Parameter	Variable	Units
Productivity	P_d	L/m^2-day
Brine Depth	δ	cm
Cover Tilt Angle	θ	degrees
Solar Irradiation	H	kWh/m^2
Wind Velocity	V	m/s
Ambient Temperature	t	C
Front Wall Height	l	cm

To measure the strength of the relation between the dependent and the independent variables of Equation 2.7, the multiple correlation coefficient (R^2) is calculated and found to be 0.99 for the still productivity (Nafey et al., 2000). This indicates that 98% of the variability of the dependent variable for productivity (P_d) has been explained by the fitted multiple regression of (P_d) on the six variables (Richard et al., 1996). Therefore, Equation 2.7 should be able to be used to predict the daily productivity with a reasonable confidence level.

2.8 Water Quality of Solar Still Distillate

The overall purpose of a solar still is to convert brackish water or water with other contaminants into a clean water source for consumption purposes. There are two water quality parameters that are typically analyzed when drinking water is concerned: total dissolved solids (TDS) and conductivity. Higher values of conductivity indicate the presence of more TDS and hence more salinity (Hanson et al., 2004) and correlations are available to relate obtainable conductivity measurements to TDS (e.g., see Mihelcic and Zimmerman, 2010) if no manner of TDS detection is possible.

$$Total\ Dissolved\ Solids\ [\frac{mg}{L}] = 0.64 * (Specific\ Conductance\ \left[\frac{S}{m}\right])$$

According to the WHO Guidelines for drinking-water quality (WHO, 2011), the palatability of water with a TDS level < 600 mg/L is generally considered to be good, while drinking water with TDS levels approaching 1,000 mg/L becomes significantly unpalatable and would not be consumed. However, the WHO does not propose any health-based guideline value for TDS as it is a measure of acceptability over health risk.

Table 2.10 displays water quality results from a study conducted on the distillate of a solar distillation experiment in Pakistan (Samee et al., 2007). Table 2.10 shows that the salt concentrations as measured by TDS and conductivity in the three samples decreased during the distillation process. This occurred especially in sample #3, where significant levels of TDS and conductivity were found before the sample was treated.

Table 2.10: Summary of water quality results taken from a solar distillation study in Pakistan. Reprinted from Renewable and Sustainable Energy Reviews, Volume 11, M.A. Samee, U.K. Mirza, T. Majeed and N. Ahmad, Design and performance of a simple single basin solar still, Pages No. 543-549, Copyright (2007), with permission from Elsevier.

Sample No.	TDS (mg/liter)		Conductivity (mS/cm)		Percent Removal	
	Before Distillation	After Distillation	Before Distillation	After Distillation	TDS	Conductivity
Sample 1	370	30	1.291	41.0×10^{-3}	91.89	96.82
Sample 2	544	84	1.668	31.0×10^{-3}	84.55	98.14
Sample 3	17,663	226	85.3	88.5×10^{-3}	98.70	99.89

Distillate from a basin-type solar still was also tested in a study (Hanson et al., 2004) conducted by New Mexico State University. In this study, removal of more than 99%, similar to values found in Table 2.10, were noted from repetitive tests run on salinity, total hardness, nitrate, and fluoride. According to the authors, this level of removal efficiency could be expected for other conservative, inorganic contaminants, such as arsenic, molybdenum, and selenium.

The solar stills tested in the Hanson et al. study were also successful in removing fecal coli and *E Coli* by more than 99.9% from the water if care was taken to avoid cross contamination from the raw water source. Table 2.11 summarizes these findings.

Table 2.11: A summary of results obtained in a 2004 study that examined the effect of solar distillation on the presence of fecal coli and *E Coli* bacteria in the distillate. This table indicates that the process of distillation may be effective at removing both fecal coliforms and *E Coli* bacteria. Reprinted from Solar Energy, Volume 76, A. Hanson, W. Zachritz, K. Stevens, L. Mimbela, R. Polka, L. Cisneros, Distillate water quality of a single-basin solar still: laboratory and field studies, Pages No. 635-645, Copyright (2004), with permission from Elsevier.

Sample # - Source	**Percent Positive Fecal Coli (%)**	**Percent Positive *E Coli* (%)**
#3 Brine	67	20
#3 Distillate	8	0
#4 Brine	60	0
#4 Distillate	0	0

In the same 2004 study, the researchers also examined the ability of the distillation process to remove pesticides from the brine. Although mixed success was reported in reducing the concentrations of the pesticides in the distillate, it was concluded that all stills are vulnerable to contamination by pesticides and that total elimination of these types of compounds cannot be guaranteed by the use of distillation. Pre-treatment of these waters with a carbon filter would ensure protection where pesticides are known or suspected to be contaminates in the drinking water supply.

CHAPTER 3: METHODS

3.1 Study Location

Figure 3.1 shows the state of San Luis Potosí, which is located in the central part of Mexico. Most of the state rests on the Mexican Plateau at an average elevation of approximately 6,000 feet above sea level. It is bordered by the states of Coahuila to the north, Nuevo León to the northeast, Tamaulipas and Veracruz to the east, Hidalgo, Querétaro, and Guanajuato to the south, and Zacatecas to the northwest. The state is divided into 58 municipalities and has an area of more than 63,000 km^2. The capital of San Luis Potosí is also named San Luis Potosí and is located in the southwestern part of the state. The state has 2,585,518 total inhabitants (National Institute of Statistics, Geography and Informatics (INEGI), 2010).

Figure 3.1: Location of the state of San Luis Potosí in Mexico. Accessedd on January 25, 2012 fromhttp://upload.wikimedia.org/wikipedia/commons/2/23/San_Luis_Potos%C3%AD_en_M%C3%A9xico.svg.

This study takes place in the rural municipality of Vanegas which is located approximately 240 km northwest of the city of San Luis Potosí and about 70 km northwest of the city of Matehuala (Figure 3.2). Within the municipality of Vanegas there are several small communities scattered across the high desert, each having an estimated population ranging from 50 – 400.

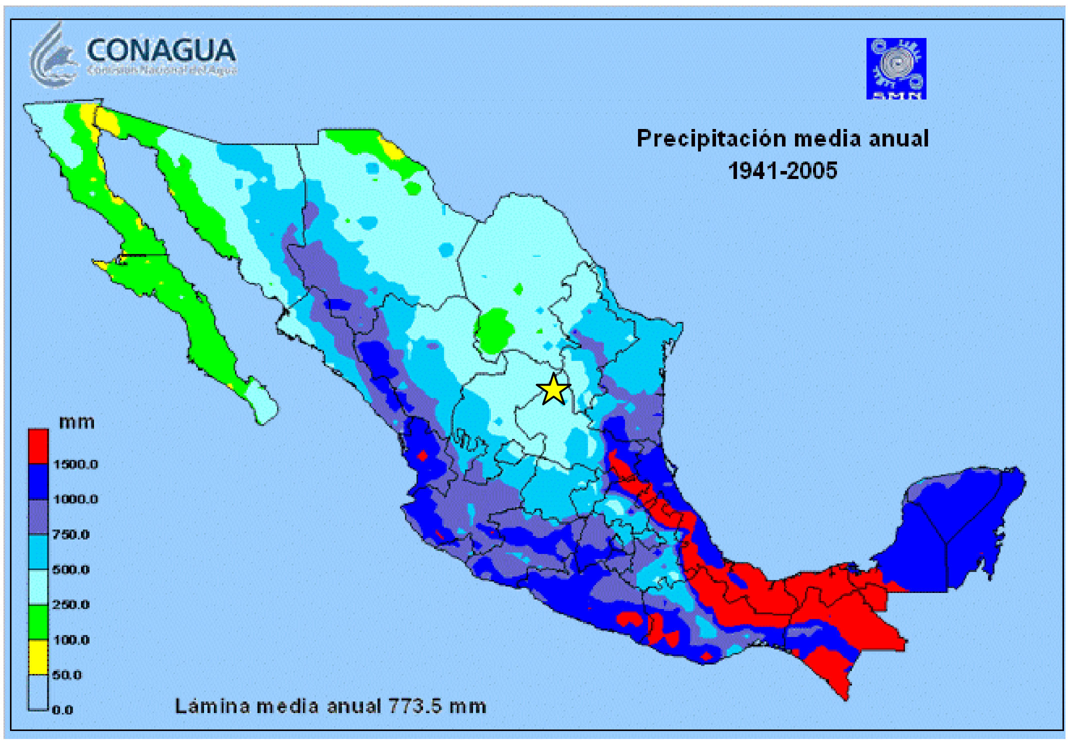

Figure 3.2: A detailed map of the annual precipitation gradients for Mexico. The state of San Luis Potosí (Mexico), at the research study location marked with the yellow star, receives about 500 mm of precipitation per year (downloaded on January 25. 2012 from http://smn.cna.gob.mx/index.php?option=com_content&view=article&id=12&Itemid=77).

The small rural farming village of El Gallo is located at 24°13’12.05” N and 100°54’54.68” W, an extremely arid part of Mexico. El Gallo has a population of approximately 200 people and average household size 3.65 people and the average rate of water for consumption purposes was determined to be 55 liters per household per day (Marlor et al 2012). The community itself is not connected to any type of domestic water supply or sanitation network, and most improved access points provide groundwater that has become brackish, most likely because of overuse for agricultural activities. Any clean water that is consumed within the community is typically transported over long distances creating a situation where access to clean drinking water is only available to those who can afford the cost associated with bringing in water from external sources when it is available.

Table 3.1 profiles the total dissolved solid content of various groundwater sources located around the study location. One measurement was taken with the ExStik II EC 400 Conductivity/TDS/Salinity Meter (Extech, U.S.A.) at each site on July 15th, 2011 from a grab sample. It can be seen from this profile that the levels of total dissolved solids exceed the palatable threshold level recognized by the WHO by two to five times.

Table 3.1: A list of total dissolved solid contents for various groundwater sources located near the study location are presented here. It can be seen that, despite water from standpipe, the local groundwater sources are brackish beyond the 1,000 mg/L threshold recognized by the WHO.

Location	Total Dissolved Solid Content (mg/L)
Standpipe #1	74.4
Well #1	3,050
Well #2	4,160
Well #3	4,780
Well #4	2,110
Well #5	2,940
Well #6	5,050
Well #7	3,770
Well #8	3,380
Well #9	3,590
Well #10	3,920

Table 3.1 also lists a total dissolved solid content for standpipe #1 which is significantly lower than the surrounding groundwater sources. This fresh water is delivered by the local government in trucks on a monthly basis where it is moved into storage tanks for use by the community members.

Because the main use of water from the local aquifer is for agriculture, the aquifer water quality may have decreased over the years due to over extraction of groundwater. For example, the typical irrigation requirements for corn production in Mexico are about 75 cm/Ha-yr (Quinones et al., 1999) and the total annual precipitation is about 49 cm/Ha (NASA 2011) or 500 mm/Ha as Figure 3.2 shows for the study location. Since aquifer recharge probably accumulates from a much larger area than the agricultural impact, it is not possible to say that the difference (26 cm/Ha of corn crop or 2.6 million L/Ha of corn crop) is being depleted from the aquifer annually. However, the difference between irrigation requirements and annual precipitation suggests that over time agricultural activity may be having a negative recharge rate on the water table, therefore increasing water brackishness.

$$\frac{(1\ Ha\ of\ Corn) \times \left(75\frac{cm}{Ha} - 49\frac{cm}{Ha}\right) \times \left(100{,}000\frac{cm^2}{Ha}\right)}{\frac{1000\ cm^3}{1\ Liter}} = 2.6\ Million\ \frac{Liters}{Ha}$$

In El Gallo, aside from the localized brackishness of the groundwater, there is the potential for heavy metal contamination as well. A study of the geochemical properties of the soil across Central Mexico found high concentrations of antimony, arsenic, cadmium, copper, and mercury near the study location (Chipres et al., 2009). Another study concluded that significant amounts of fluoride are found in the abstracted groundwater of San Luis Potosí (Carrillo-Rivera et al., 2002). While these studies do not analyze any samples within the study location, the close proximity of these investigations to the study location does suggest that a similar situation may be occurring with the groundwater in El Gallo and leads to solar distillation as a simple and appropriate method to repair the groundwater chemistry to potable quality.

The variables associated with the meteorological conditions are available for most of the world's locations from NASA (2011). This data set has collected global data related to meteorology (including solar radiation measurements) for the past 22 years. The database is searchable based upon latitude and longitude coordinates for a location. Available data are broken down into monthly averages for an entire host of measurements. Table 3.2 provides surface meteorology and solar energy data for the study location, which can be useful when designing a solar still and predicting its performance.

Table 3.2: Study location surface meteorology and solar energy data (NASA, 2011).

Parameter	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
Solar Insolation, kWh/m^2 - day	4.05	4.84	5.9	6.24	6.52	6.48	6.28	6.01	5.3	4.94	4.46	3.93
Ambient Temperature, ^oC	11.8	13.7	16.3	19.2	20.7	21.0	20.8	21.0	19.3	17.1	14.6	12.2
Wind Speed, m/s	4.01	4.15	4.37	4.26	3.9	3.7	3.88	3.76	3.62	3.60	3.93	3.9

3.2 Methods

In this study, two solar distillation systems were constructed and operated in the Mexican Altiplano to determine the volume and quality of distillate produced. One system is made from adobe, a locally available material, and the other system is made from concrete. The following sections describe the experiment used to test the hypotheses outlined in Chapter 1.

3.2.1 Solar Distillation Field Unit

A single sloped basin type solar still was designed and constructed for use in this study. The basin is constructed from adobe blocks that are assembled (see Figure 3.3) and parged by a mixture of cement, water and sand (see Figure 3.4) at a ratio of cement to water to sand of 1:2:3. The water ratio varied slightly depending on the moisture of the sand used and local weather conditions. The adobe brick is made from a mixture of clay-rich earthen material (about 8 cubic feet or one heaped wheel-barrel full), water (added until appropriate plasticity is achieved) and fresh or dry manure (one five gallon bucket) from a horse, mule or cow. These ingredients are mixed until a heavy clump of material with plastic properties is created. It is important to manage the water additions during the mixing as too much water will create an unworkable paste while insufficient water will cause the brick to break apart while drying. The adobe is then spread into wooden forms for the respective pieces of the distillation reactor basin and then tamped until a tight pack is achieved. The form is removed immediately and the resulting brick is left to cure in the sun for 10-14 days with no movement until day 6 or 7 when the block is moved into an up-right position to expose the other side of the block for drying. Although not shown in Figure 3.3, to reduce the breakage of dry bricks during movement and reactor assembling (very common), it is recommended that one or both sides of each adobe piece is parged with a layer of mortar as defined above and allowed to dry before it is placed in the reactor assembly.

Figure 3.3: The basin of the field unit is assembled from adobe blocks that have been pre-cast. The larger pieces are interwoven with steel matting for added support, especially when moving them from the casting site to the solar still location.

Illustrated in Figure 3.3, the reactor basin has a base and sides that are 4 cm thick. Two of these sides are of rectangular shape, while the other sides are trapezoidal as they form the cover angle for the condenser.

Figure 3.4: The basin made from precast adobe blocks in Figure 3.3 is then parged with cement to ensure water tightness and erosion protection. The positioning of the three access tubes can be seen also.

Three holes are made in the basin. The first hole serves as the filling port for the still as well as an eye-level control of the brine depth. The second hole is a drain to clear out the entire basin after a period of use. The third hole is located in the collection trough to collect the distillate produced. The collection trough is made from the placement of a cement mixture along the front of the basin, where the mason hand makes a small inclined channel in which the distillate collects and by which the distillate exits the distillation unit. The angle of the incline is controlled by a piece of wood cut to fit the inside dimension of the basin. Figure 3.5 shows the trough in more detail.

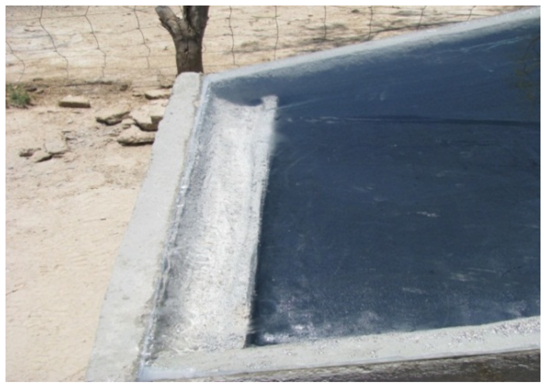

Figure 3.5: The cement channel has two functions: first, it is intended to separate the clean distillate from the brine solution waiting to be cleaned; and second it provides the fastest exit route for the distillate as possible.

The condenser cover is a piece of 3 mm clear glass, and the basin liner material is made from a cotton fabric that has been coated with black vinyl. The basin liner is held in place on the basin bottom by an epoxy.   The unit is made vapor tight by caulking the edges of the basin and the glass where they join. A general use silicone, with a transparent color, is used for this step. Figure 3.6 shows the completed field unit.

Figure 3.6: The completed adobe field unit, with the exception of plumbing connections, shown in the study location. The base is constructed from wood.

The overall dimensions of the still used in this study are provided in Table 3.3. In this study, the total evaporative area was not equal to one square meter which will require that the quantity of distillate produced will need to be modified to represent the amount produced on one square meter.

Table 3.3: A summary of the design dimensions for the model solar still constructed for use in this study. In some cases, the size of the cover that is available will determine the exact length and width of the unit. In this case, 3 mm thick glass was obtainable in custom dimensions which added to the flexibility of the design.

Dimension	Measurement	Units
Basin Length	100	cm
Basin Width	85	cm
Cover Length	100	cm
Cover Width	100	cm
Front Wall Height	10	cm
Back Wall Height	44	cm
Brine Depth	1.5	cm
Evaporative Surface Area	0.6536	m^2
Cover Angle	19.88	degrees
Cover Area	1	m^2

Figure 3.7 shows an interpretation of the still dimensions in a schematic view of the field units. Both the concrete and adobe field units followed this pattern during construction. Similar pieces were constructed with the use of wooden forms to control the dimensions.

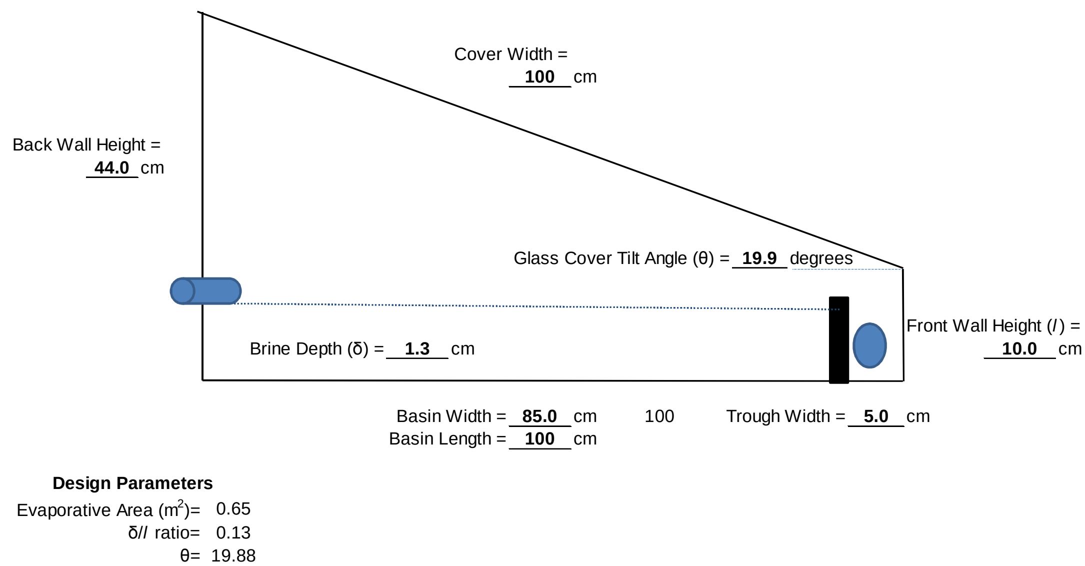

Figure 3.7: Schematic view of the solar distillation systems designed and constructed for this study. The yellow box highlights the design parameters that are terms in the Nafey et al. (2000) model.

Figure 3.8 shows a photograph of the solar distillation units in the field. Having the units in the same basic location is an important requirement of the investigation. This photograph also demonstrates how similar the units look once they are parged with a fine cement and sand mixture.

Figure 3.8: A photograph of the field units built for the study, the adobe unit is on the right and the concrete unit is on the left.

3.2.2 Experiment Design

The purpose of the experiment is to operate the solar distillation field unit made from adobe in the study location and collect water samples from both the distillate and basin over a time series of twenty-four hour intervals. Thirty-three water samples were collected on various days from the brine and distillate streams during the time period of August 15 until October 25th, 2012. These samples were then analyzed in the field in terms of their volume and total dissolved solid content to gain a better understanding of the performance characteristics of the field unit. Thirty-three samples were also taken on test days from a similarly constructed field unit made from concrete in the same study location; however, these samples were limited to the distillate stream only as the design of the concrete system did not include a brine sampling port.

The experiment was conducted over eleven sets of three-day intervals during the months of August, September and October 2011, typically from 7AM on one day until 7 AM the following day. The experiment was run for three consecutive days to allow the system to operate at a near steady state. In this study there was eleven three-day experiments. This was achieved by allowing only one addition of brine to the distillation system on day one, which was followed by three consecutive days of measurements on the system at twenty-four hour intervals.

The brine used in this study came from a variety of groundwater sources within the study area, and varied on each day of the study, which follows the typical pattern of multiple water source utilization for users in the region. The water quality from these sources is described in Table 3.1, and pertinent water quality characteristics for the brine solutions used during the experiment are located on the data collection sheet found in Table 4.1 and Table 4.2.

3.2.3 Water Sampling Procedure – Volume Sample (Adobe and Concrete Units)

The following procedure was used to obtain a sample to measure the volume of distillate produced in the field units.

1. Prepare a sample bottle with a minimum volume of 6,000 ml.
    a. Wash each sample bottle with a brush and phosphate-free detergent.
    b. Rinse three times with cold tap water.
    c. Rinse three times with distilled or de-ionized water; de-ionized water available at local supermarket.
2. On day one of each interval, fill the solar distillation field unit with 10 liters of brine at 7 AM on experiment day. This is noted as $t_{s,d}$=0 on the data collection sheet (the notation for this day could be 1.1, which refers to set number one on day one of the set).
3. Place the clean sample bottle in position to collect the distillate stream, making sure to protect the opening of the sample container from the ambient conditions
4. Clean the glass cover of the field unit with a glass cleaner or best available method.

5. Monitor the system over the twenty-four hour interval when possible.
6. At $t_{s,d}$=24 hours, carefully remove the sample container and replace it with a container that has been prepared according to steps 1 and 2.
7. Repeat steps 4 through 7 for two additional twenty-four hour intervals.

3.2.4 Water Sampling Procedure – Distillate Water Characteristic Sample (Adobe and Concrete Units)

The following procedure was used to obtain a sample to measure the concentration of total dissolved solids in the distillate of each experiment set.

1. Take the 6,000 ml sample bottle from the field unit and move it inside to the workspace.
2. Prepare a 1,000 ml polypropylene graduated cylinder.
    a. Wash with a brush and phosphate-free detergent.
    b. Rinse three times with cold tap water.
    c. Rinse three times with distilled or de-ionized water.
3. Clean the outside edge of the sample container opening to remove any dust that may have collected over the interval. Carefully transfer all of the water from the sample bottle into the graduated cylinder. It is important to determine if the sample will have to be transferred into multiple graduated cylinders before the transfer process begins. It is necessary to transfer the sample into the 1,000 ml graduated cylinder because the 6,000 ml sample container cannot be easily poured into the 35 ml sample cup.
4. Prepare the 35 ml sample cup and cap provided with the salinity meter kit.
    a. Wash with a brush and phosphate-free detergent.
    b. Rinse three times with cold tap water.
    c. Rinse three times with distilled or de-ionized water.

5. After the appropriate volume measurement is made with the graduated cylinder, transfer at least 20 ml of distillate into the sample cup.
6. The sample cup should be capped immediately until the water characteristics are measured.

3.2.5 Water Sampling Procedure – Brine Water Characteristic Sample (Day One)

The following procedure was used to obtain a sample to measure the concentration of total dissolved solids in the brine water on day one of each experiment set.

1. On day one of each interval, fill the solar distillation field unit with 10 L of brine at 7 AM.
2. Prepare the 35 ml sample cup and cap provided with the salinity meter kit.
    a. Wash with a brush and phosphate-free detergent.
    b. Rinse three times with cold tap water.
    c. Rinse three times with distilled or de-ionized water.
3. After 30 minutes the system should be well mixed. Remove the cap from the brine tank drain allowing the system to drain; collect a sample in the sample cup by filling and discarding the sample cup three times before collecting the measured brine water sample. It should be noted on the field data sheets an estimation of the amount of brine that was removed from the field unit. A typical value in this experiment may be 120-140 ml, while the calculations in the results assume a loss of 140 ml from the overall volume of brine at each sampling event.
4. The sample cup should be capped immediately until the water characteristics are measured. This sample represents the beginning measurement of the first interval.

3.2.6 Water Sampling Procedure – Brine Water Characteristic Sample (Days Two and Three)

The following procedure was used to obtain a sample to measure the concentration of total dissolved solids in the brine water on days two and three of each experiment set.

1. Prepare the 35 ml sample cup and cap provided with the salinity meter kit.
    a. Wash with a brush and phosphate-free detergent.
    b. Rinse three times with cold tap water.
    c. Rinse three times with distilled or de-ionized water.
2. At 7 AM remove the cap from the brine tank drain allowing the system to drain; collect a sample in the sample cup by filling and discarding the sample cup three times before collecting the measured brine water sample. It should be noted on the field data sheets if an unusual amount of brine is removed from the field unit. A typical value in this experiment may be 120-140 ml, while the calculations in the results assume a loss of 140 ml from the overall volume of brine at each sampling event unless otherwise noted.
3. The sample cup should be capped immediately until the water characteristics are measured. This sample represents the final measurement for the previous interval and the beginning measurement for the current interval and should be noted appropriately on the data collection sheet.
4. The final measurement of the third day is made at 7 AM on the fourth day, and steps 1 through 3 should be followed to complete the required measurements for the three day set.

3.2.7 Water Sample Analysis – Volume

The following procedure was used to determine the volume of distillate produced in the study.

1. Take the 6,000 ml sample bottle from the field unit and move it inside to the workspace. This would be performed in conjunction with the distillate water sampling procedure.
2. Prepare a 1,000 ml polypropylene graduated cylinder.
    a. Wash with a brush and phosphate-free detergent.
    b. Rinse three times with cold tap water.
    c. Rinse three times with distilled or de-ionized water.
3. Clean the outside edge of the sample container opening to remove any dust that may have collected over the interval. Carefully transfer all of the water from the sample bottle into the graduated cylinder. It is important to determine if the sample will have to be transferred into multiple graduated cylinders before the transfer process begins.
4. Place the now full graduated cylinder(s) on a level surface and read the volume of the sample following the 10 ml graduation markings. Record this value on the data collection sheet for the appropriate experiment day, adding the multiple volumes if necessary. It should be noted that this value represents a volume produced from an evaporative area of 0.6536 square meters (as measured on the field unit) and needs to be converted to an equivalent volume for an evaporative area of one square meter for comparison. This conversion is applied to the results of the experiment during the analysis phase, however, the raw volumes measured in the field are found on the data collection sheets.

3.2.8 Water Sample Analysis – Total Dissolved Solids (TDS)

The following sample analysis procedure for electrical conductivity, applies to the use of the conductivity meter ExStik II EC 400 Conductivity/TDS/Salinity Meter (Extech, U.S.A.) to analyze the water samples from the distillate and brine streams.

1. Rinse the probe with distilled or de-ionized water.
    a. Use a conductivity standard solution (usually potassium chloride or sodium chloride) to calibrate the meter for the range that will be measured. Following the instructions that accompany the salinity meter. The calibration record and procedure can be found in Appendix A, a conductivity standard solution of 1,000 mg/l was used.
2. Turn the probe on and wait for the self-calibration feature to stop if necessary. Set the meter to your desired unit of measurement, in this case total dissolved solids (TDS) in mg/L, and wait for a reading of zero on the meter.
3. Remove the cap from 35 ml sample cup and place the readied meter in the solution.
4. Once the reading has not changed for a ten second count, record the value in the appropriate data location taking note of the units for the reading as some meters automatically change when concentrations are too high.
5. Return the conductivity meter to its proper storage container and clean any spills that occurred.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Distillate Production Rate Analysis

4.1.1 Distillate Production Rate Analysis – Adobe Unit

This study found evidence that the rate of distillate produced (mL/m^2-day) in a single-sloped single-basin passive solar distillation system constructed from adobe would not be statistically similar to the Nafey et al. (2000) model, nor an identical still made from concrete. Table 4.1 provides details on the thirty-three sample data set for the field unit constructed from adobe. Data are provided in this table on the following items: the volume of brine used in the basin, the initial and final total dissolved solids concentration of the brine, the volume of distillate produced on each experiment day, and the total dissolved solids concentration of the distillate.

From the data in Table 4.1, it can be observed that the greatest volume of distillate produced was 930 mL/m^2-day while the average distillate production rate over the entire study averages about 844 mL/m^2-day (standard deviation = 147). The adobe field unit was not constructed to be exactly one square meter so a conversion of 0.6536 is applied to the volume of distillate produced in the field to obtain a true volume per one square meter of evaporative area

Table 4.1: The data collected regarding the volume of distillate produced in the adobe field unit. Since the volume of distillate produced in the field unit is derived from an evaporative area of less than one square meter (0.6536 m^2 in the study), this value must be converted to represent one square meter and is shown in the second volume column. The average volume produced over the study is 844 mL/m^2-day.

Date (start)	Identification (Set, Day)	Volume Brine (mL)	TDS Brine (mg/L)	Volume Distillate Field Unit (mL)	Volume Distillate (mL/m2-day)	TDS Distillate (mg/L)
8/14/11	A1,1	10000	954	720	1102	48.5
8/15/11	A1,2	9000	756	710	1086	33.1
8/16/11	A1,3	8000	831	770	1178	35.7
9/4/11	A2,1	10000	702	680	1040	39.4
9/5/11	A2,2	9000	782	660	1010	41.6
9/6/11	A2,3	8000	877	630	964	38.1
9/12/11	A3,1	10000	718	520	796	48.8
9/13/11	A3,2	9000	686	600	918	43.5
9/14/11	A3,3	8000	1091	580	887	41.8
9/15/11	A4,1	10000	821	540	826	37.5
9/16/11	A4,2	9000	845	490	750	39.6
9/17/11	A4,3	8000	966	540	826	47.3
9/27/11	A5,1	10000	1024	520	796	36.8
9/28/11	A5,2	9000	1298	510	780	32.9
9/29/11	A5,3	8000	1013	520	796	40.3
9/30/11	A6,1	10000	1620	540	826	36.2
10/1/11	A6,2	9000	1790	450	688	34.7
10/2/11	A6,3	8000	1930	470	719	32.5
10/3/11	A7,1	10000	942	510	780	31.6
10/4/11	A7,2	9000	1410	380	581	30.1
10/5/11	A7,3	8000	1560	510	780	31.9
10/6/11	A8,1	10000	1117	560	857	43.8
10/7/11	A8,2	9000	1309	270	413	36.1
10/14/11	A8,3	8000	1020	610	933	33.1
10/15/11	A9,1	10000	1045	590	903	40.1
10/16/11	A9,2	9000	1193	580	887	50.6
10/17/11	A9,3	8000	1450	570	872	53.5
10/18/11	A10,1	10000	1131	500	765	48.1
10/19/11	A10,2	9000	1319	600	918	41.7
10/20/11	A10,3	8000	1005	530	811	39.2
10/21/11	A11,1	10000	1077	530	811	36.4
10/22/11	A11,2	9000	1101	450	688	43.5
10/23/11	A11,3	7000	981	550	841	61.6
STD DEV	-	-	**310**	-	**147.93**	**7.1**
MEAN	-	-	**1102**	-	**843.35**	**40.3**
n	-	-	**33**	-	**33**	**33**

Figure 4.1 shows the relationship between the amount of distillate produced and the date of the experiment. The negative slope of the line fitted to the data set indicates that less distillate is being produced each day during the experiment. Data collected in August 2011 appear to be uncharacteristically high when compared to the remaining data set; however, is not unexpected as more solar energy is available in the month of August as demonstrated in Figure 4.2.

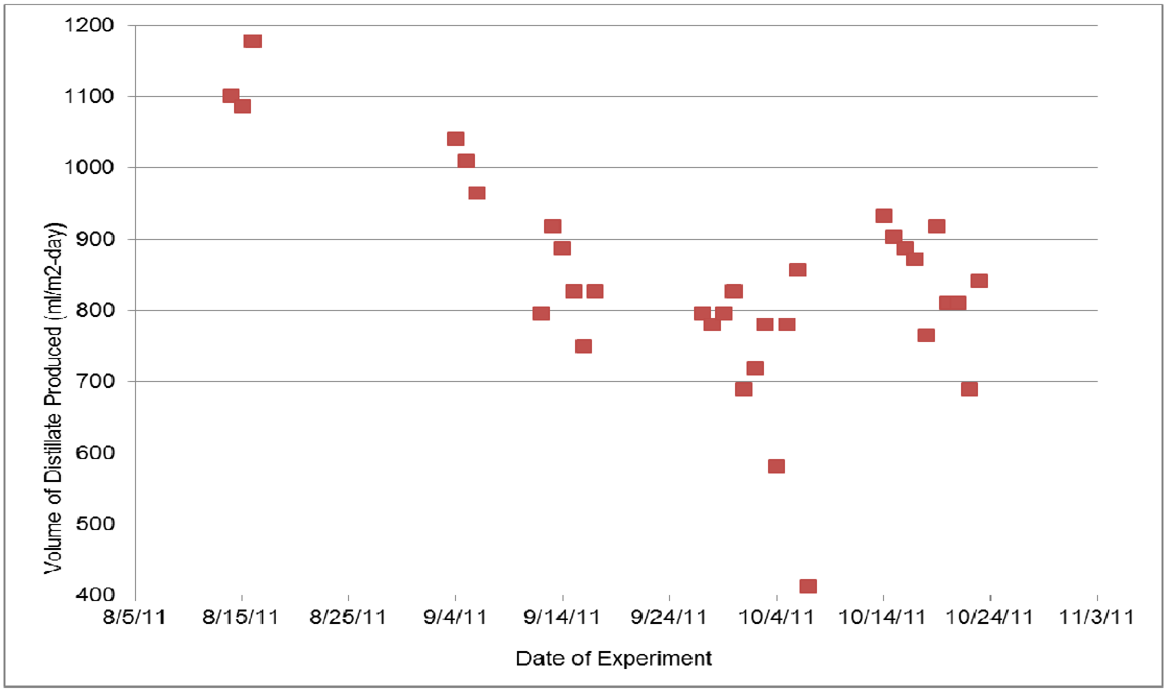

Figure 4.1: The amount of distillate produced (mL/m^2-day) each experiment day from the adobe field unit. The downward trend of the points is consistent with the reduced solar energy available in winter.

Figure 4.2 shows in August that approximately four (kWh/m2-day) of solar energy was available for distillation, while by the end of October that value had fallen 25 percent to three (kWh/m2-day). Looking at the results in Table 4.1 it is shown that the average output in August was 710 mL/day while the average output in October was 510 mL/day. These values represent a 28 percent reduction of distillate output over the study period, which is similar to the observed solar insolation pattern during the same time interval.

This observation should also be occurring in the results for the concrete distillation system and the output of the Nafey et al. (2000) model as well.

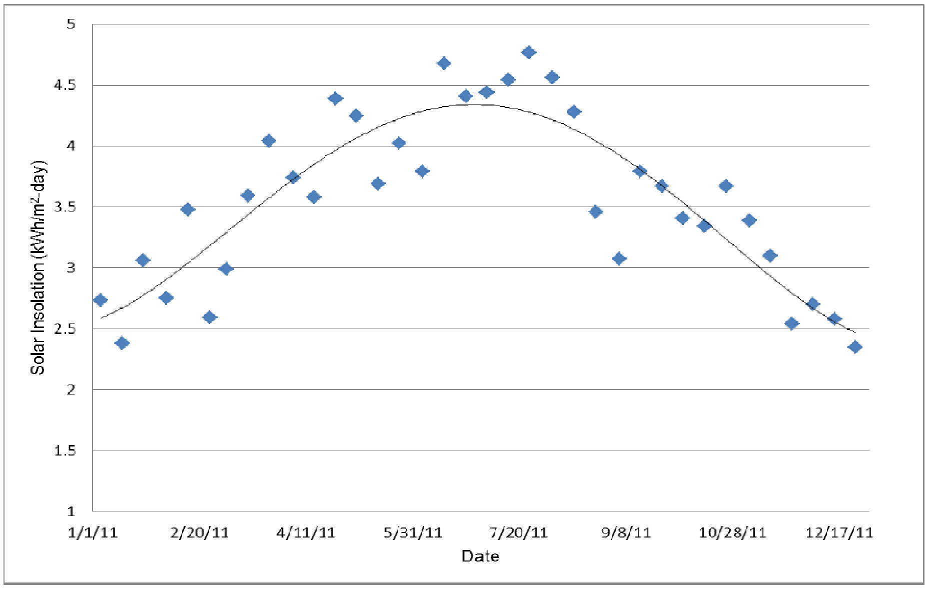

Figure 4.2: The daily solar insolation values (kWh/m^2-day) observed during 2011 at a weather observation station approximately 50 kilometers from the study location.

4.1.2 Distillate Production Rate Analysis – Concrete Unit

Table 4.2 provides the data for the thirty-three sample set for the field unit constructed from concrete. For this system the data collected related to the volume of distillate produced on each experiment day and the TDS measurement of the distillate. Data related to the total dissolved solids concentration of the brine was only available on the days when brine was added to the basin.

Table 4.2: The data collected regarding the volume of distillate produced in the concrete field unit. The average volume produced by the concrete unit over the study is 979 mL/m^2-day.

Date (start)	on (Set, Day)	Volume Distillate Field Unit (mL)	Volume Distillate (mL/m2-day)	TDS Brine (mg/L)	Distillate (mg/L)
8/14/11	C1,1	820	1255	2180	50.7
8/15/11	C1,2	860	1316	2310	40.3
8/16/11	C1,3	795	1216	2200	31.9
9/4/11	C2,1	735	1125	702	36.1
9/5/11	C2,2	730	1117		33.1
9/6/11	C2,3	630	964		41.7
9/12/11	C3,1	520	809	718	37.8
9/13/11	C3,2	600	926		36.2
9/14/11	C3,3	580	892		38.5
9/15/11	C4,1	640	979	821	35.1
9/16/11	C4,2	690	1056		34.7
9/17/11	C4,3	540	826		41.1
9/27/11	C5,1	720	1102	1024	35.9
9/28/11	C5,2	610	933		39.6
9/29/11	C5,3	620	949		38.9
9/30/11	C6,1	540	826	1620	33.5
10/1/11	C6,2	650	994		35.6
10/2/11	C6,3	670	1025		36.7
10/3/11	C7,1	510	780	942	33.1
10/4/11	C7,2	380	581		42.1
10/5/11	C7,3	510	780		33.6
10/6/11	C8,1	560	857	1117	45.3
10/7/11	C8,2	540	826		41.2
10/14/11	C8,3	630	964		31.9
10/15/11	C9,1	750	1147	1045	34.3
10/16/11	C9,2	760	1163		39.1
10/17/11	C9,3	750	1147		46.1
10/18/11	C10,1	740	1132	1131	42.1
10/19/11	C10,2	680	1040		41.6
10/20/11	C10,3	760	1163		37.3
10/21/11	C11,1	700	1071	1077	38
10/22/11	C11,2	650	994		41.7
10/23/11	C11,3	620	949		32.1
STD DEV	**-**	**-**	**160**	**578.345**	**4.45**
MEAN	**-**	**-**	**997**	**1299**	**38**
n	**-**	**-**	**33**	**11**	**33**

From the data provided in Table 4.2, it can be observed that the greatest volume of distillate produced by the concrete unit was 1,335 mL/m^2-day while the average distillate production rate over the entire study averaged about 979 mL/m^2-day (standard deviation = 160). Similar to the adobe field unit, the concrete field unit was not constructed to be exactly one square meter so a conversion of 0.6536 is applied to the volume of distillate produced in the field to obtain a true volume per one square meter of evaporative area.

Figure 4.3 illustrates the relationship between the amount of distillate produced and the date of the experiment for the concrete field system. Figure 4.3 also illustrates higher than average measurements during the month of August 2011 for the concrete unit, which is similar to the data shown for the adobe unit in Figure 4.1. Following the same logic applied to the adobe system, it can be seen that the output of the concrete system was reduced by about 22 percent over the experiment which is similar to the 25 percent reduction in available solar energy.

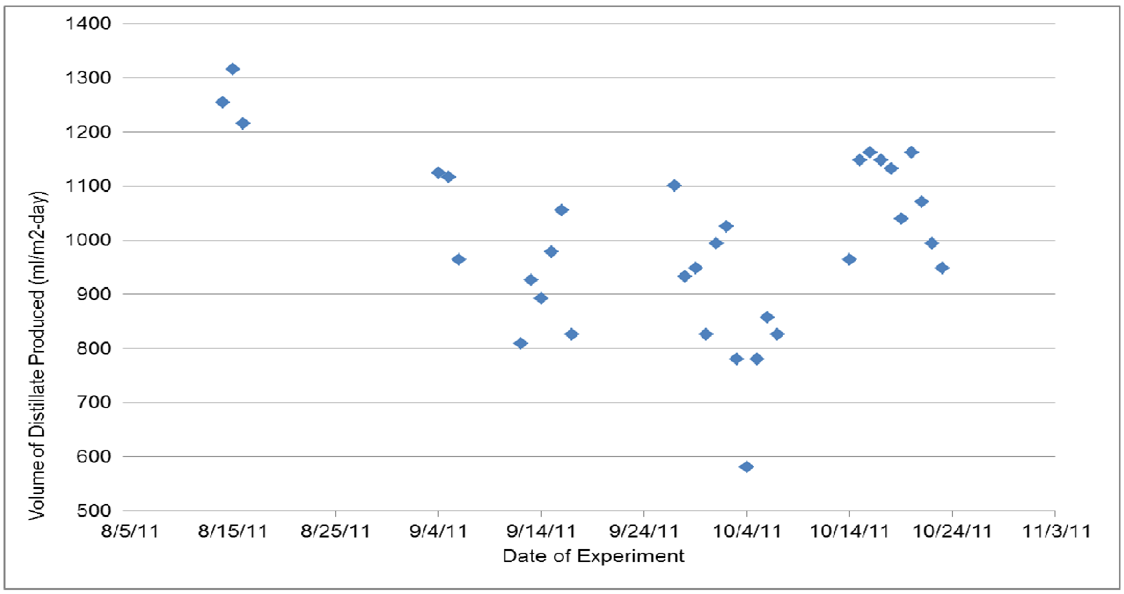

Figure 4.3: The amount of distillate produced (mL/m^2-day) each experiment day from the concrete field unit. The downward trend of the data is consistent with the reduced solar energy available as demonstrated in Figure 4.2.

4.1.3 Distillate Production Rate Prediction – Nafey et al. (2000) Model

Table 4.3 provides data for the thirty-three sample data set and includes the predicted distillate production rate. The data in this table are obtained from the Nafey et al. (2000) model, which utilizes the physical dimensions of the distillation unit (Table 3.3) and daily meteorological observations to estimate the amount of distillate produced in one square meter of evaporative area.

The observations of meteorological parameters for temperature and solar insolation were obtained from a weather observation station in Matehuala, San Luis Potosí, Mexico, which is located approximately 50 kilometers from the study location. This station records 144 measurements each day for parameters such as solar insolation, temperature, wind direction and speed, and precipitation amounts. The meteorological values provided in Table 4.3 are averages of the 144 measurements collected for each day. The values used for average wind speed were obtained from the NASA meteorological database because the Matehuala weather station did not have a working anemometer at the time of the experiment. These values were provided previously in Table 3.1.

From Table 4.3, it can be observed that the greatest estimated volume of distillate was 2,700 mL/m^2-day while the predicted average distillate production rate over the entire study averages about 2,100 mL/m^2-day (compared to measured averages of 979 mL/m^2-day for concrete and 848 mL/m^2-day for adobe units).

Table 4.3: Predicted data for distillate volume generated. The average temperature and solar insolation values were provided by a weather station (CONAGUA, 2011) near the study location, and the average wind speed was provided by NASA (NASA, 2011). The average volume estimated over the study is 2,110 milliliters per day.

Date	Identification (Set, Day)	Average Temperature (^{o}C)a	Average Wind Speed (m/s)b	Solar Insolation (kWh/m^2/day)a	Predicted Volume of Distillate mL/m2-day)
8/14/11	P1,1	23.60	3.72	4.21	2750
8/15/11	P1,2	23.20	3.72	4.28	2800
8/16/11	P1,3	23.10	3.72	4.27	2787
9/4/11	P2,1	21.20	3.62	3.89	2387
9/5/11	P2,2	21.70	3.62	3.67	2207
9/6/11	P2,3	23.20	3.62	3.70	2283
9/12/11	P3,1	20.90	3.62	3.51	2037
9/13/11	P3,2	22.10	3.62	3.75	2291
9/14/11	P3,3	22.30	3.62	3.66	2217
9/15/11	P4,1	20.90	3.62	3.87	2359
9/16/11	P4,2	22.80	3.62	3.42	2019
9/17/11	P4,3	21.20	3.62	3.32	1877
9/27/11	P5,1	22.40	3.62	3.65	2212
9/28/11	P5,2	21.30	3.62	3.89	2390
9/29/11	P5,3	21.60	3.62	3.88	2391
9/30/11	P6,1	22.70	3.62	3.42	2016
10/1/11	P6,2	18.44	3.60	2.91	1420
10/2/11	P6,3	18.94	3.60	3.40	1874
10/3/11	P7,1	17.94	3.60	2.68	1198
10/4/11	P7,2	17.95	3.60	3.33	1779
10/5/11	P7,3	18.81	3.60	3.41	1879
10/6/11	P8,1	20.20	3.60	3.52	2023
10/7/11	P8,2	20.87	3.60	3.71	2215
10/14/11	P8,3	19.37	3.60	3.64	2103
10/15/11	P9,1	19.68	3.60	3.35	1854
10/16/11	P9,2	19.94	3.60	3.72	2193
10/17/11	P9,3	19.29	3.60	3.74	2190
10/18/11	P10,1	20.37	3.60	3.74	2226
10/19/11	P10,2	17.99	3.60	3.23	1691
10/20/11	P10,3	15.75	3.60	3.73	2064
10/21/11	P11,1	18.17	3.60	3.67	2090
10/22/11	P11,2	17.94	3.60	3.58	2002
10/23/11	P11,3	17.89	3.60	3.37	1813
STD DEV		**2.01**	**0.03**	**0.34**	**341**
MEAN		**20.4**	**3.62**	**3.61**	**2110**
n		**33**	**33**	**33**	**33**

Figure 4.4 depicts the relationship between the amount of distillate estimated and the date of the experiment. The negative drift of this data set also indicates that less distillate is being produced each day during the experiment; this is consistent with the measured observations made with the adobe and concrete field unit as well.

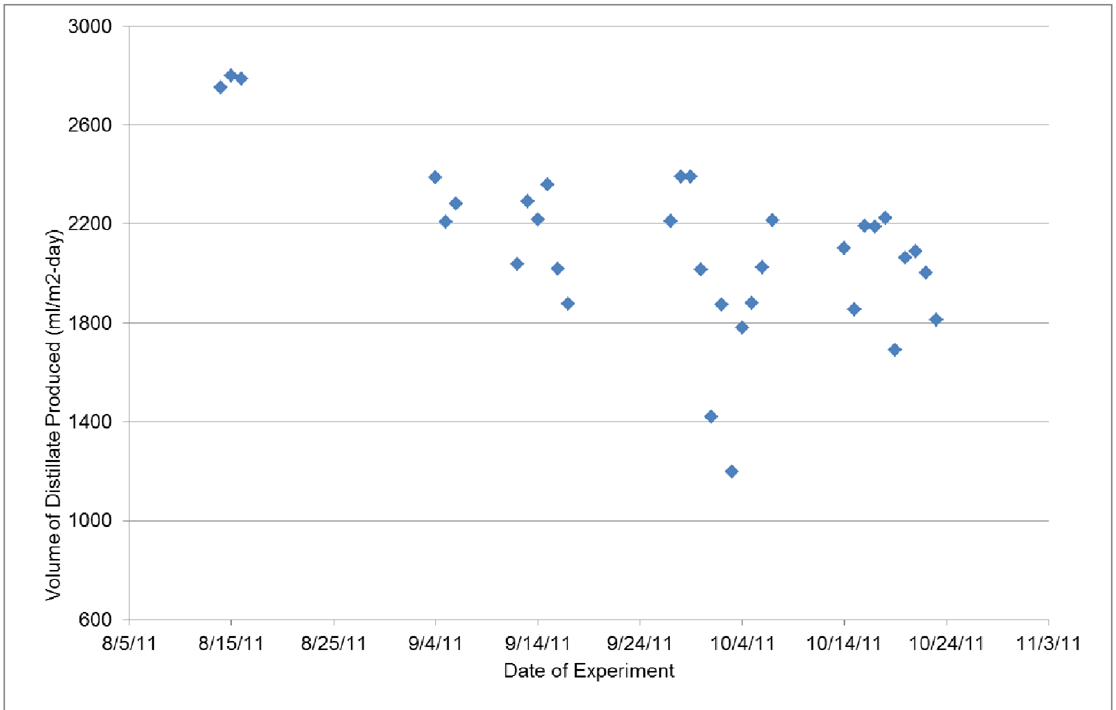

Figure 4.4: The estimated amount of distillate produced (mL/m^2-day) each experiment day from the Nafey et al. (2000) model. The downward trend of the points is consistent with the reduced solar energy available as the winter solstice approaches and follows the adobe and concrete trend as well.

Figure 4.4 also illustrates higher than average predictions during the month of August 2011, which is similar to the data shown for both the adobe unit in Figure 4.1 and the concrete unit in Figure 4.3. Following the same analysis that was used for the adobe and concrete units pertaining to the reduction of distillate output as less solar energy is available, it is demonstrated in Table 4.3 that predicted distillate output was reduced by 28 percent from August to October. This value is in line with the reduction percentages found in the adobe and concrete systems (28 and 23 respectively) and may indicate that the Nafey et al. (2000) model is calibrated well for meteorological effects.

4.1.4 Distillate Production Rate Comparison

Figure 4.5 combines data from Figures 4.1, 4.3, and 4.4 to provide a comparison of the volume of distillate predicted (blue line) and the volume of distillate produced in the adobe unit (red line) and the concrete field unit (green line) over the course of the study. Figure 4.5 shows that the production of distillate from the adobe (average = 850 mL/m^2-day) and concrete (average = 997 mL/m^2-day) systems are similar, while the Nafey et al. (2000) model predicts a higher amount of distillate (average = 2,100 mL/m^2-day). This suggests that the adobe system operates at a 60 percent reduction in output than estimated by the Nafey et al. (2000) model. The concrete system fared better while operating at a 40 percent reduction in output.

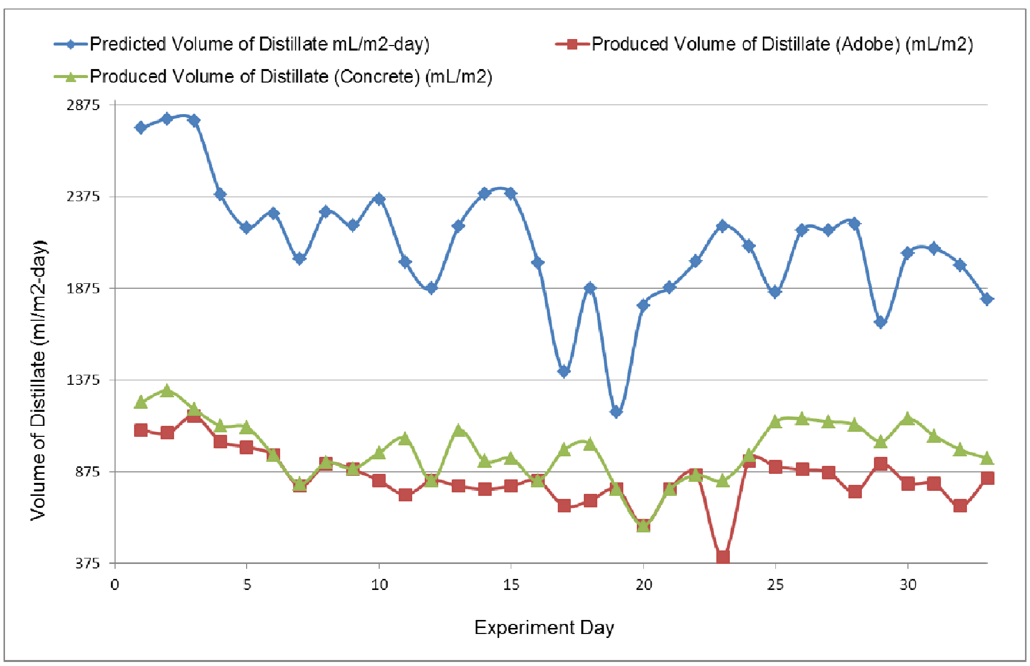

Figure 4.5: Distillate produced (mL/m^2-day) for each experiment day for the estimated and measured values. A difference between the predicted volume and the adobe volume is illustrated here; however, the volumes produced between the adobe and the concrete units appear to be similar.

Figure 4.6 combines both the experiment results for the adobe and concrete systems and the Nafey et al. (2000) model results for the cumulative amount of distillate produced over the entire experiment. It can be seen in Figure 4.6 that the adobe and concrete distillation units appear to produce a similar volume over the 33 experiment days, approximately 28 and 33 liters respectively. However, these values are less than the predicted amount of 70 liters obtained from the model. Based upon these observations it might be concluded that adobe system does not operate according to the Nafey et al. (2000) model. However, the data can be analyzed further to determine if the output of the adobe reactor is similar to the predicted results.

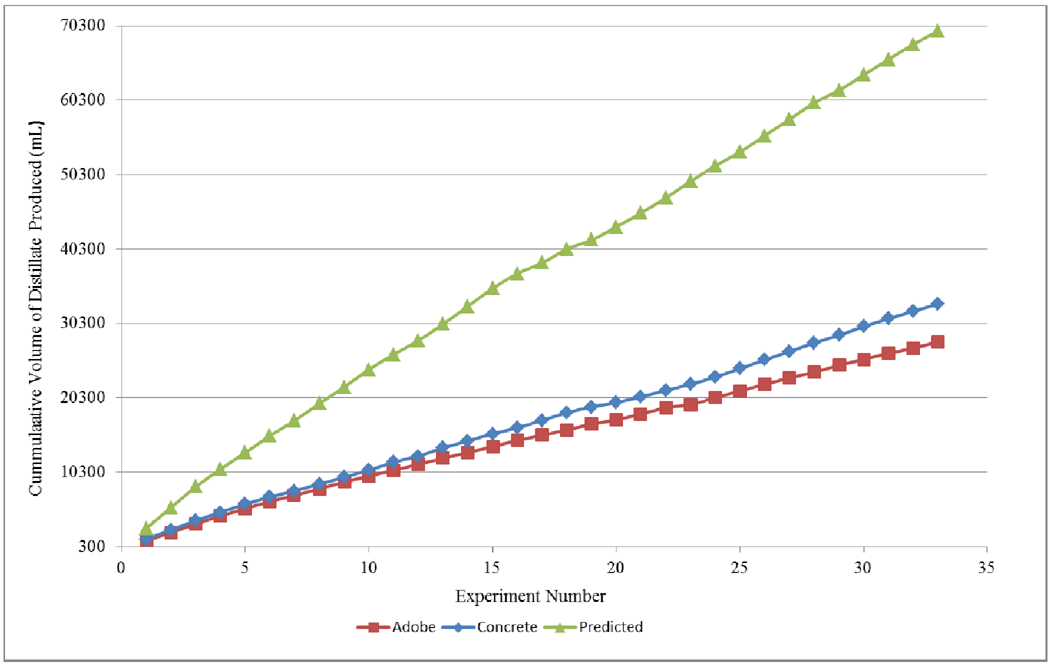

Figure 4.6: The cumulative amount of distillate produced (mL/m^2-day) for each experiment day for the three comparisons. A significant difference between the predicted volume and the adobe volume is illustrated here; however, the volumes between the adobe and the concrete units appear to be similar.

To mathematically determine the likeness of the volumes produced in each experiment, Table 4.4 summarizes the statistical parameters required to conduct a t-test to determine the statistical similarity of two means (Freund and Wilson, 2003). The formula, shown in Equation 4.1, for the t-test is a ratio; where the top part of the ratio is the difference between the two means or averages and the bottom part is a measure of the variability or dispersion of the scores. In this study the average volume of the distillate produced in the adobe and concrete field units were compared, as well as, the average volume of distillate produced in the adobe system to the prediction of the model published in Nafey et al. (2000).

$$t = \frac{\bar{X}_T - \bar{X}_C}{\sqrt{\frac{var_T}{n_T} + \frac{var_C}{n_C}}} \quad \text{(Equation 4.1)}$$

Table 4.4: The t-test is used to determine if two means are statistically similar to each other. In this aspect of the study, the average volumes of distillates produced or predicted are compared to each other using this method. In this study, neither comparison yields statistically similar volumes of distillate produced.

T-Test: Statistical Similarity of Two Means	Similar Volume Test		
	Adobe	Concrete	Pred
Mean	843	997	2110
Standard Deviation	148	260	341
Population Size	33	33	33
T-Statistic (Adobe:X)	-	3.0	20
Critical Value (α=0.05)	-	1.7	1.7
Reject Null ($\mu_{adobe}=\mu_x$)	-	YES	YES

Interpreting the results in Table 4.4, the t-statistic for the adobe to concrete and the adobe to literature comparisons is 3 and 20. The mean is not considered to be statistically similar if the t-statistic value is greater than the critical value, which is 1.70 for both the concrete and the literature comparison, and is based upon the significance level and number of the degrees of freedom involved (degrees of freedom = 66). In this case, the volume of distillate produced by the adobe field unit was not statistically similar at the 95% confidence interval to the volume produced by the concrete field unit or the predicted output based upon the Nafey et al. (2000) model.

An interesting observation from Table 4.4 is the relatively large variance in the predicted results compared to field results obtained from the adobe system. The predicted value is based on meteorological measurements made near the site which may indicate that the daily performance of the system represented by the Nafey et al. (2000) model is more dependent on weather fluctuations than a system made from adobe where less variability was measured over the experiment. Table 4.4 also shows that this is true for the concrete system. This behavior might be explained by the high thermal capacity of earthen materials such as adobe and concrete that is used in this study’s field measurements, versus the different material (i.e., aluminum sheet, polystyrene insulation board) used in the experiments that lead to the model development. Different from thermal conductivity, thermal capacity characterizes the amount of heat required to change a substance's temperature by a given amount. In other words a higher heat capacity indicates that more energy (heat) can be stored inside the mass. Since adobe has a relatively high thermal capacity (Revuelta-Acosta et al., 2010) it is efficient at absorbing heat and storing it until ambient conditions are favorable to trigger its release. During the storage period the stored heat would act as a temperature regulator and help offset any immediate fluctuations in the weather. This property could be useful to optimize nocturnal production as well, especially on days with the most available solar energy.

To further analyze the lack of similarity between the distillate production means of the adobe, concrete, and Nafey et al. model an analysis of variance (ANOVA) was performed to determine the total sum of squares in each comparison group. The total sum of squares will increase if the variance within the data set increases, which can indicate non-similarity between the set of means. Table 4.5 compares the values of the total sum of squares for different groupings in this study, in addition to the F-values and F-critical values for each comparison. The F and F-critical values serve a similar purpose as the t-statistic and t-critical values found in Table 4.4 to determine if the means are similar. That is when F is greater than F-critical the means are not similar.

Table 4.5: A comparison of the total sum of squares and F-values for various groupings in this study. Based upon this data none of the means for distillate output are considered similar and the most variability exists in the adobe:predicted comparison unless all three groups are compared as demonstrated in the last row.

Comparison Groups	TSS	F	F-critical	Similar Mean
Adobe:Predicted (Nafey et al. (2000))	3.01E+07	382	3.99	no
Adobe:Concrete	1.91E+06	16	3.99	no
Concrete:Predicted (Nafey et al. (2000)	2.49E+07	287	3.99	no
Adobe:Concrete:Predicted	3.68E+07	288	3.09	no

Table 4.5 lists the results of four ANOVAs performed on the data collected in this study. Interpreting these results requires a comparison of the total sum of squares values for each grouping of means to determine the amount of variance that is there. In this case, the most variance among the two mean comparisons (the first three rows of Table 4.5) exists between the adobe and the Nafey et al. model which is determined by the largest TSS value (3.01E+07). Table 4.5 also indicates that the variance within the concrete and Nafey et al. model data sets is high when compared to the variance between the adobe and concrete systems (2.49E+07 versus 1.91E+06).

Another important observation that can be made from the ANOVA and the information presented in Table 4.5 is an inference on the similarity of the means. From this data it can be seen that the F-value for each comparison group is much larger than the F-critical value. This suggests that the means in each comparison are not similar, which verifies the results of the t-test performed earlier in this section.

Table 4.6 compares the output of the distillation system in this study to other results reported in literature. These results are for studies that investigated passive single-sloped single-basin distillation systems that were operated in different geographical locations during different time periods with similar but unique design variations (orientation of cover angle, basin construction and insulating materials, depth of water, etc.). These design variations, in addition to the spatial and temporal variations in these studies can be used to explain the diverse range of results typically reported in literature or observed in the field.

Based on the results provided in Table 4.6, the volume produced for similar single-sloped single-basin distillation system ranges from 1,450 to 5,900 mL/m^2-day based on the time of year of the study and the characteristics of the given system. The adobe system for this study, however, falls short of this range indicating that there are several design changes that may be needed to optimize the distillate production rate.

Table 4.6: Summarizes some of the published results regarding volume of distillate produced. The results are not easy to compare because of the design variability in each study, however, the results do provide some context to where an adobe system may fit in.

Study	**Volume (mL/m^2 -day)**	**Comments**
Nafey et al (2000)	4,250	February 1998, 20^o glass cover slope
Nafey et al (2000)	5,900	July 1998, 20^o glass cover slope
Al-Hinai (2002)	4,100	annual average, 20^o glass cover slope
El-Sebaii (2004)	3,750	winter day, 20^o glass cover slope
Al-Karaghouli et al (2004)	1,600	insulated still, Febraury
Al-Karaghouli et al (2004)	2,800	insulated still, June
Al-Karaghouli et al (2004)	1,450	non-insulated still, Febraury
Al-Karaghouli et al (2004)	2,500	non-insulated still, June
Velmurugan et al (2011)	2,000-5,000	annual range
Chow (2012)	750-3,750	annual range, Pakistan
Manser (2012)	850	August to October 2011, Mexico

For example, a current solar distillation project in Pakistan funded by Action Against Hunger that has observed production rates of basin type passive distillation systems vary from 750 to 3,750 mL/m^2-day depending on the local weather conditions (Chow, 2012). In this case, the difference between distillate outputs measured in the Chow study compared to this study can be traced to the basin design and the local weather conditions. Figure 4.7 shows how the design of the double-slope single-basin distillation reactor differs from the reactor designed in this study, as well as the use of aluminum and steel to construct the basin frame.

Figure 4.7: The Chow (2012) study in Pakistan examined the performance of a double-sloped single-basin distillation reactor constructed from aluminum and steel. This design allows for a larger evaporative area without increasing the overall height of the distillation reactor, which will have favorable impacts on the distillate volume produced.

Table 4.6 and Figure 4.7 also highlight a potential reason for the difference in volumes produced in the adobe system and the prediction as it relates to the materials used to construct the basins. In this experiment the basin is made from 40-mm thick adobe bricks (a mixture of clay, water and manure) that are cured and mortared together with a fine grained concrete. The outside is parged one time with fine grained cement mixture while the inside of the basin is parged two to three times to ensure water tightness. The ratio of materials is defined in Methods section 3.1.2. The condensing surface is a 3-mm glass cover and the base is covered with a black acrylic fabric to increase solar absorptivity of the basin. The model is based upon distillation units with sides made of steel sheet, 2 mm thick. The sides of each box are painted white on the inside to reflect the solar radiation to the water surface and the base of each unit is painted black to increase the solar absorptivity. The outside walls and the base of each unit are insulated with 4-cm foam and the condensing surface in each still unit is a 3 mm glass cover.

The biggest difference between the systems that is the basis for the model is the white paint on the inside walls and the use of a foam insulation. Table 4.7 shows some common thermal conductivity values for construction materials. Thermal conductivity is the quantity of heat transmitted through a unit thickness in a direction normal to a surface of unit area, due to a unit temperature gradient under steady state conditions.

Table 4.7: Thermal conductivities of some common building materials. All values from http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html except for the adobe measurement (Parra-Saldivar and Batty, 2005).

Material	Thermal Conductivity - k - W/(m*K)
Copper	401
Adobe	1.5
Foam Insulation	0.033
Concrete	0.8
Plywood	0.13
Glass	0.15
Steel	43

From Table 4.7 it can be seen that the thermal conductivity of the model using foam insulation is estimated to be 0.033 (W/m*K) while the thermal conductivity of concrete and adobe are about 1.5 (W/m*K). This indicates that the basin constructed from adobe would be more willing to lose heat through its mass than the foam insulated system would be which would be amplified by the increased porosity of the side wall material. Since this vapor is being absorbed into the adobe before it can be condensed on the glass cover and become harvestable distillate, the adobe system produces less distillate overall. Further experiments to quantify vapor loss and improve the basin design are needed to address this issue and are discussed in more detail in Chapter 5.

4.1.5 Modeling the Adobe Distillation System

The field measurements of this study suggest that the model provided in the Nafey et al. (2000) model does not adequately describe the productivity of a single-sloped single-basin distillation unit constructed from adobe. This could be due to the difference in porosity or thermal conductivities between the basin materials, as well as the fact that the Nafey et al. (2000) model does not take into account the salinity of the influent. This is important because dissolved salt in water will lower the solution's vapor pressure according to Henry's Law. Since evaporation rate is proportional to the difference in vapor pressure of the solution and the vapor pressure of the bulk gas phase over the water surface, the evaporate rate would be lower as the difference between the two vapor pressures would be smaller.

Given this it is therefore necessary to establish a variation of model to better describe the system in this study. This can be done by inquiry of regression for each variable for the data collected during the study. The regression analysis combines the data regarding the meteorological observations made during the study, as well as the data regarding the initial total dissolved solids concentration of the brine and the amount of distillate produced on those days from the adobe system and finally the relative operating parameters of the abode distillation unit. This data is summarized in Table 4.8.

The goal of the regression analysis is to develop an expression that is based upon the observations made in this study and determine new values for x1 through x7 shown in Equation 4.2, where *t* represents the temperature in degrees Celsius, *V* represents the wind speed (m/s), *H* represents the daily solar insolation value (kWh/m^2-day), *Θ* represents the angle of the cover on the still, □/*l* represents the ratio of water depth to front wall height, C_{TDS} is the initial total dissolved solids concentration of the brine (mg/L) and k_{basin} is the thermal conductivity of the basin material (W/(m*K)).

$$\mathrm{Volume}_{\mathrm{Adobe}} = x_1 t + x_2 V + x_3 H + x_4 + x_5 \frac{}{l} + x_6 C_{\mathrm{TDS}} + x_7 k_{\mathrm{basin}} \quad \text{(Equation 4.2)}$$

Table 4.8: A summary of data required to perform a regression analysis on the experiment results. The three meteorological and two design parameters are found to be influential by past studies are analyzed here.

Day #	Temp (celcius)	Wind Speed (m/s)	Solar Insolation (kWh/m^2-day)	Glass Cover Angle	Depth Ratio	Thermal Conductivity (W/(m*K)	Brine TDS (mg/L)	Volume
1	23.60	3.72	4.21	19.88	0.152	1.5	954	1102
2	23.20	3.72	4.28	19.88	0.138	1.5	756	1086
3	23.10	3.72	4.27	19.88	0.122	1.5	831	1178
4	21.20	3.62	3.89	19.88	0.152	1.5	702	1040
5	21.70	3.62	3.67	19.88	0.138	1.5	782	1010
6	23.20	3.62	3.70	19.88	0.122	1.5	877	964
7	20.90	3.62	3.51	19.88	0.152	1.5	718	796
8	22.10	3.62	3.75	19.88	0.138	1.5	686	918
9	22.30	3.62	3.66	19.88	0.122	1.5	1091	887
10	20.90	3.62	3.87	19.88	0.152	1.5	821	826
11	22.80	3.62	3.42	19.88	0.138	1.5	845	750
12	21.20	3.62	3.32	19.88	0.122	1.5	966	826
13	22.40	3.62	3.65	19.88	0.152	1.5	1024	796
14	21.30	3.62	3.89	19.88	0.138	1.5	1298	780
15	21.60	3.62	3.88	19.88	0.122	1.5	1013	796
16	22.70	3.62	3.42	19.88	0.152	1.5	1620	826
17	18.44	3.60	2.91	19.88	0.138	1.5	1790	688
18	18.94	3.60	3.40	19.88	0.122	1.5	1930	719
19	17.94	3.60	2.68	19.88	0.152	1.5	942	780
20	17.95	3.60	3.33	19.88	0.138	1.5	1410	581
21	18.81	3.60	3.41	19.88	0.122	1.5	1560	780
22	20.20	3.60	3.52	19.88	0.152	1.5	1117	857
23	20.87	3.60	3.71	19.88	0.138	1.5	1309	413
24	19.37	3.60	3.64	19.88	0.122	1.5	1020	933
25	19.68	3.60	3.35	19.88	0.152	1.5	1045	903
26	19.94	3.60	3.72	19.88	0.138	1.5	1193	887
27	19.29	3.60	3.74	19.88	0.122	1.5	1450	872
28	20.37	3.60	3.74	19.88	0.152	1.5	1131	765
29	17.99	3.60	3.23	19.88	0.138	1.5	1319	918
30	15.75	3.60	3.73	19.88	0.122	1.5	1005	811
31	18.17	3.60	3.67	19.88	0.152	1.5	1077	811
32	17.94	3.60	3.58	19.88	0.138	1.5	1101	688
33	17.89	3.60	3.37	19.88	0.122	1.5	981	841

The regression analysis tool provided by the data analysis package in Microsoft Excel was used to produce the results in in Table 4.9. The regression analysis is based upon the data in Table 4.8. The regression statistics in Table 4.9 summarizes the important components of the regression analysis, namely the R-square statistic, which measures the overall fitness of the expression to the data. In this case the R-square value is 0.98 which indicates that the expression developed from the experimental data fits the data very well.

Table 4.9: Results of the regression analysis performed on the data from Table 4.8. These results indicate that four of the five variables had significant impact on the volume produced, while the angle of the glass cover did not.

Regression Statistics	
Multiple R	0.993005661
R Square	0.986060242
Adjusted R Square	0.909404731
Standard Error	111.7103587
Observations	33

Regression Coefficients	
Temp (celcius)	-2.299047826
Wind Speed (m/s)	2357.34982
Solar Insolation (kWh/m2-day)	10.23161924
Glass Cover Angle	-369.2272057
Depth Ratio	-1227.403859
Thermal Conductivity (W/(m*K)	0
Brine TDS (mg/L)	-0.15299906

Table 4.9 also shows the calculated coefficients to be used in Equation 4.2. It can be seen that the coefficient for the thermal conductivity is zero and the coefficient related to influent salinity is very small (-0.153). This indicates that these parameters have little effect on distillation reactor performance despite strong suspicions to the contrary. Rewriting Equation 4.1 with the coefficients and constant determined from data shown in Table 4.9 results in the following expression which can be used to estimate the amount of distillate produced in a single-sloped single-basin solar distillation constructed from adobe based upon the local meteorological conditions. This expression will be referred to as the Manser (2012) model.

$$\mathrm{Volume}_{\mathrm{Adobe}} = -2.3\mathrm{t} + 2357\mathrm{V} + 10.2\mathrm{H} - 369 - 1227\frac{}{\mathrm{l}} - 0.15\mathrm{C}_{\mathrm{TDS}} + 0\mathrm{k}_{\mathrm{basin}}$$

Using this expression it is possible to estimate the amount of distillate that could be produced over the entire year with the adobe system. Figure 4.8 provides a graphical representation of the predicted amount of distillate that is predicted using the Manser (2012) model and the amount of distillate measured during the experiment. The data for Figure 4.8 is provided in Appendix B. Weather information for three days (the 5th, 15th and 25th) from each month were used to estimate the production of the adobe system in 2011.

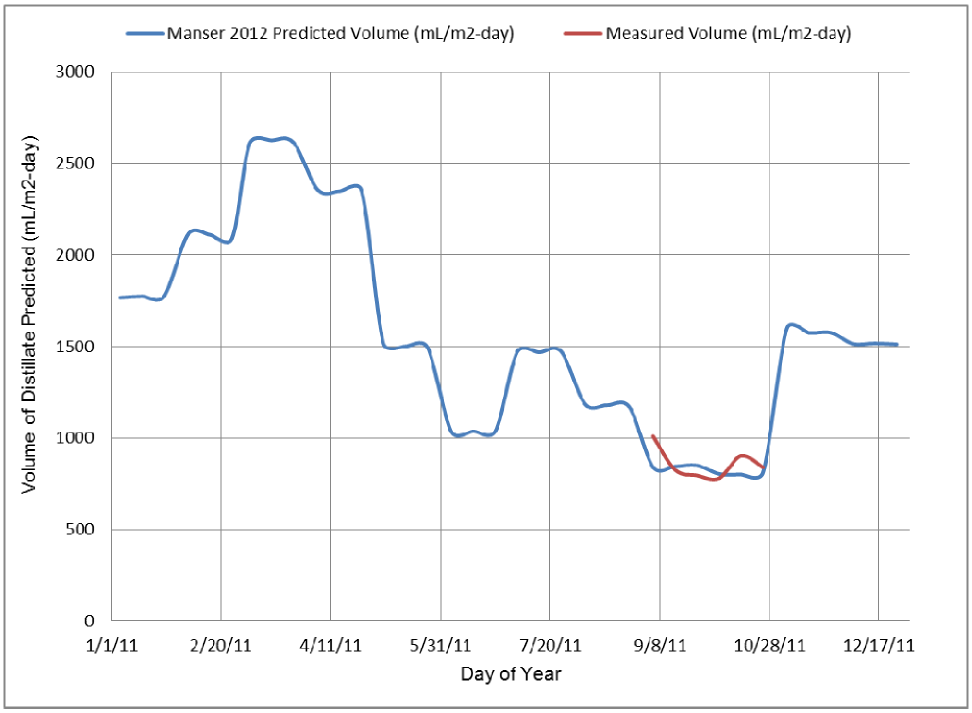

Figure 4.8: A prediction of distillate produced during 2011 based upon the weather observations for the year and the model developed in Equation 4.2.

Figure 4.8 demonstrates that the estimated production of distillate ranges from 700 to 2,700 mL/m^2-day over the year for the adobe model developed in this study, with the lowest production occurring during the same months as the study was performed. Assuming a target value of 2,000 mL/day (a typical value for daily drinking water need for a person), this model indicates that the adobe distillation system would meet the goal for about one quarter of the year. For a better representation of the production potential of the adobe system and the ability to satisfy the target value, the Manser (2012) model would have to be developed based upon measurements from the entire year.

Figure 4.8 also shows that the maximum production season occurs during the months of March and April. These months are typically very sunny and dry at the study location, and are usually the hottest part of the year. The same can be said about the dip in distillation system productivity in June also, as this time of the year is when the wet season begins and ends in the area, producing more cloud cover and cooler temperatures than normal. Figure 4.9 illustrates the range of data for the distillate measured in this study and the predicted productivity from the Nafey et al. (2000) and the Manser (2012) models. As shown, the adobe system analyzed was operating in the lower part of the annual range predicted by the Manser (2012) model.

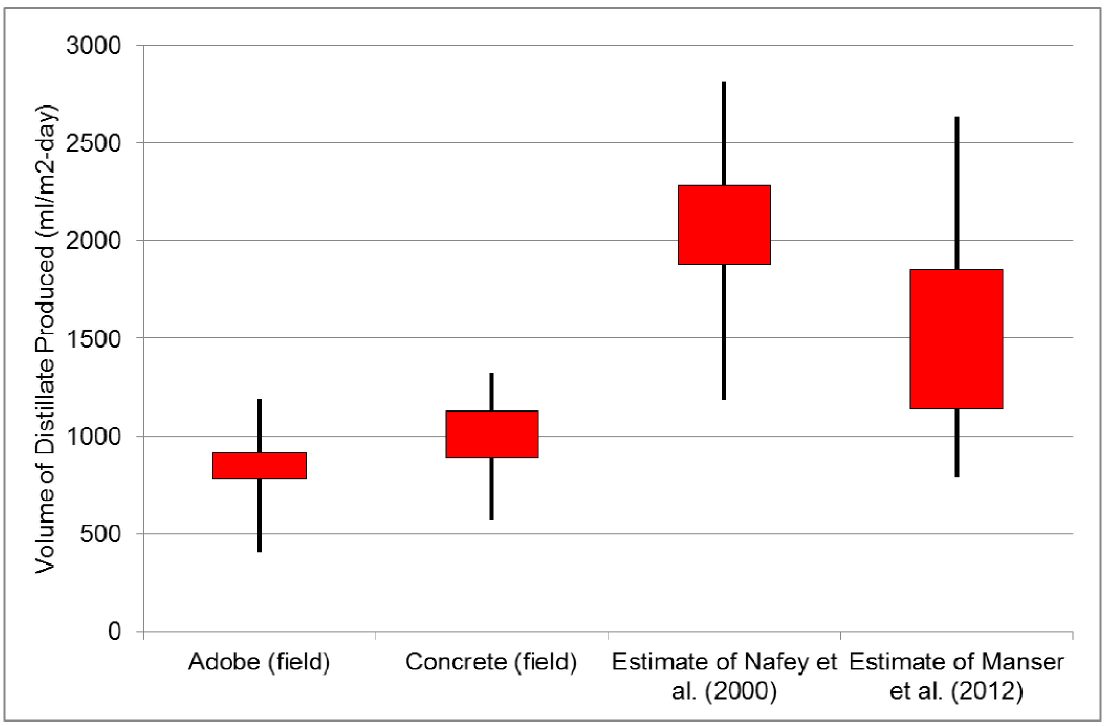

Figure 4.9: A box plot illustrating the minimum, maximum and average range of distillate produced or predicted in this study.

4.2 Percentage of Domestic Water Need Satisfied

This study found evidence that the distillate produced from a solar distillation unit made from adobe will be sufficient to satisfy small percentage (10.7%) of the daily demand for consumption water for a typical family in the study location. This value is less than the hypothesized value of 75 percent. Table 4.10 shows the volume of distillate collected over the investigation for the adobe system and the percentage of drinking water demand that is satisfied each day by the distillate produced. This calculation assumes that 7.8 liters per day (2.75 20-liter garaphones per week) is required in each household as determined in a 2012 study (Marlor) at the study location.

Table 4.10 indicates the adobe distillation unit will satisfy 10.7 percent of consumption water demand for a typical household; however this percentage will increase to 12.6% if the average amount of distillate produced (995 mL/m^2-day) is used from the new model (Equation 4.2) based upon the adobe unit results in this study is used. Because the adobe unit satisfies a small portion of the typical daily demand it may be difficult to integrate this technology into a community unless other benefits, such as an economic advantage, can be demonstrated.

Table 4.10: Volume of distillate produced on a given day in the study by the adobe distillation system and the percentage of typical local drinking water demand that is satisfied by it. This calculation assumes that a daily amount of 7.85 liters of drinking water is required per family each day.

Date (start)	Volume of Distillate (mL/m^2)	Percentage of Daily Demand (%)	Date (start)	Volume of Distillate (mL/m^2)	Percentage of Daily Demand (%)
8/14/11	1102	14%	10/1/11	688	9%
8/15/11	1086	14%	10/2/11	719	9%
8/16/11	1178	15%	10/3/11	780	10%
9/4/11	1040	13%	10/4/11	581	7%
9/5/11	1010	13%	10/5/11	780	10%
9/6/11	964	12%	10/6/11	857	11%
9/12/11	796	10%	10/7/11	413	5%
9/13/11	918	12%	10/14/11	933	12%
9/14/11	887	11%	10/15/11	903	11%
9/15/11	826	11%	10/16/11	887	11%
9/16/11	750	10%	10/17/11	872	11%
9/17/11	826	11%	10/18/11	765	10%
9/27/11	796	10%	10/19/11	918	12%
9/28/11	780	10%	10/20/11	811	10%
9/29/11	796	10%	10/21/11	811	10%
9/30/11	826	11%	10/22/11	688	9%
10/1/11	688	9%	**AVERAGE**	**843**	**10.7%**

4.3 Economic Analysis of the Adobe System

Since the production characteristics of the adobe distillation system does not satisfy a large percentage of the daily drinking water need another advantage of the system will need to be demonstrated in order to determine if this system is an appropriate solution. Table 4.11 demonstrates the material costs associated with constructing each unit, where one U.S. dollar is equivalent to approximately 12.7 Mexican pesos.

Table 4.11: Material costs associated with the adobe and concrete systems. In this comparison the tools are not included and the number of hours of labor required is about equal between the two systems. Values are for 2011.

Material	Adobe Unit (pesos)	Concrete Unit (pesos)
Concrete	50	150
Sand/Gravel	50	150
Glass Cover	200	200
Plumbing Connections	50	50
Black Fabric	80	80
Total Cost	430	630
2-Year Volume Produced (L)	402	475
Unit Cost (pesos/L) Pesos	**1.07**	**1.33**
3-Year Volume Produced (L)	603	712
Unit Cost (pesos/L) Pesos	**0.71**	**0.89**

Table 4.11 estimates the volume of distillate produced for each unit type studied assuming a life-span of two and three years, along with the unit cost of clean drinking water that is associated with each unit and life-span. In this study, the unit cost over a two-year period for the adobe unit is 1.07 pesos per liter for the adobe unit and 1.33 pesos per liter for the concrete unit. From this comparison it can be seen that the despite the lower volume of distillate produced by the adobe unit over the life span, the actual unit cost of the water on a per volume is less in both assumptions. This analysis is useful to compare costs in year zero; however, it does not demonstrate the long-term costs associated with owning and operating such systems, nor does it favorably compare to garaphone use which has a cost of 0.875 pesos per liter. Table 4.11, however, does suggest that the cost of distillate from both the adobe and concrete system would be less than purchasing garaphones if the systems were operated for at least three years (0.71 pesos/L for adobe, 0.83 pesos/L for concrete and 0.875 pesos/L to purchase).

Table 4.12 provides a comparison of net present value scenarios pertaining to owning and operating the adobe system compared to purchasing drinking water from a private vendor in 20-L garaphones. This analysis assumes that the glass cover will need to be replaced every two years and that annual maintenance of 100 pesos per distillation unit will be needed during the subsequent years. The most common maintenance cost will be associated with the silicone sealant used to prevent vapor loss at the glass cover and basin joint. Table 4.12 also assumes that the cost of 20-Liter garaphones will not increase over time and that a typical family in this region would purchase approximately 2.75 garaphones per week at a cost of 17.4 pesos per garaphone (Marlor et al, 2012). The interest rate used in the calculation was four percent annually.

It can be seen in Table 4.12 that the ten-year NPV of typical study location garaphone use is almost equivalent to the NPV of the construction and owning/operating costs for thirteen or fourteen adobe distillation units over the ten-year period. In other words, the same amount of money would be spent on a garaphone water supply over ten years as if thirteen solar distillation systems were built and maintained instead. The distillate production deficit observed in the study can be improved by optimizing distillate production which will reduce the number of distillation units required and is discussed further in Chapter 5.

If it is assumed the annual average of distillate produced per day is estimated from the model developed in this study (995 mL/distillation unit) is used in place of the average of the field data (551 mL/distillation unit),then only eight distillation units would be required to satisfy the typical household demand for drinking water instead of thirteen. Table 4.13 shows that the more efficient adobe distillation reactor would cost the user about 12,600 pesos over ten years versus the 21,800 pesos needed to purchase water the same amount of water from garaphones or less efficient distillation reactors.

A 2012 study on the income levels of the families in the study location found that the average monthly income for a typical family in the area is approximately 3,850 pesos while the maximum monthly income is approximately 10,300 pesos (Marlor, 2012). If you look at the percentage of income, or cost, which would be dedicated to purchasing drinking water in garaphones for ten years to the total ten-year income (discounted under same constraints as Table 4.10), 5.3% of the average family's monthly income would be used to provide drinking water over a ten-year period. On the other hand if you looked at the same ratio with the adobe solar distillation system, assuming that the average volume of distillated produced follows the estimated production of the model developed in this study (995 mL/m^2-day), only 3.1% of monthly income would be spent of drinking water over ten years versus 5.3%. Based upon the data available for current drinking water use and cost at the study location, approximately 5.4% of monthly income is used for drinking water supply.

Finally, it is important to recognize that the total economic impact of the distillation reactor examined in this study depends upon more than just the cost of the water in terms of owning and operating expenses. For example; the benefits associated with improved user and community-member health can include greater income potential of the family; also the possible reduction in drinking water collection time can lead to better family time management; and furthermore the lessening of the carbon footprint associated with producing and trucking drinking water to the study location is sure to reduce the societal cost of the distilled water.

Table 4.12: A summary of net present value scenarios comparing the costs, in Mexican pesos, associated with building/owning/operating and set of more efficient distillation reactors made from adobe and purchasing 20L garaphones each week. From this analysis, based upon i=4%, it is possible that 13 or 14 distillation systems could be built and used for the same price as purchasing 2.75 garaphones weekly.

Scenario	**NPV**	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Liters/Year**
Purchase 20L Garaphone (2.75/week)	$ 21,798	2,488	2,488	2,488	2,488	2,488	2,488	2,488	2,488	2,488	2,488	2,488	2860
4 Reactors	$ 6,303	1,720	400	800	400	800	400	800	400	800	400	800	804
5 Reactors	$ 7,878	2,150	500	1,000	500	1,000	500	1,000	500	1,000	500	1,000	1006
6 Reactors	$ 9,454	2,580	600	1,200	600	1,200	600	1,200	600	1,200	600	1,200	1207
7 Reators	$ 11,030	3,010	700	1,400	700	1,400	700	1,400	700	1,400	700	1,400	1408
8 Reactors	$ 12,605	3,440	800	1,600	800	1,600	800	1,600	800	1,600	800	1,600	1609
9 Reactors	$ 14,181	3,870	900	1,800	900	1,800	900	1,800	900	1,800	900	1,800	1810
10 Reactors	$ 15,757	4,300	1,000	2,000	1,000	2,000	1,000	2,000	1,000	2,000	1,000	2,000	2011
11 Reactors	$ 17,332	4,730	1,100	2,200	1,100	2,200	1,100	2,200	1,100	2,200	1,100	2,200	2212
12 Reactors	$ 18,908	5,160	1,200	2,400	1,200	2,400	1,200	2,400	1,200	2,400	1,200	2,400	2413
13 Reactors	$ 20,484	5,590	1,300	2,600	1,300	2,600	1,300	2,600	1,300	2,600	1,300	2,600	2614
14 Reactors	$ 22,059	6,020	1,400	2,800	1,400	2,800	1,400	2,800	1,400	2,800	1,400	2,800	2816
15 Reactors	$ 23,635	6,450	1,500	3,000	1,500	3,000	1,500	3,000	1,500	3,000	1,500	3,000	3017
16 Reactors	$ 25,211	6,880	1,600	3,200	1,600	3,200	1,600	3,200	1,600	3,200	1,600	3,200	3218

Table 4.13: A discounted cash flow of the water use scenarios examined in this study, with an assumption of 995mL/m^2-day as an average volume of distillate produced by the distillation system. Monetary amounts are in pesos. Notice how this volume relates to only eight distillation units for an equivalent volume of garaphone water when compared to 13 or 14 from Table 4.11.

Scenario	NPV	0	1	2	3	4	5	6	7	8	9	10	Liters/Year
Purchase 20L Garaphone	$21,796	2,488	2,488	2,488	2,488	2,488	2,488	2,488	2,488	2,488	2,488	2,488	2,860
4 Reactors	$6,303	1,720	400	800	400	800	400	800	400	800	400	800	1,453
5 Reactors	$7,878	2,150	500	1,000	500	1,000	500	1,000	500	1,000	500	1,000	1,816
6 Reactors	$9,454	2,580	600	1,200	600	1,200	600	1,200	600	1,200	600	1,200	2,179
7 Reators	$11,030	3,010	700	1,400	700	1,400	700	1,400	700	1,400	700	1,400	2,542
8 Reactors	$12,605	3,440	800	1,600	800	1,600	800	1,600	800	1,600	800	1,600	2,905
9 Reactors	$14,181	3,870	900	1,800	900	1,800	900	1,800	900	1,800	900	1,800	3,269
10 Reactors	$15,757	4,300	1,000	2,000	1,000	2,000	1,000	2,000	1,000	2,000	1,000	2,000	3,632
11 Reactors	$17,332	4,730	1,100	2,200	1,100	2,200	1,100	2,200	1,100	2,200	1,100	2,200	3,995
12 Reactors	$18,908	5,160	1,200	2,400	1,200	2,400	1,200	2,400	1,200	2,400	1,200	2,400	4,358
13 Reactors	$20,484	5,590	1,300	2,600	1,300	2,600	1,300	2,600	1,300	2,600	1,300	2,600	4,721
14 Reactors	$22,059	6,020	1,400	2,800	1,400	2,800	1,400	2,800	1,400	2,800	1,400	2,800	5,084
15 Reactors	$23,635	6,450	1,500	3,000	1,500	3,000	1,500	3,000	1,500	3,000	1,500	3,000	5,448
16 Reactors	$25,211	6,880	1,600	3,200	1,600	3,200	1,600	3,200	1,600	3,200	1,600	3,200	5,811

4.4 Distillate Water Quality Analysis

4.4.1 Distillate Water Quality Analysis – Adobe Unit

This study found evidence that the water quality of the distillate produced in a solar distillation unit will satisfy local and World Health Organization (WHO) drinking water guidelines in terms of total dissolved solids. Table 4.1 shows the measured total dissolved solids content (as determined by TDS, mg/L) of the distillate observed during the experiment with the adobe field unit. Figure 4.10 provides total dissolved solids measurements for the distillate measured from the adobe field unit.

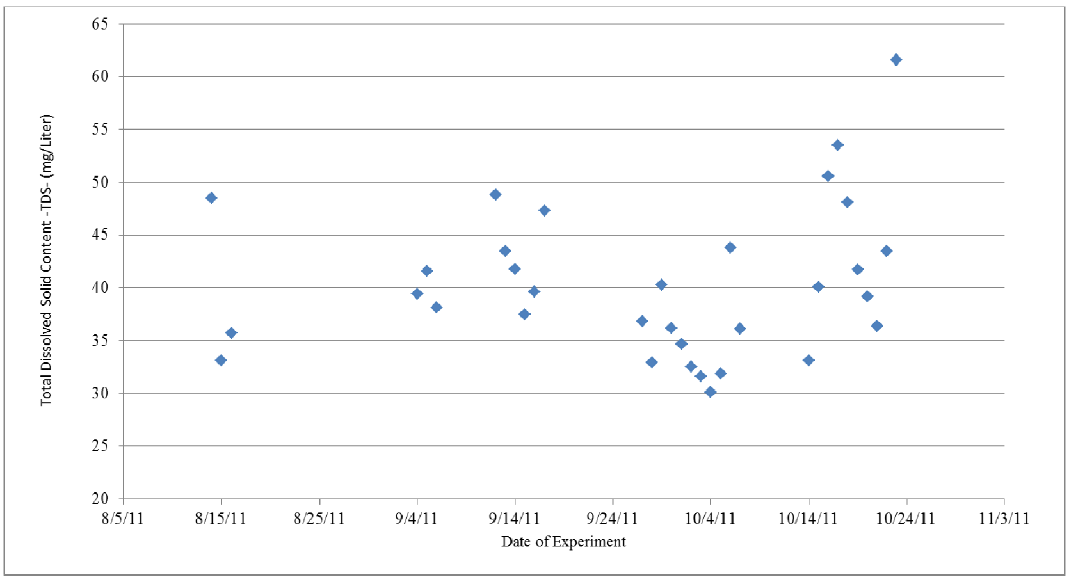

Figure 4.10: Total dissolved solid concentrations for the distillate produced in the adobe field unit. These points are based upon the data from Appendix D. As shown, the range of concentrations that were measured was between 30 and 65 mg/L; a significant reduction from the initial average concentration of 1,100 mg/L.

Table 4.1 also includes the initial total dissolved solid content of the brine used in the study to illustrate the removal efficiency of the system (96%) on each experiment day. A comparison of removal efficiencies can be found in Table 4.14 later in the section.

4.4.2 Distillate Water Quality Analysis – Concrete Unit

Table 4.2 shows the measured total dissolved solid content of the distillate observed during the experiment with the concrete field unit. The table also includes the initial total dissolved solid content to illustrate the removal efficiency of the system (96%). Due to the design of the concrete field unit it was only possible to collect a sample from the brine tank to measure the total dissolved solids on the first day of each set when the initial brine total dissolved solids were known. Figure 4.11 depicts the total dissolved solids in the distillate over time for the concrete field unit.

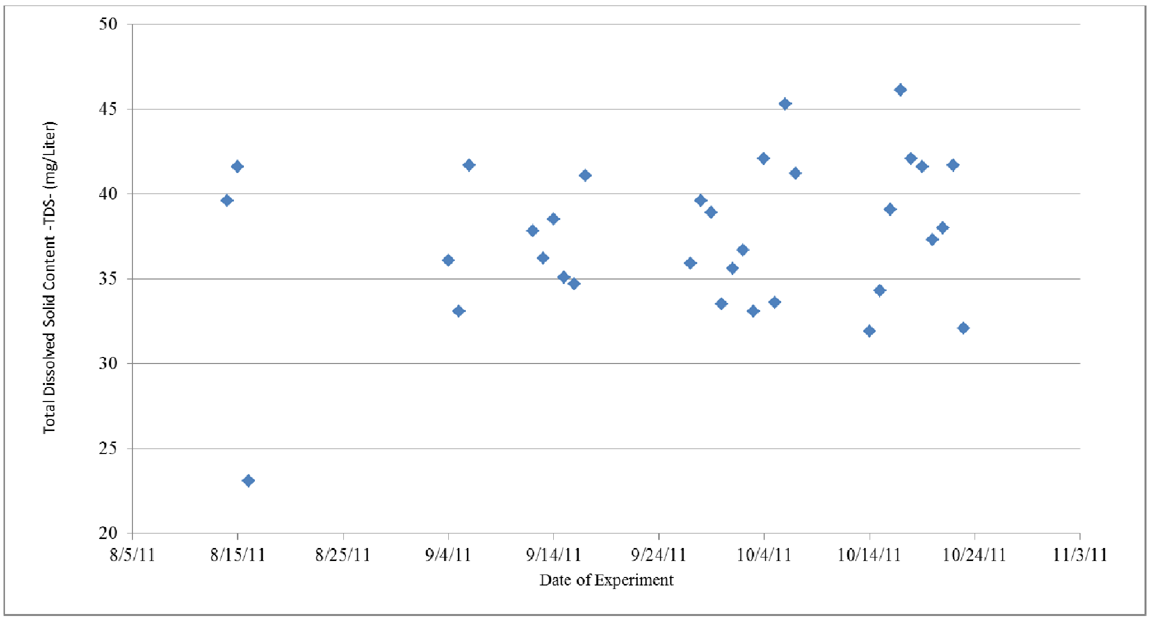

Figure 4.11: Total dissolved solids measurements for the distillate produced in the concrete field unit. These points are based upon the data from Appendix C. As shown, the range of concentrations that were measured was between 30 and 65 mg/L; a significant reduction from the initial average concentration of 1,100 mg/liter.

4.4.3 Distillate Water Quality Comparison

The average total dissolved solids concentration for the distillate streams in the adobe field unit is compared to three results published in literature (Hanson et al., 2004; Samee et al., 2007). This comparison is shown in Table 4.14. The range of the data points from the literature regarding total dissolved solids of distillates produced used in this study is 30 mg/L to 226 mg/L, while the range of the data points from the adobe and concrete systems regarding total dissolved solids of the distillates produced is 30.1 mg/L to 61.6 mg/L and 31.9 mg/L to 50.7 mg/L. Recalling Table 2.10 and a 2004 study on some of the removal efficiencies found in literature the adobe distillation system produces a distillate with similar levels of total dissolved solids concentration (Table 4.14).

Table 4.14: A summary of the removal efficiencies looked at in this study compared to some found in literature. In this study, both the concrete and adobe systems were able to remove at least 96 percent of the total dissolved solid content from the brine. This is useful in areas with brackish water.

Sample Source	TDS (mg/L)		% Removal
	Before Distillation	After Distillation	
Hanson et al (2004)	370	30	91
Samee et al (2007)	544	84	84
Samee et al (2007)	17,663	226	98
Chow (2012)	17,000-18,000	300-800	95-98
Manser (2012) Concrete	1,299	37	97
Manser (2012) Adobe	1,101	40	96

Table 4.14 shows that all of the published studies have had success at meeting WHO guidelines for TDS. The WHO reports that water becomes increasingly unpalatable as the TDS concentrations reach and exceed 1,000 mg/L. Table 4.14 also indicates that the removal efficiencies of the systems built and monitored for this study are similar or greater than most of the published results, with the concrete system being slightly more effective of the two (97.1 versus 96.3 percent removal of TDS). Based upon these results it can be concluded that a single basin solar distillation unit constructed primarily from adobe will produce a high quality distillate in terms of reduced total dissolved solid content.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusions

Many studies have shown that passive solar distillation systems can be used to remove salinity from water (Fath, 1998; Tiwari et al., 2003; Samee et al., 2007; Kaushal, 2010) as a means of improving access to drinking water. The systems highlighted in the literature are constructed from a variety of materials, some of which are difficult to obtain due to their cost or availability, making it difficult to apply the technology in many rural underdeveloped settings. Other systems are studied under laboratory controlled conditions in an effort to optimize each design and operational constraint involved with solar distillation, and it is these systems that often lack simplicity and are not suitable for realistic operating environments.

This study has demonstrated that a single-slope single-basin passive solar distillation system can be constructed mostly from adobe, a widely available and sustainable construction material, and be used to remove total dissolved solids from local water sources as verified by this experiment that examined the system in a real-time environment through an examination of the following hypotheses:

1. The quantity of distillate produced (L/m^2-day) in a single basin passive solar still constructed from adobe will be similar to published performance models using other materials for construction;
2. The distillate produced from the adobe distillation reactor in this study will be sufficient to provide 75% of the daily water consumption required for drinking for a typical family in the study location;

3. The water quality of the distillate will satisfy the World Health Organization (WHO) drinking water guidelines for total dissolved solids concentration; and
4. The economic cost of the distillate (pesos/L) produced by the adobe distillation unit will be less than the cost of purchasing drinking water from a water vendor at the study location (0.875 pesos/L).

In this study it was determined that a distillation system made from adobe produced less distillate per unit area than other reported studies, not satisfying hypothesis #1 and in turn hypothesis #2. It was concluded that the physical properties of adobe, such as its relatively higher thermal conductivity and porosity, lead to above average vapor loss to the surroundings. Despite these findings, evidence does suggest that the experimental data were collected during the lower solar energy potential months at the study location, which may indicate that the actual distillation potential of the adobe system is higher than measured. Regardless of how efficient the system currently is one conclusion is that adobe cannot be ruled out as a construction material for basin-type distillation systems. With optimization of the design distillation systems can become a more efficient distillate producer. A discussion related to performance optimization and experiment design is located in Section 5.2.

Third, hypothesis #3 claimed that the distillate produced would satisfy the WHO guidelines in terms of total dissolved solids concentration. This study verified that distillate output had undergone significant (approximately 96%) total dissolved solids removal during treatment, often producing water with TDS concentrations less than 50 mg/L that would be palatably acceptable to drink and well under the WHO recommendation of 1,000 mg/L. The author had conversations with several end users, and these conversations covered many themes, but the theme of taste was normally discussed. Here end users typically talked of the distillate tasting very “*dulce*” or sweet, which is a cultural reference in this area for good drinkable water.

Finally, hypothesis #4 considered the owning and operating economic benefit that the distillation system provides to the user, this research was performed at a location where a typical family purchases about 2.75 garaphones (20L) of drinking water per week at a cost of approximately 0.87 pesos/L. It was shown that the solar distillation unit modeled in this study provides similar quality water for 0.71 to 1.03 pesos/L, depending on the life span of the glass cover. Further analysis indicated that over a ten-year period the NPV of typical garaphone use would be equivalent to the costs associated with building eight to fourteen of the adobe distillation systems presented in this study. The same analysis also demonstrated that the same amount of drinking water could be obtained for the same cost. Therefore, despite the large capital investment that would be required to build a farm of distillation units, the economic benefit over an extended period appears favorable for the user.

In conclusion, adobe appears to be a sustainable material as the primary construction material in this study, mainly because of its economic benefit and partially because of its production potential, but also because it utilizes a skill set of the local population as most of their homes and structures are constructed from adobe blocks made by the homeowner. This familiarity and wide availability of adobe will have favorable effects on the user’s ability to own and operate the distillation system.

5.2 Recommendations for Future Research

This study successfully determined the effects that adobe will have, as the primary construction material in a single-slope single-basin distillation unit, on factors such as the quality and quantity of distillate produced. However, there was a significant deficit in the volume of distillate produced when compared to other published studies.

This difference was likely due to several inefficiencies that exist in the design of the system. These are believed to include: 1) the lighter color of the basin, 2) lack of water/vapor tightness on the adobe walls due to porosity of the parged walls and basin wall material, 3) insufficient absorbing materials that change the solar insolation energy into heat for transfer into the brine, 4) ineffective distillate collection trough, and 5) lack of a more effective thermal insulation layer to keep the heat inside the basin while minimizing heat losses into the basin wall. Considering that each of these areas of improvements could increase the output of the distillation system to some degree, one recommendation of this study is that further investigations should be made into the effects of these modifications. This is important because any increase in distillate volume will further advance the favorable impacts on the economic and functional appropriateness of this technology.

In addition to design changes, there are modifications to the experiment performed in this study that are recommended. In this study sampling and testing was performed only for total dissolved solid, and given the ability of distillation technology to remove many kinds of contaminants from the source water, it will be important to design an experiment that demonstrates removal of other dissolved constituents such as volatile organic compounds (especially important as many absorbing materials are synthetic or petroleum based) and metals (e.g. arsenic) to better understand how to apply this technology. Finally, a more detailed sampling protocol is required to better understand the nocturnal production properties of adobe.

REFERENCES

Abbot CG (1940) Utilizing the sun's rays. *The Scientific Monthly* **51**(3):195-200.

Abdelkader MA (1998) An Investigation of the parameters involved in a simple solar still with inclined jute. *Journal of Renewable Energy* **14**:333-338.

Aboabboud MM, Horvath L, Szepvolgyi J, Mink G, Radhika E, and Kudish AI (1996) The use of a thermal energy recycle unit in conjunction with a basin-type still for enhanced productivity. *Energy* **22**:83–91.

Aboul-Enein S, El-Sebaii AA, El-Bialy E (1998) Investigation of a single-basin solar still with deep basins. *Renewable Energy* **14**:299–305.

Adhikari RS, Kumar A and Sodha GD (1995) Simulation studies on a multi-stage stacked tray solar still. *Journal of Solar Energy* **54**(5):317-325.

Akash BA, Mohsen MS, Osta O and Elayan Y (1998) Experimental evaluation of a single-basin solar still using different absorbing materials. *Renewable Energy* **14**:307-310.

Al-Hinai H, Al-Nassri MS, and Jubran BA (2002) Effect of climatic, design and operational parameters on the yield of a simple solar still. *Energy Conversion and Management* **43**:1639–1650.

Al-Karaghouli AA and Alnaser WW (2004) Experimental comparative study of the performances of single and double basin solar-stills. *Applied Energy* **77**:317-325.

Bassam AH and Rababa'h HM (2003) Experimental Study of a solar still with sponge cubes in basin. *Energy Conversion and Management* **44**:1411-1418.

Badran OO (2007) Experimental study of the enhancement parameters on a single slope solar still productivity. *Desalination* **209**:136-143.

Barrera E (1992) A technical and economic analysis of solar water still in Mexico. J*ournal of Renewable Energy,* **2**(4):489-495.

Barrera E (1993) Double effect spherical solar still. *Journal of Sun World*,**17**:111-117.

Cairncross S and Feacham R (1993) Environmental Health Engineering in the Tropics: An Introductory Text, 2nd Edition. Jon Wiley and Sons, Chichester, UK.

Camacho LM, Gutiérrez M, Alarcón-Herrera MT, Villalba ML, and Deng S (2011) Occurrence and treatment of arsenic in groundwater and soil in northern Mexico and southwestern USA. *Chemosphere* **83**:211–225.

Carrillo-Rivera JJ, Cardona A and Edmunds WM (2002) Use of abstraction regime and knowledge of hydro-geological conditions to control high fluoride concentration in abstracted groundwater: San Luis Potosí Basin, Mexico. *Journal of Hydrology* **261**:24-47.

Chaibi MT (2000) An overview of solar desalination for domestic and agriculture water needs in remote arid areas. *Desalination* **127**:119-133.

Chiprés JA, Calleja A, Tellez JI, Jiménez F, Cruz C, Guerrero EG, Castro J, Monroy MG and Salinas JC (2009) Geochemistry of soils along transect from Central Mexico to the Pacific Coast: A pilot study for continental-scale geochemical mapping. *Applied Geochemistry* **24**:1416–1428.

Chow J (2012) Personal communication.

Coffey JP (1975) Vertical solar distillation: technical note. *Journal of Solar Energy* **17**:375-378.

Cooper PI (1969) Digital simulation of transient solar still processes. *Journal of Solar Energy* **12**:313-331.

Coskun C, Oktay Z and Dincer I (2011) Estimation of monthly solar radiation distribution for solar energy system analysis. *Energy* **36**:1319-1323.

Dunkle RV (1961) Solar water distillation: the roof type still and multiple effect diffusion still. *International Developments in Heat Transfer ASME: Proceedings of International Heat Transfer Part V*, University of Colorado.

Elbling JA, Talbert SG and Lof GOG (1971) Solar stills for community used-digest of technology. *Solar Energy* **13**:263–276.

El-Sebaii AA, (2004) Effect of wind speed on active and passive solar stills. *Energy Conversion and Management* **45**:1187–1204.

Fath HS (1996) Improvement of basin solar still productivity by purging its vapor to a second effect still. *Desalination* **107**(3):223-233.

Fath HS (1998) Solar distillation: a promising alternative for water provision with free energy simple technology and a clean environment. *Desalination* **116**:45-56.

Fath HS, El-Samanoudy M, Fahmy K and Hassabou A (2003) Thermal-economic analysis and comparison between pyramid-shaped and single slope solar still configurations. *Desalination* **159**:69–79.

Feilizadeh M, Soltanieh M, Jafarpur K and Karimi-Estahbanati MR (2010) A new radiation model for a single-slope solar still. *Desalination* **262**:166–173.

Foster RE, Eby S and Amos V (2005) Ten years of solar distillation application along the U.S.-Mexico border. Solar World Congress, International Solar Energy Society Orlando, Florida, August 11, 2005.

Franco J, and Saravia L (1994) A new design for a passive atmospheric multistage still. *Journal of Renewable Energy* **4**(1):119-122

Freund R and Wilson W (2003) Statistical Methods. Second Edition. Academic Press, Burlington, VT.

Frick G and Sommerfeld J (1973) Solar stills of inclined evaporating cloth. *Journal of Solar Energy* **14**(4):427-431.

Garg HP and Mann HS (1976) Effect of climatic, operational and design parameters on the year-round performance of single-sloped and double-sloped solar stills under Indian arid zone conditions. *Solar Energy* **18**:159–164.

Gleick PH (1993) Water Crisis: a Guide of the World's Freshwater Resources. Oxford University Press, New York.

Gueymard CA (2004) The sun's total and spectral irradiance for solar energy applications and solar radiation models. *Solar Energy* **76**:423-453.

Hanson A, Zachritz W, Stevens K, Mimbela L, Polka R and Cisneros L (2004) Distillate water quality of a single-basin solar still: laboratory and field studies. *Solar Energy* **76**:635–645.

Harris NC, Miller CE and Thomas IE (1985) Solar Energy Systems Design. New York: Wiley.

Hollands KT (1963) The regeneration of lithium chloride brine in a solar still for use in solar air conditioning. *Solar Energy* **7**(2):39-43.

Hongfei Z, Xiaoyan Z, Jing Z and Yuyuan W (2002) A group of improved heat and mass transfer correlations in solar stills. *Energy Conversion and Management* **43**:2469–2478.

Hou S and Zhang H (2008) A hybrid solar desalination process of the multi-effect humidification dehumidification and basin-type unit. *Desalination* **220**:552–557.

Howard G and Bartram J (2003) Domestic water quality, service level and health. World Health Organization, New York.

INEGI (2005) XII Censo general depoblación y vivienda 2005. Instituto Nacional de Estadística, Geografía e Informática. <http://www.inegi.gob.mx>. Accessed on February 15, 2012.

IPCS (1994) *Environmental Health Criteria 170: Assessing human health risks of chemicals: derivation of guidance values for health-based exposure limits*. World Health Organization, Geneva.

IRC (1981) Small community water supplies: technology, people and partnerships*. (Technical paper series; no. 40). Rijswijk, The Netherlands, IRC International Water and Sanitation Center.*

IWMI (2007) International Water Management Institute 2006-2007 Annual Report. http://www.iwmi.cgiar.org/About_IWMI/Strategic_Documents/Annual_Reports/2006_2007/theme1.html (accessed on February 18, 2012)

Jubran BA, Ahmed MI, Ismail AF and Abakar YA (2000) Numerical modeling of a multi-stage solar still. *Energy Conversion and Management* **41**:1107-1121.

Kaushal A (2010) Solar stills: A review. *Renewable and Sustainable Energy Reviews* **14**:446–453.

Kennedy PM (2006) *An analysis of the relationship between water accessibility, use and health in Muthara, Kenya.* http://cee.usf.edu/peacecorps/Resources.htm (accessed on March 8, 2011).

Khalifa AJ (2011) The effect of cover tilt angle of the simple solar still on its productivity in different seasons and latitudes. *Energy Conversion and Management* **52**:431–436.

Khalifa AJ, Hamood N and Ahmad M (2009) Performance correlations for basin type solar stills. *Desalination* **249**:24-28.

Kiatsiriroat T (1989) Review of research and development on vertical solar stills. *ASEAN Journal of Science Technology Development* **6**(1):15-22.

Kiatsiriroat T, Bhattacharya SC and Wibulswas P (1987) Transient simulation of vertical solar still. *Journal of Energy Conversion Management*. **27**(2):247-252.

Kumar BS, Kumar S and Jayaprakash R (2008) Performance analysis of a "V" type solar still using a charcoal absorber and a boosting mirror. *Desalination* **229**:217–230.

Madhlopa A and Johnstone C (2009) Model for computation of solar fraction in a single-slope solar still. *Solar Energy* **83**:873–882.

Mahdi JT, Smith BE and Sharif AO (2011) An experimental wick-type solar still system: Design and construction. *Desalination* **267**:233–238.

Malik MS, Tiwari GN, Kumar A and Sodha MS (1982) *Solar Distillation*. Pergamon Press, Oxford, UK.

Malik MS and Tran V (1973) A simple mathematical model for predicting the nocturnal output of a solar still. *Solar Energy* **14**:371–385.

Marlor KM (2012) Examining the economic costs and sources of potable and non-potable water in northern Mexico, unpublished thesis manuscript University of South Florida. <http://usfmi.weebly.com/thesesreports.html>

Mathioulakis E, Voropoulos, K and Belessoitis V (1999) Modeling and prediction of long-term performance of solar stills. *Desalination* **122**:85-93.

Mihelcic JR, Fry LM, Myre EA, Phillips LD and Barkdoll BD (2009) *Field Guide to Environmental Engineering for Development Workers.* American Society of Civil Engineers. Reston, Virginia.

Mihelcic JR and Zimmerman (2010) Environmental Engineering: Fundamentals, Sustainability, Design. Jon Wiley and Sons. Hoboken, New Jersey.

Miller GT (1991) *Environmental Science.* 3rd Edition, Wadsworth, Belmont, CA.

Morse RN and Read WW (1968) A rational basis for the engineering development of a solar still. *Solar Energy* **12**(1):5-17.

Mowla D and Karimi G (1995) Mathematical modeling of solar stills in Iran. *Solar Energy* **55**(5):389-93.

Murugavel KK, Chockalingam KnK and Srithar K (2008a) Progresses in improving the effectiveness of the single basin passive solar still. *Desalination* **220**:677-686.

Murugavel KK, Chockalingam KnK and Srithar K (2008b). An experimental study on a single basin double slope simulation solar still with a thin layer of water in the basin. *Desalination* **220**:687-693.

Nafey AS, Abdelkader M, Abdelmotalip A and Mabrouk AA (2002). Enhancement of solar still productivity using a floating perforated black plate. *Energy Conversion and Management* **43**:937-946.

Nafey AS, Abdelkader M, Abdelmotalip A and Mabrouk AA (2001) Solar still productivity enhancement. *Energy Conversion and Management* **42**:1401-1408.

NASA (2011) *Surface Meteorology and Solar Energy: A renewable energy resource website*. NASA: Applied Sciences Program. <http://eosweb.larc.nasa.gov/>

Parra-Saldivar M and Batty W (2005) Thermal behavior of adobe constructions. *Building and Environment* **41**:1892–1904.

Phadatare MK and Verma SK (2007) Influence of water depth on internal heat and mass transfer in a plastic solar still. *Desalination* **217**:267-275.

Philibert C (2005) The present and future use solar thermal energy as a primary source of energy. *International Energy Agency,* Paris, France.

Quinones PH, Unland H, Ojedab W and Sifuentesb E (1999) Transfer of irrigation scheduling technology in Mexico. *Agricultural Water Management* **40**:333-339.

Rajvanshi, A.K., and Hsieh, C.K., (1979) Effect of dye on solar distillation: analysis and experimental evaluation. *Proceedings of International Congress of ISES*, Georgia.

Revuelta-Acosta JD, Garcia-Diaz A, Soto-Zarazua GM, Rico-Garcia E (2010) Adobe as a sustainable material: a thermal performance. *Journal of Applied Science* **10**(19):2211-2216.

Richard AJ and Gouri K (1996) *Statistics: principle and methods.* 3rd edition. New York: Wiley:507-532.

Sadineni SB, Hurt R, Halford CK and Boehm RF (2008) Theory and experimental investigation of a weir-type inclined solar still. *Energy* **33**:71–80.

Samee MA, Mirza UK, Majeed T and Ahmad N (2005) Design and performance of a simple single basin solar still. *Renewable and Sustainable Energy Reviews* **11**:543-549.

Sampathkumar K, Arjunan TV, Pitchandi P and Senthilkumar P (2010) Active solar distillation—A detailed review. *Renewable and Sustainable Energy Reviews* **14**:1503–1526.

Shanmugan S, Rajamohan P and Mutharasu D (2008) Performance study on an acrylic mirror boosted solar distillation unit utilizing seawater. *Desalination* **230**:281–287.

Sodha MS, Kumar A, Tiwari GN and Tyagi RC (1981) Simple multiple-wick solar still: analysis and performance. *Journal of Solar Energy* **26**(2):127-131.

Soliman SH (1972) Effect of wind on solar distillation. *Solar Energy* **13**:403–415.

Suneja S and Tiwari GN (1999) Optimization of number of effects for higher yield from an inverted absorber solar still using the Runge–Kutta method. *Desalination* **120**(3):197-209

Talbert SG, Eibling JA and Lof GG (1970) Manual on solar distillation of saline water. R&D Progress Report No. 546, US Department of the Interior.

Tanaka H and Nakatake Y (2009) Increase in distillate productivity by inclining the flat plate external reflector of a tilted-wick solar still in winter. *Solar Energy* **83**:785-789.

Tanaka H, Nosoko T and Nagata T (2000a) A highly productive basin-type-multiple-effect coupled solar still. *Desalination* **130**(3):279-293.

Tanaka H, Nosoko T and Nagata T (2000b) Parametric investigation of a basin-type-multiple-effect coupled solar still. *Desalination* **130**(3):295-304.

Tiwari GN and Madhuri H (1987) Effect of water depth on daily yield of still. *Desalination* **61**(1):67-75.

Tiwari GN (1984) Demonstration plant of multi-wick solar still. *Journal of Energy Conversion and Management* **24**(4):313-316.

Tiwari GN (1992) *Contemporary physics—solar energy and energy conservation: Recent Advances in Solar Distillation*. Wiley Eastern Ltd., New Delhi, India. Chapter 2.

Tiwari GN, Singh HN and Tripathi R (2003) Present status of solar distillation. *Solar Energy* **75**:367-373.

Tiwari GN, Kupfermann A and Agrawal S (1997) A new design of double condensing chamber solar still. *Desalination* **114**(1):153-164.

Tleimat BW and Howe ED (1967) Comparison of plastic and glass condensing covers for solar distillers. In: *Proceedings of Solar Energy Society, Annual Conference, Arizona*.

Torchia-Nunez JC, Porta-Ga'ndara MA and Cervantes-de Gortaria JG (2008) Exergy analysis of a passive solar still. *Renewable Energy* **33**:608–616.

Tsilingiris PT (2009) Analysis of the heat and mass transfer processes in solar stills – The validation of a model. *Solar Energy* **83**:420–431.

United Nations (UN) (2006) World Water Development Report 2. http://www.unesco.org/new/en/naturalsciences/environment/water/wwap/wwdr/wwdr2-2006/ (accessed on February 18, 2012)

Velmurugan V and Srithar K (2011) Performance analysis of solar stills based on various factors affecting the productivity—A review. *Renewable and Sustainable Energy Reviews* **15**:1294-1304.

White G, Bradley D and White A (1972) *Drawers of water: Domestic water use in East Africa.* University of Chicago Press, Chicago.

WHO/UNICEF (2010) *WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation*. WHO Press, Geneva, Switzerland.

World Health Organization (2000) *Global water supply and sanitation assessment 2000 report.* World Health Organization and United Nations Children Fund, New York.

World Health Organization (2011) *Guidelines for drinking-water quality, recommendations*. Fourth edition. Switzerland, Geneva: World Health Organization.

World Wildlife Fund (2011) Freshwater: what's at stake, what we're missing, what we're losing, what it's worth. Accessed from: http://wwf.panda.org/about_our_earth/about_freshwater/importance_value/

Yeh HM and Chen LC (1986) The effect of climatic, design and operational parameters on the performance of wick-type solar distiller. *Energy Conversion and Management* **26**:175–180.

APPENDICES

Appendix A: TDS Meter Calibration Record

Date	TDS Meter Reading	Notes/Comments (Calibration Standard Used = 1000 ppm)
8/14/11	1.00 g/L	new meter (TDS Calibration Solution 1000 ppm, NaCl, 25°)
8/15/11	1.00 g/L	
8/16/11	1.00 g/L	
9/4/11	1.00 g/L	
9/5/11	999 mg/L	rinsed meter, re check @ 1.00 g/L
9/6/11	999 mg/L	rinsed meter, re check @ 1.00 g/L
9/12/11	1.00 g/L	
9/13/11	1.00 g/L	
9/14/2011	1.00 g/L	
9/15/11	1.00 g/L	
9/16/11	1.00 g/L	
9/17/11	1.00 g/L	
9/27/11	999 mg/L	Rinsed meter probe, re check 1.00 g/L
9/28/11	1.00 g/L	
9/29/11	1.00 g/L	
9/30/11	1.00 g/L	
10/1/11	1.00 g/L	
10/2/11	1.01 g/L	Rinsed meter probe, rechecked @ 1.00 g/L
10/3/11	1.00 g/L	
10/4/11	1.00 g/L	
10/5/11	1.00 g/L	
10/6/11	1.00 g/L	
10/7/11	1.00 g/L	
10/14/11	1.00 g/L	
10/15/11	999 mg/L	rinsed meter, re check @ 1.00 g/L
10/16/11	1.00 g/L	
Oct/17/11	1.01 g/L	rinsed meter probe, retest @ 1.00 g/L
10/18/11	1.00 g/L	
10/19/11	1.01 g/L	rinsed meter, new TDS @ 1.00 g/L
10/20/11	998 mg/L	rinsed meter, re check @ 1.00 g/L
10/21/11	1.00 g/L	
10/22/11	1.00 g/L	
10/23/11	1.00 g/L	

Appendix B: Data Set for Equation 4.2 with Estimated Production

Day	Temperature (Celsius)[a]	Wind Speed (m/s)[b]	Solar Insolation (kWh/m^2-day)[a]	Glass Cover Angle	Depth Ratio	Brine TDS (mg/L)	Manser 2012 Predicted Volume (mL/m^2-day)	Measured Volume (mL/m^2-day)
1/5/2011	16.89	4.01	2.73	19.88	0.14	1100	1768.1	
1/15/2011	12.3	4.01	2.38	19.88	0.14	1100	1775.1	
1/25/2011	15.28	4.01	3.06	19.88	0.14	1100	1775.1	
2/5/2011	9.76	4.15	2.75	19.88	0.14	1100	2114.7	
2/15/2011	14.93	4.15	3.48	19.88	0.14	1100	2110.2	
2/25/2011	19.69	4.15	2.59	19.88	0.14	1100	2090.2	
3/5/2011	20.8	4.37	2.99	19.88	0.14	1100	2610.2	
3/15/2011	15.96	4.37	3.59	19.88	0.14	1100	2627.5	
3/25/2011	23.3	4.37	4.04	19.88	0.14	1100	2615.2	
4/5/2011	21.29	4.26	3.74	19.88	0.14	1100	2357.5	
4/15/2011	24.48	4.26	3.58	19.88	0.14	1100	2348.5	
4/25/2011	25.55	4.26	4.39	19.88	0.14	1100	2354.3	
5/5/2011	19.38	3.9	4.25	19.88	0.14	1100	1518.6	
5/15/2011	24.1	3.9	3.69	19.88	0.14	1100	1502.0	
5/25/2011	27.9	3.9	4.02	19.88	0.14	1100	1496.6	
6/5/2011	22.86	3.7	3.79	19.88	0.14	1100	1034.5	
6/15/2011	25.5	3.7	4.68	19.88	0.14	1100	1037.5	
6/25/2011	24.36	3.7	4.41	19.88	0.14	1100	1037.4	
7/5/2011	21.14	3.88	4.44	19.88	0.14	1100	1469.3	
7/15/2011	22.2	3.88	4.54	19.88	0.14	1100	1467.9	
7/25/2011	21.16	3.88	4.77	19.88	0.14	1100	1472.6	
8/5/2011	22.25	3.76	4.56	19.88	0.14	1100	1185.2	
8/15/2011	23.19	3.76	4.28	19.88	0.14	1100	1180.1	1102
8/25/2011	23.23	3.76	3.46	19.88	0.14	1100	1171.7	
9/5/2011	21.92	3.62	3.07	19.88	0.14	1100	840.7	1010
9/15/2011	23.07	3.62	3.79	19.88	0.14	1100	845.4	826
9/25/2011	20.16	3.62	3.67	19.88	0.14	1100	850.9	796
10/5/2011	18.81	3.6	3.41	19.88	0.14	1100	804.2	780
10/15/2011	19.67	3.6	3.34	19.88	0.14	1100	801.5	903
10/25/2011	16.91	3.6	3.67	19.88	0.14	1100	811.2	841
11/5/2011	10.5	3.93	3.39	19.88	0.14	1100	1600.9	
11/15/2011	20.4	3.93	3.1	19.88	0.14	1100	1575.2	
11/25/2011	17.46	3.93	2.54	19.88	0.14	1100	1576.3	
12/5/2011	13.52	3.9	2.7	19.88	0.14	1100	1516.2	
12/15/2011	12.13	3.9	2.58	19.88	0.14	1100	1518.2	
12/25/2011	13.29	3.9	2.35	19.88	0.14	1100	1513.2	

Appendix C: Permissions

C.1 IWMI (2007) Permission

FW: request for permission to use map USF/Thesis x

De Silva, Sanjiv (IWMI) S.S.DESILVA@cgiar.org
to me

Feb 17 (4 days ago)

Dear Nathan,

Thanks you for your interest in using our work. Please go ahead and use the map with the standard reference practice.

Kind regards,

Sanjiv de Silva
Intellectual Property Focal Point
International Water Management Institute
127, Sunil Mawataha,
Battaramulla, Palawatte,
Sri Lanka
+94 11 2880000

Appendix C (Continued)

C.2 Torchia-Nunez et al. (2008) Permission

This is a License Agreement between Nathan D Manser ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

All payments must be made in full to CCC. For payment instructions, please see information listed at the bottom of this form.

Supplier	Elsevier Limited The Boulevard,Langford Lane Kidlington,Oxford,OX5 1GB,UK
Registered Company Number	1982084
Customer name	Nathan D Manser
Customer address	19817 Haapapuro Road Houghton, MI 49931
License number	2837220431282
License date	Jan 27, 2012
Licensed content publisher	Elsevier
Licensed content publication	Renewable Energy
Licensed content title	Exergy analysis of a passive solar still
Licensed content author	J.C. Torchia-Núñez,M.A. Porta-Gándara,J.G. Cervantes-de Gortari
Licensed content date	April 2008

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

20. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of the complete thesis and include permission for UMI to supply single copies, on demand, of

Appendix C (Continued)

C.3 Al-Hanai et al. (2002) Permission

This is a License Agreement between Nathan D Manser ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

Supplier	Elsevier Limited The Boulevard,Langford Lane Kidlington,Oxford,OX5 1GB,UK
Registered Company Number	1982084
Customer name	Nathan D Manser
Customer address	19817 Haapapuro Road
	Houghton, MI 49931
License number	2835610728102
License date	Jan 24, 2012
Licensed content publisher	Elsevier
Licensed content publication	Energy Conversion and Management
Licensed content title	Effect of climatic, design and operational parameters on the yield of a simple solar still
Licensed content author	H. Al-Hinai,M.S. Al-Nassri,B.A. Jubran
Licensed content date	September 2002
Licensed content volume number	43
Licensed content issue number	13

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

20. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of

Appendix C (Continued)

C.4 Khalifa (2011) Permission

This is a License Agreement between Nathan D Manser ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

Supplier	Elsevier Limited The Boulevard,Langford Lane Kidlington,Oxford,OX5 1GB,UK
Registered Company Number	1982084
Customer name	Nathan D Manser
Customer address	19817 Haapapuro Road
	Houghton, MI 49931
License number	2847080226912
License date	Feb 13, 2012
Licensed content publisher	Elsevier
Licensed content publication	Energy Conversion and Management
Licensed content title	On the effect of cover tilt angle of the simple solar still on its productivity in different seasons and latitudes
Licensed content author	Abdul Jabbar N. Khalifa
Licensed content date	January 2011
Licensed content volume number	52
Licensed content issue number	1

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

20. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of

Appendix C (Continued)

C.5 Khalifa et al. (2009) Permission

This is a License Agreement between Nathan D Manser ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

Supplier	Elsevier Limited The Boulevard,Langford Lane Kidlington,Oxford,OX5 1GB,UK
Registered Company Number	1982084
Customer name	Nathan D Manser
Customer address	19817 Haapapuro Road
	Houghton, MI 49931
License number	2847081454990
License date	Feb 13, 2012
Licensed content publisher	Elsevier
Licensed content publication	Desalination
Licensed content title	Performance correlations for basin type solar stills
Licensed content author	Abdul Jabbar N. Khalifa,Ahmad M. Hamood
Licensed content date	30 November 2009
Licensed content volume number	249

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

20. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of

Appendix C (Continued)

C.6 Nafey et al. (2001) Permission

This is a License Agreement between Nathan D Manser ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

Supplier	Elsevier Limited The Boulevard,Langford Lane Kidlington,Oxford,OX5 1GB,UK
Registered Company Number	1982084
Customer name	Nathan D Manser
Customer address	19817 Haapapuro Road
	Houghton, MI 49931
License number	2847090836954
License date	Feb 13, 2012
Licensed content publisher	Elsevier
Licensed content publication	Energy Conversion and Management
Licensed content title	Solar still productivity enhancement
Licensed content author	A.S Nafey,M Abdelkader,A Abdelmotalip,A.A Mabrouk
Licensed content date	July 2001
Licensed content volume number	42
Licensed content issue number	11

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

20. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of

Appendix C (Continued)

C.7 El-Sebaii (2004) Permission

This is a License Agreement between Nathan D Manser ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

Supplier	Elsevier Limited The Boulevard,Langford Lane Kidlington,Oxford,OX5 1GB,UK
Registered Company Number	1982084
Customer name	Nathan D Manser
Customer address	19817 Haapapuro Road Houghton, MI 49931
License number	2847100046667
License date	Feb 13, 2012
Licensed content publisher	Elsevier
Licensed content publication	Energy Conversion and Management
Licensed content title	Effect of wind speed on active and passive solar stills
Licensed content author	A.A. El-Sebaii
Licensed content date	May 2004
Licensed content volume number	45

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

20. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of

Appendix C (Continued)

C.8 Murugavel et al. (2008) Permission

This is a License Agreement between Nathan D Manser ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

Supplier	Elsevier Limited The Boulevard,Langford Lane Kidlington,Oxford,OX5 1GB,UK
Registered Company Number	1982084
Customer name	Nathan D Manser
Customer address	19817 Haapapuro Road
	Houghton, MI 49931
License number	2837230077518
License date	Jan 27, 2012
Licensed content publisher	Elsevier
Licensed content publication	Desalination
Licensed content title	Progresses in improving the effectiveness of the single basin passive solar still
Licensed content author	K. Kalidasa Murugavel,Kn.K.S.K. Chockalingam,K. Srithar
Licensed content date	1 March 2008
Licensed content volume number	220
Licensed content issue number	1–3

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

20. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of

Appendix C (Continued)

C.9 Samee et al. (2007) Permission

This is a License Agreement between Nathan D Manser ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

Supplier	Elsevier Limited The Boulevard,Langford Lane Kidlington,Oxford,OX5 1GB,UK
Registered Company Number	1982084
Customer name	Nathan D Manser
Customer address	19817 Haapapuro Road
	Houghton, MI 49931
License number	2847210212964
License date	Feb 13, 2012
Licensed content publisher	Elsevier
Licensed content publication	Renewable and Sustainable Energy Reviews
Licensed content title	Design and performance of a simple single basin solar still
Licensed content author	Muhammad Ali Samee,Umar K. Mirza,Tariq Majeed,Nasir Ahmad
Licensed content date	April 2007
Licensed content volume number	11
Licensed content issue number	3

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

20. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of

Appendix C (Continued)

C.10 Hanson et al. (2004) Permission

This is a License Agreement between Nathan D Manser ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

Supplier	Elsevier Limited The Boulevard,Langford Lane Kidlington,Oxford,OX5 1GB,UK
Registered Company Number	1982084
Customer name	Nathan D Manser
Customer address	19817 Haapapuro Road
	Houghton, MI 49931
License number	2847210835753
License date	Feb 13, 2012
Licensed content publisher	Elsevier
Licensed content publication	Solar Energy
Licensed content title	Distillate water quality of a single-basin solar still: laboratory and field studies
Licensed content author	A Hanson,W Zachritz,K Stevens,L Mimbela,R Polka,L Cisneros
Licensed content date	2004
Licensed content volume number	76
Licensed content issue number	5

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

20. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of