Water Purification with Direct Solar Desalination for Arid Areas in Ethiopia

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Abstract

The use of solar energy in thermal desalination processes is one of the most promising applications of in water purification. Solar desalination can either be direct; use solar energy to produce distillate directly in the solar collector, or indirect; combining conventional desalination techniques, such as vapor compression (VC) and multistage flash desalination (MSF), with solar collectors for heat generation. This paper describes a pilot study of direct desalination technology. The pilot experiment of desalination system was made up of a single basin (1.5m x 1.8m basin area) and two sided roof with 15 degree to the horizontal and sealed roof of 4 mm thick glasses. The glass cover roof was positioned from East to West orientation and obstruction free area to increase the efficiency of available sunlight utilization. Water quality parameters of the water and treated water were tested at Arba Minch University Water quality Laboratory. The study revealed that, the average yield of the distillate water was 2.6 L/m^2/ day, where the average efficiency of the system was 29.5 %. Regression analysis showed that climatic variables such as temperature, wind speed and solar intensity were observed to affect the treatment efficiency of the production of distilled water in this pilot study. Accordingly, the experiment output transposed to Dollo Ado, Somali Regional state and the solar still was predicted to produce 3.4 - 5 L/m^2/day with climate condition of the area. Although the system requires large area with relatively low production, it is still suitable for use in remote and arid with high temperature.

Keywords: Arba Minch; arid regions; desalination; Dollo Ado; solar still; distillate yield

1. Introduction

Although water is abundant on our planet, it is a scarce resource from readily availability point of view. Only about 3% the global water resources is fresh water, which still exist in different forms: 77% in ice, 22 % in ground water and 1% available in lakes, rivers and streams (Kalogirou, 2005; El-Ghonemy, 2012; Gorjian et al., 2014). Most of the water available on earth has salinity up to 10,000 ppm. Moreover, seawater and brackish water could have extremely high (35,000 - 45,000 ppm) in terms of total dissolved solids (Tiwari, et al. 2003). Likewise, the quality of ground water is highly influenced by the geogenic solutes that could cause salinity and induce sensitive trace elements. The WHO guideline suggests the amount of dissolved solids to be 1000 ppm an acceptable limit for potable water quality standard (WHO, 2006). Thus, only about 0.05% is global fresh water which is readily available for human consumption and in the context of Sub-Saharan countries the most accessible source is ground water (Groundwater glossary, 2006).

Hence, groundwater is one of the major drinking water sources for many countries worldwide including Ethiopia. In Ethiopia the use of surface water and rain water harvesting is practiced at lower scale, majority of low land areas, which are characterized by arid and semi-arid climate use groundwater for domestic water supply. However, salinity has become a challenge for the provision of potable water from groundwater in the land areas of the country, particularly in the Somali regional state. Dollo Ado district is one of the districts of the Somali regional state, where this study was conducted. Bore holes at Dollo Ado district have concentrations of total dissolved solids (TDS) ranging between (3000- 4000 mg/L), total hardness (1000-2000 mg/L), chloride (1000-2000mg/L) and sulphate (> 500mg/L) (Kalab, 2013). Moreover, the coverage of clean water supply is very low in the area (Kene. 2011). Therefore, provision of low cost and affordable technologies is crucial to amend the saline water of deep boreholes at least for drinking purpose.

The use of solar energy in thermal desalination processes is one of the most promising applications of the renewable energies. Solar desalination can either be direct; use solar energy to produce distillate directly in the solar collector, or indirect; combining conventional desalination techniques, such as vapor compression (VC) and multistage flash desalination (MSF), with solar collectors for heat generation. The better option in terms of production cost is the direct use of solar energy in desalination processes (El-Sayed Gabr, 2007). Therefore, direct solar desalination can be considered as an affordable means of water desalination in tropical regions, since solar energy is available uniformly throughout the year.

This research aims at investigating direct solar desalination technology for the selected study area, quantity of the yield of the system, the efficiency of salt removal, the effect of climate on the treatment process and developing a mathematical relation between yield and climate variables. The pilot study was conducted at Arba Minch University and the results are transposed to Dollo Ado district based on the mathematical relations that found to affect the production most.

2. Materials and Methods

The description of the study area, experimental setup and operation of the solar still, synthetic saline solution preparation and water quality analysis, model development and prediction of the distillate yield are described in this section.

2.1. Description of the study area

Dolo Ado is one of the districts in the Somali Regional state of Ethiopia with a total area of 4640.8 km^2 and stretched in the altitudinal range between 200 and 1000 meters above sea level (Wikpedia, 2017). The climate of the district is semi-arid in the northwest and arid in the southern part with average minimum and maximum temperature of 22^0C and 35^0C, respectively. The rainfall pattern of the study area is bimodal and erratic with average monthly rainfall of 112.4 mm. The Somali regional state is characterized by water scarce region with a few areas assessed to perennial rivers (Wabwshebele and Genale rivers) and the majority of the area relay on deep groundwater aquifers which are partly salty. Some water quality parameters of boreholes in Somali region are excessive beyond the acceptable limit for domestic use: TDS, 3000 - 4000 mg/l; total hardness, 1000- 2000; chloride, 1000 -2000, and sulphate, >500mg/l at some wells (SHACC Consulting, 2011 and Kalab, 2013). Moreover, the drinking water supply coverage of the region is estimated to be 58.8% (Kene. 2011). Population growth and livestock number increases the demand to provide sufficient water to the population in an effective, economical and sustainable manner.

2.2. Experimental setup and operation of the solar still

A concrete basin with double slope solar still was constructed as shown in Figure 1. The basin has dimensions of 1.8 m length, 1.5 m width and 0.027 m depth. The roof is made from 4 mm thick plain glass (available at local market) and framed with a galvanized iron. The slope of the glass roof is tilted 15^0 from the horizontal on both sides and positioned in East and West directions to access the incoming sun radiation throughout the day. The joints of the system were sealed with silicon sealant to make the system vapor tight. Moreover, the base of the still was made of water proof masonry block with the dimensions of 2.2 m long, 1.95 m wide, and 0.40 m high above the ground. The floor of the still was coated by black paint to enhance maximum absorption of light energy.

Figure 1. Photo of solar still desalination set up (*modified from Sardella, et al, 2012)*

The condensed water was collected at the lower edges of the still with a V-shaped gutter (1^0 inclinations) and directed to the storage through the collection pipe as shown in Figure 1. The raw water feeding inlet was installed on the opposite side of the distillate collection and the sludge removal outlet was installed at the bottom of the basin.

The operation time of the experiment was from 8:30 to 18:50 hour. The experiment was conducted batch-wise for four days duration after adding fifty liters of raw water. During operations, air temperature and distillate yield was measured and the weather data records were taken from an automatic weather station of the university.

2.3. Preparation of synthetic saline solution and water quality analysis

Sodium chloride salt was used to prepare 2500- 3000 mg/L of synthetic saline solution to bring the salinity of water from the university boreholes water to simulate to the level of salinity with the water quality of the Dollo Ado district's borehole water. The synthetic water and distillate water were analyzed before and after the treatment for the selected water quality parameters such as, total dissolved solid (TDS), electrical conductivity and pH using HACH HQ40D multi-meter following Standard Methods (APHA 2005). The analysis was tripled for the same sample to avoid workmanship errors. The distillate water quality was evaluated based on the WHO (2011) standards for drinking water purpose.

2.4. Development of mathematical model

In order to develop a general formula from the collected data at Arba Minch, multiple regression analysis using Microsoft EXCEL (Stephen *et al.* 2013) was done between the dependent variable (distillate yield) and independent variables (wind speed, temperature, relative humidity, and solar radiation) collected from Arba Minch metrological station located in the University. Statistically non-significant other independent variables were omitted and the significant variables on the distillate yield were included in the general regression equation.

Multiple regressions analysis was performed for the solar still using wind speed, temperature and humidity as independent variables represented with X1, X2, X3 and X4, respectively while yield was denoted as Y. Thus, the general formula is presented in the following equation.

$$Y = b_0 + b_1 x_1 + b_2 x_2 + ... + b_n x_n \quad (1)$$

Where b_o = intercepts;

b_1 = Coefficient of X_1 variable (daily solar radiation);

b_2 = Coefficient of X_2 variable (wind speed);

b_3 = Coefficient of X_3 variable (average temperature);

b_4 = Coefficient of X_4 variable (average relative humidity);

n= the number of climate variables.

Regression analysis was conducted on 24 observations in order to identify significant variable (intercept, solar radiation, wind speed, temperature and relative humidity) at 95% confidence level; the output variable was significant if the $P< 0.05$ and not significant when $P>0.05$. The prediction was done for Dollo Ado district, by assuming the implementation of the same type of solar still. This regression model coefficients and constants identified were applied to predict distillate yield at different climatic conditions.

3. Results and Discussion

In this section, the amount of distillate produced, efficiency of the solar still, the level of water quality of the distillate and the effect of the climatic conditions on the yield of the distillate from the experiment are discussed. Moreover, the implication of the same system in Dollo Ado district will be explained.

3.1. Yield of the distillate and required size for a family

At Arba Minch University, the average production (yield of the treatment) of the solar still was 2.6 l/m2/day. This result agrees with the findings of different scholars such as; Kalidasa et al., 2008; Kabeel et al., 2011; and Tiwari et al., 2003. According to the study, the average yield of a solar still of this kind could fall between 2 and 5 l/m2/day for an area which has similar climatic condition with Arba Minch.

According to the recommendation of by Sphere Project (2011), the minimum demand of water for drinking and cooking per person per day is about 6 liters (Table 1). WHO (2003) also recommended 20 litres per capita per day as minimum requirement to assure basic food and hygiene. Of these 20 litres, only 2-3 litres are the actual recommended daily fluid intake. According to the output of the experiment at Arba Minch, this demand can be satisfied with approximately 2 m^2 area of the solar still. For a family size of 6 (average family size of Somali Region), 6 m^2 solar still may be required for producing drinking water or 12 m^2 for both cooking and drinking based on the Arba Minch climatic conditions. However, it is needed to estimate the productivity of the same size solar still for at Dollo Ado climatic conditions.

Table 1: The water demand for survival and cooking

Type of need	Demand (liters per day per person)
Survival water	2.5-6
Hygiene	2-6
Cooking needs	3-6
Basic water needs	7.5-15

Source: Sphere Project (2011)

The rate of production of water from the same solar still at Dollo Ado, Somali Region was predicted in Table 3 which ranges between 3.5 to 5 liters of water per a unit of area. This is better than the production rate at Arba Minch. The implication of this result is that, the surface area requirement of a given volume could decrease at Dollo Ado, and thus, reduce the expenditure for construction material which in turn improves the demand and acceptance the technology by the communities because of its affordability.

3.2. Efficiency of the solar still

According to Al-Hayek, et al. (2004), efficiency is the ratio of the sum of the quantity of heat from sunlight that is transferred to the water for evaporation and condensation to the total daily radiation that falls on the device. The average efficiency of the developed experimental system was 29.5 %, and a minimum of 16 % and with a maximum of 39 % under local conditions. This is in close agreement with the general efficiency range of solar stills (Kabeel, et al., 2011). According to these authors, the efficiency of solar stills is in the range of 25%- 40% during cloudy days and 30%-60% on sunny days.

3.3. Water quality of the distillate

The average distillate water quality produced from the solar still had a total dissolved solid (TDS) of 38.7 mg/l, a conductivity of 79.8 µs/cm and pH of 6.7 and all the values are within the WHO standards for the drinking water (WHO, 2006). It is also proved that nitrates, chlorides, iron, heavy metals and dissolved solids can be completely removed from solar still (Al-Hayek, et al., 2004).

The solar still system and the way it process the water also proved to be effective in the destruction and isolation of microbiological organisms present in the raw water (Al-Hayek et al. 2004). This is an interesting simple technology to provide clean water for areas with low sanitation like Dollo Ado, whose sanitation coverage is only limited to about 11% (Somali regional state, 2010) and wide use of open defecation. This study has also proved that the quality of the distilled water produced from the solar still experimental setup did not vary with time, temperature and concentration of the raw water.

3.4. Effect of climatic conditions on distillate yield

From the analysis, temperature, wind speed and solar radiation were significant while relative humidity was not significant (P= 0.46) on the production of water distillate. Relative humidity is not significant because the solar still is not exchanged mass (that is vapor) with the external environment as it is sealed and saturated in the solar still. If the system were open to the environment, then the effect of relative humidity would have been significant. The rate of evaporation at a given place is always dependent on the humidity of that place because if the air is already filled with water vapor, it will not have any place to hold the excess vapor and therefore, evaporation will occur at an extremely slow rate.

The cooling of the condensing cover was improved when wind was blowing over solar still. It is a concept that the higher the air flows over the condensing cover, the higher the convective heat loss to the ambient air. Therefore, a place with high wind speed has a high significance effect on the production of distillate. Temperature and solar radiation were also significant as they directly heat up the water in the solar still which results in evaporation and finally to condensation.

The regression analysis was conducted again omitting relative humidity to obtain the coefficients and the significance. The regression output results are presented in Table 2.

Table 2: Summary of the regression output

Regression Statistics						
Multiple R	0.97					
R Square	0.94					
Adjusted R Square	0.93					
Standard Error	0.23					
Observations	24					
ANOVA						
	Df	***SS***	***MS***	***F***	***Significance F***	
Regression	3	17.187	5.729	105.425	1.99 E-12	
Residual	20	1.087	0.054			
Total	23	18.274				
	Coefficients	***SE***	***t-Stat***	***P-value***	***Lower 95%***	***Upper 95%***
Intercept	-7.194	0.625	-11.515	2.81E-10	-8.497	-5.890
Solar radiation	0.647	0.099	6.538	2.26E-06	0.440	0.853
Wind speed (m/s)	0.540	0.250	2.162	0.043	0.019	1.062
Temperature (^{0}C)	0.185	0.022	8.336	6.13E-08	0.139	0.231

Based on the analysis result shown in Table 2, the intercept solar radiation, wind speed and temperature was found to be significantly affecting the yield of distill water of the solar still. Therefore, the regression equation can be given as equation 2.

$$DW = -7.194 + 0.647\ SRD + 0.540WS + 0.185\ T \qquad (2)$$

Where, DW= distilled water yield ($l/m^2/day$);

SRD = daily solar radiation intensity (Kwh/m^2);

WS = wind speed (m/s);

T = temperature (^0C).

Based on the adopted regression formula, the performance of the solar still desalination can be predicted by substituting solar radiation, temperature and wind speed of a given location in Equation 2. Therefore, a location that has high solar radiation, temperature and wind speed compared to Arba Minch is expected to produce better quantity of distillate. It can also be concluded that distillate water yield is directly related to daily solar radiation, wind speed and temperature.

The yield of distillate at Dollo Ado was predicted using equation 2 as in Table 3 and is higher than the Arba Minch distillate yield.

Table 3: Amount of distilled water calculated by replacing Dollo Ado temperature, solar radiation and wind speed condition in Equation 2.

SRD (X1) (Kwh/m^2)	WS (X2), (m/s)	T (X3) (^0C)	Predicted DW (Y), (litres)
5.97	3.05	30.98	4.5
5.90	3.53	31.48	4.8
5.54	3.76	29.67	4.3
5.06	3.18	28.22	3.4
5.71	3.23	30.04	4.2
5.01	3.32	28.05	3.4
6.43	3.13	32.13	4.9
6.41	3.02	32.31	5.0
5.98	3.41	31.17	4.7
6.06	3.59	31.07	4.9
5.45	3.65	29.47	4.2
5.35	4.76	28.31	4.5
5.44	3.20	29.15	3.8
5.92	3.42	30.84	4.6
5.96	3.67	30.89	4.8
5.64	3.45	29.85	4.3
6.05	3.49	31.80	4.9
5.77	3.47	30.12	4.4
5.85	3.53	30.56	4.6
6.34	3.58	30.88	5.0
6.30	3.67	31.05	4.9
6.16	3.49	32.01	5.0
5.87	3.36	30.59	4.5
5.99	3.18	31.46	4.7
Average			4.5 ± 0.47

Based on the calculated value at Dollo Ado with the local temperature, wind speed and solar intensity, 3.4 to 5 liters per meter square per day of water can be produced. The size of solar still required to produce the same amount of water at Dollo Ado could be less than that of the Arba Minch town to obtain the same distillate yield.

4. Conclusions

With a square meter trough area of water still, it is possible to produce a maximum of 5 liters per day at Dollo Ado district free of bacteria and ions (very low salinity). The generated model relation can be used to predict the sizing of the solar still in any place.

Direct solar desalination technique, although requires large area and has a relatively low distillate water production is suitable for use in remote areas, especially in areas with high temperature and the available natural water is saline. This applies to tropical and least developed countries which have low capital income to invest for high technologies. The method can also be applied to water sources which are prone to pathogenic contamination where sanitation is coverage is low. Solar stills are competitive to the indirect desalination plants in small-scale production due to their relatively low cost, simplicity and long term use. Thus, the developed formula can be used to estimate the yield with a given climatic variables. Further research is required to make the setup mobile with other alternative materials.

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References

Al-Hayek, I., Badran, O.O. (2004). The effect of using different designs of solar stills on water distillation. Desalination.

APHA 2005 Standard Methods for the Examination of Water and Wastewater, 21st edn, American public Health Association (APHA), American Water works Association (AWWA), and the Water Environment Federation (WEF), Washington, DC.

El-Ghonemy M.K. (2012).Water desalination systems powered by renewable energy sources: review. Renew Sustain Energy Rev 16(3):1537–56.

Groundwater Glossary. 27 March 2006. Retrieved 26 May 2017.

Kalogirou S. (2005). Seawater desalination using renewable energy sources. Prog. Energy Combust Sci.

Gorjian, S., Ghobadian B, Tavakkoli Hashjin T, Banakar, A. (2014). Experimental performance evaluation of a stand-alone point-focus parabolic solar still. Desalination.

http://www.unf.edu/~dtanner/dtch/dt_ch6.htm accessed 25 May 2017: linear regression using Excel 2010

El-Sayed Gabr, I.K. (2007). Experimental and Numerical Optimization of Reverse Osmosis Desalination Plant. MSc. Thesis, 31-35.

Kabeel, A.E. and El-Agouz, S.A. (2011). Review of researches and developments on solar stills. Elsevier: Desalination 276:1-12.

Kalidasa Murugavel, K., Chockalingam, Kn.K.S.K. and Srithar, K. (2008) Progress in improving the effectiveness of the single basin passive solar still. Elsevier: Desalination 220:667-686.

Kalab (2013) Feasibility study of Dollo Ado woreda, Interoxfam, Addis Ababa, Ethiopia

Kene, H.E. (2011). Baseline Survey of 55 Weredas of PCDP Phase II, Part I Archived July 20, 2011, at the Wayback Machine. (Addis Ababa: August 2008), Annexes 16 & 17.

Sardella, C. S., Waterloo, M. J., de Haas, S., Gijsbertsen, C. (2012). Evaluation of the implementation of the solar still principle on runoff water reservoirs in Budunbuto, Somalia. Thematic research M. Sc. Hydrology, Vrije Universiteit Amsterdam, 1-15.

SHACC Consulting. (2011). Hydrogeological investigation of 19 sites in Gode, Afder, Liban, Dhagahbu, Korahe, and Warder Zones SRS of Ethiopia final draft report.

Somali Regional state (2010). Five year strategic plan, SPM draft, Agriculture sector,, Jigjiga, Ethiopia.

Stephen, L., Nelson, E., Nelson, C. (Excel 2013). How to use the Regression Data Analysis Tool in Excel: http://www.dummies.com/software/microsoft-office/excel/how-to-use-the-regression-data-analysis-tool-in-excel; Accessed 04/01/2018.

The Sphere Handbook (2011). The humanitarian Charter and Minimum Standards in Humanitarian Response.

Tiwari, G.N., Singh, H.N. and Tripathi, R. (2003). Present status of solar distillation. Elsevier: Solar Energy 75:367-373.

WHO (World Health Organization) (2003). Domestic water quantity, service level and health. Geneva, Switzerland.

WHO (World Health Organization) (2011). Guidelines for drinking-water quality: fourth edition, Geneva, Switzerland.

WHO (World Health Organization) (2006). Guidelines for drinking-water quality [electronic resource]: incorporating first addendum. Vol. 1, Recommendations. – 3rd ed. Geneva, Switzerland.

Wikipedia (2017) https://en.wikipedia.org/wiki/ Dolo Ado, accessed 24 May 2017: Dollo Ado.