Evaluation of the implementation of the solar still principle on runoff water reservoirs in Budunbuto, Somalia.

Carolina S.E. Sardella
1617370

Supervisors:
Maarten J. Waterloo (VU Amsterdam)
Sander de Haas (SamSamWater Foundation)
Cedrick Gijsbertsen (SamSamWater Foundation)

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Carolina S.E. Sardella, VU University, Faculty of Earth and Life Sciences, Department of Hydrology and Geo-Environmental Sciences, De Boelelaan 1085 HV, Amsterdam, e-mail: csa800@student.vu.nl

Abstract

The availability of fresh water resources and their quality is essential for poverty reduction in rural areas of numerous developing countries worldwide. This study focuses on the improvement of the water resources in the village of Budunbuto, in north-eastern Somalia. The objective is to evaluate the applicability of the solar still principle on surface water runoff reservoirs (so-called *berkads*), widely used in the study area. A solar still consist of an airtight basin, in which saline or contaminated water is evaporated and condensed on the top cover for collection. The collected water has been purified during the process and can be used as drinking water. The implementation of solar stills is expected to improve both the water availability and quality as it minimizes the evaporation losses from the berkads and, at the same time, it purifies the water. Using the Penman open water equation, it has been calculated that the daily evaporation loss from the berkads varies between 8 and 12 mm/d throughout the year. This is on average about 1.4 m^3/d per berkad. When implementing a solar still on a berkad, the output is estimated to vary between 100 and 590 litres of clean drinking water per day, depending on the efficiency of the system. Rain water harvesting on the top cover of the solar still would produce about 40 m^3 of water a year. This, in combination with the distillate water, would suffice for the drinking water demand of Budunbuto when constructing between 3 and 11 berkads with solar stills. These results indicate that the implementation of solar stills is a feasible measure for Budunbuto, even though there are some uncertainties associated with the results.

Keywords: solar still, berkad, water purification, Somalia

Introduction

The inadequate access to fresh water resources or the inappropriate quality of these same resources is a common problem in developing countries and it forms the major constraint on poverty reduction in these areas (FAO, 2008). The current and predicted climate change will aggravate the water stress presently faced by several developing countries by imposing additional pressures on the availability and demand of water (Boko et al., 2007). Improving the availability of fresh water resources and its quality with simple technological innovations can therefore contribute to a rapid enhancement in the livelihoods of the rural population in these areas.

This research focuses on the improvement of the water quantity and quality in the village Budunbuto, in the Nugaal region in Somalia (Figure 1). The major water source for the nomadic and settled pastoralist population of this area is surface water collected during the rainy season in artificial runoff catchments, which are known as *berkads* (see *Research area*). The current design of the berkads makes them sensitive to pollution as organic matter, animal faeces and garbage can easily end up in the water. Moreover, evaporation of water is estimated to be a great loss.

The objective of this study is to evaluate if the availability of clean fresh water could be improved through the implementation of a solar water purification system (*i.e.* a solar still) on the berkads. The analysis will start with an estimation of the yearly water demand and consumption in Budunbuto. After this, the evaporation loss from the berkads will be calculated. The implementation of a solar still on the berkads is a solution to minimize this evaporation loss and at the same time purify the water. Essential for the applicability of a solar still is to know if the system will be capable of satisfying the water demand of the area. The output of the solar still will therefore be estimated using a theoretical approach. So far, little research has been done regarding the use a solar still for the purification of contaminated fresh water, and thus little is known about the quality of the water produced. This will be shortly discussed in order to establish if the output is of appropriate quality for human consumption.

List of symbols

α	Albedo for open water (0.06)
A	Aperture area of the still (m^2)
c_p	Specific heat of air at constant pressure ($J\ kg^{-1}\ K^{-1}$)
γ	Psychiometric constant ($hPa\ K^{-1}$)
Δ	Change of the saturation vapour pressure with temperature ($hPa\ K^{-1}$)
e	Water vapour pressure in air (hPa)
e_s	Saturation vapour pressure (hPa)
E	Overall efficiency of the solar still (-)
E_a	Aerodynamic component of the evaporation ($W\ m^{-2}$)
E_0	Penman open water evaporation ($W\ m^{-2}$)
G	Daily global solar radiation ($MJ\ m^{-2}$)
λ	Latent heat of vapourization of water ($J\ kg^{-1}$)
n	Duration of bright sunshine (h)
N	Maximum possible sunshine duration (h)
P	Air pressure (hPa)
Q	Daily solar still output ($l\ d^{-1}$)
R_{ln}	Net longwave radiation ($W\ m^{-2}$)
R_n	Net radiation for an open water surface ($W\ m^{-2}$)
$R_s{\downarrow}$	Incoming short-wave solar radiation ($W\ m^{-2}$)
σ	Stefan-Boltzamann constant ($5.670 \cdot 10^{-8}\ W\ m^{-2}\ K^{-4}$)
T	Temperature (K)
u	Wind speed ($m\ s^{-1}$)

Research area

The village Budunbuto is located in the Nugaal region, a semi-desert area in north eastern Somalia (Figure 1). Somalia has an arid to semi-arid climate, where rainfall is the most determining characteristic with its great spatial and temporal variability (Muchiri, 2007).

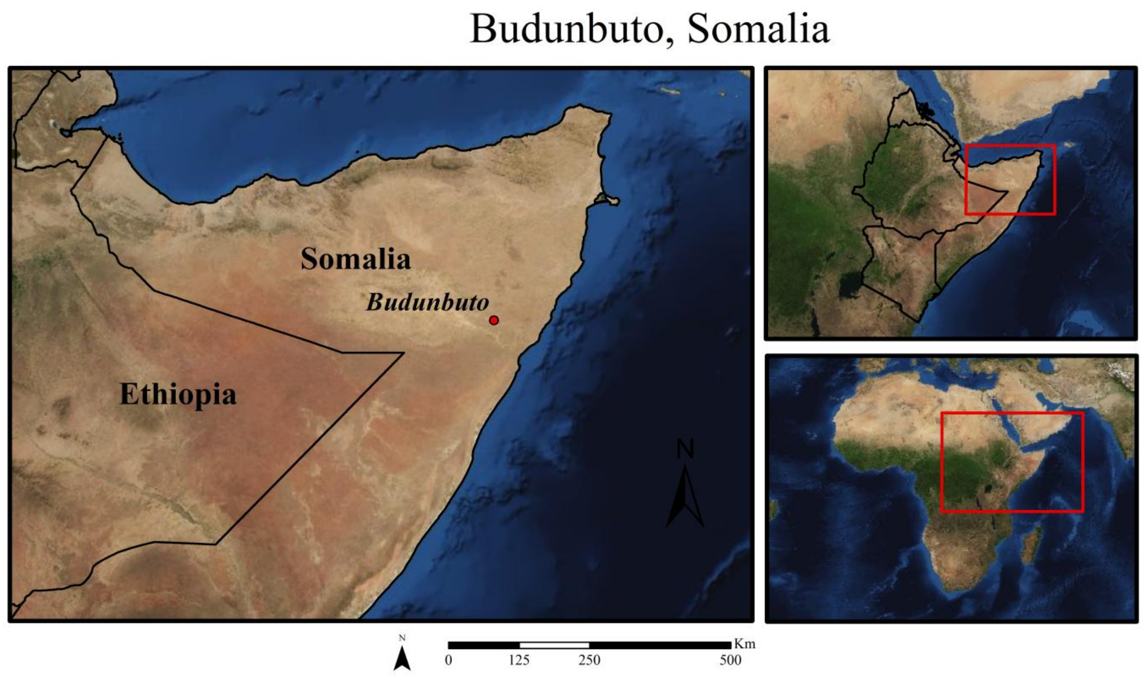

Figure 1: Location of Budunbuto, Somalia.

In general, there are two rainy seasons in Somalia: one in March-June (called *Gu*) and one in October-December (called *Deyr*) (Banks, 2008). The average yearly precipitation in Budunbuto is estimated to be 195 mm and the evapotranspiration is estimated to be about 2400 mm/yr (Figure 2) (FAO Web LocClim). Evapotranspiration is overall higher than precipitation, resulting in a large water deficit all year round. The mean annual temperature is 26.5ºC, with little variation throughout the year (FAO Web LocClim).

From a geological point of view, the research area is located on both Eocene 'Karker' Limestone and Pleistocene and Holocene sands and gravels which are filling the main ephemeral streams (Abbate et al., 1994). The Eocene 'Karker' formation consists of inter-bedded limestone and marls with some gypsum beds (SWALIM, 2009). It is assumed that this formation underlies the sand and gravel filling of the basin.

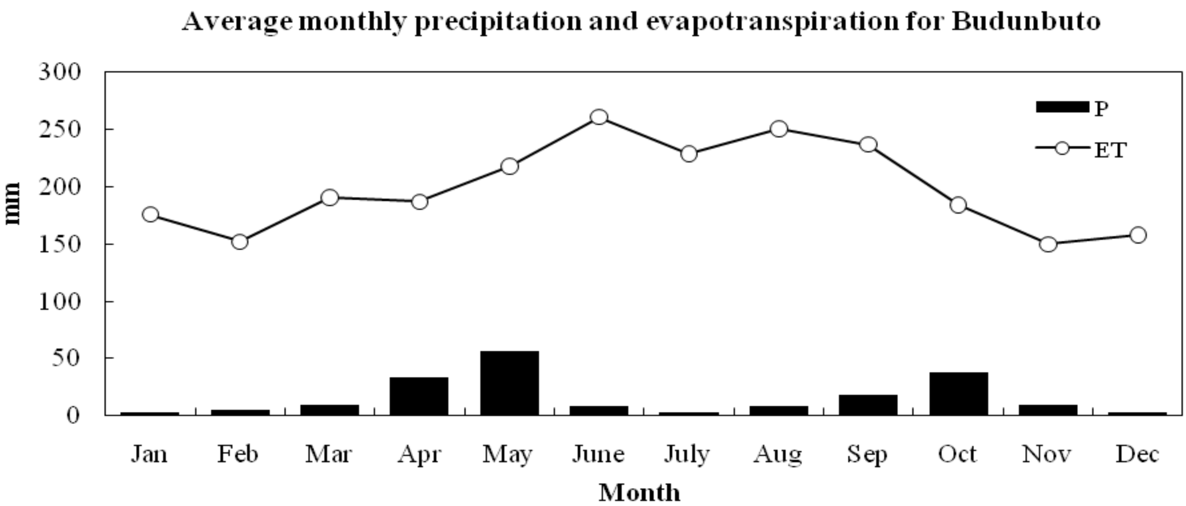

Figure 2: Average monthly precipitation and evapotranspiration for Budunbuto, Somalia (FAO Web LocClim).

Berkads

Berkads are a simple water supply option that is extensively used in Somalia since the 1950's (Brich, 2008). A berkad is an artificial catchment that collects surface runoff that results from intense rainfall episodes. They are usually lined with masonry and/or concrete, and often include on one side a catch-pool that traps the coarse sediment (Figure 3) (Banks, 2008). Berkads are generally constructed in gently sloping areas, where low barriers are sometimes present to direct runoff towards the catch-pool and then to the cistern. During the intense rainfall episodes, berkads may fill up within several hours and last for months throughout a dry period (Banks, 2008).They are the main water source for both the human and livestock water needs. The studied berkads are on average 20 m long, 10 m wide and 3.5 m deep. Their volume thus is 700 m^3.

Figure 3: An example of a berkad in Somalia (Source: Banks, 2008)

Project

In 2010 Kaalo, Wilde Ganzen and SamSamWater Foundation have started a joint project to identify the most suitable option to improve the water supply of Budunbuto village. Berkads seemed to be the best option for the area, but there were major concerns on the water quality of the berkads and the evaporation losses. SamSamWater identified the possibility to reduce evaporation losses and purify the water in the berkads using the solar still concept. Since this concept hasn't been applied before on berkads it was decided to carry out a literature research to determine if the concept is feasible and which output (both in terms of water quantity and quality) can be expected. If the concept seems feasible a pilot project will be constructed and evaluated.

Water demand and consumption

According to the World Health Organization (WHO, 2003) 20 litres of water per capita per day are the minimum requirement to assure the basic hygiene needs and basic food hygiene (WHO, 2003). Of these 20 litres, only 2-3 litres are the actual recommended daily fluid intake. This is the: "*amount that equals losses and prevents adverse effects of insufficient water, such as dehydration*" (WHO, 2004a p. 3). The estimated total water consumption for humans in the study area is 5 litres per day, which is 75% less than the minimum requirement for basic hygiene needs (EC Somalia Unit, 2004).

It is estimated that Budunbuto has a population of about 750 inhabitants, of which 1/3 (250) are nomads (SamSamWater, 2010). Animal husbandry is the main livelihood activity in the area, but it is unknown how many animals come to Budunbuto for watering. It has been chosen to use the data from a comparable village (Heema, about 280 km southwest of Budunbuto) to estimate the number of animals (per capita) in Budunbuto (Table 1) (OTP/CAS, 2005). Based on this information it is possible to calculate the daily and yearly water demand for the area, which is shown in Table 1.

Table 1: Water users and estimated water demand for Budunbuto, Somalia.

Water users	Number	Animals per capita	Consumed water (l/d)	Water demand (m^3/day)	Water demand (m^3/year)
Humans	750	-	20	15	5,500
Camels	1,179	3.7	12	14	5,200
Cattle	2,786	1.6	22.5	63	22,900
Sheep/Goats	5,357	7.1	1.5	8	2,900
Total				100	36,500

The total daily water demand of Budunbuto is 100 m^3. Of this amount, only 2.25 m^3 is for actual human consumption. Only this water should thus be of appropriate bacteriological and mineralogical quality in order to prevent waterborne diseases.

Current evaporation loss

The evaporation of water from *berkads* is calculated using de Bruin and Kohsiek's (1981) adapted formula for the Penman open water evaporation λE_0 (in W m^{-2}):

$$\lambda E_0 = \frac{\Delta R_n + \gamma \lambda E_a}{\Delta + \gamma} \quad (1)$$

Where the change of the saturation vapour pressure with temperature (Δ, in hPa K^{-1}) is calculated with (WMO, 2008):

$$\Delta = \frac{5420.32}{T^2} \exp^{21.6562 - \frac{5420.32}{T}} \quad (2)$$

And where the net radiation for an open water surface (R_n, in W m^{-2}) is given by:

$$R_n = R_s \downarrow (1-\alpha) - R_{ln} \tag{3}$$

Where the net long-wave radiation (R_{ln}, in W m^{-2}) is calculated with (de Bruin and Kohsiek, 1981):

$$R_{ln} = \sigma T^4 (0.53 - 0.67\sqrt{e})(0.2 + 0.8n/N) \tag{4}$$

The duration of the bright sunshine (n in h) has been derived from the following empirical relationship (Rietveld, 1978):

$$R_s = (0.24 + 0.5n/N)R_{ext} \tag{5}$$

The psychometric constant (γ, in hPa K^{-1}) is given by (Bringfelt, 1986):

$$\gamma = \frac{c_p \cdot P}{0.622 \cdot \lambda} \tag{6}$$

And the aerodynamic component of the evaporation is given by (de Bruin and Kohsiek, 1981):

$$\lambda E_a = (3.7 + 4.0u)(e_s - e) \tag{7}$$

Where the latent heat of vaporization of water (λ, in MJ m^{-2}) was calculated with (Bringfelt, 1986):

$$\lambda = 4185.5(751.78 - 0.5655T) \tag{8}$$

The data used for the calculations is shown in Table 2. The results indicate that the open water evaporation in the study area varies between 8 and 12 mm/d. The evaporation loss from one single berkad is calculated to be 1.4 m^3/d on average (Figure 4). This is a significant evaporation loss, which amounts to about 500 m^3/year. This evaporated water from one berkad equals the yearly water demand of about 70 persons (~10% of Budunbuto's population). This result clearly evidences how a reduction in the evaporation loss would result in a significant increase in the water availability in the area.

Table 2: Input parameters for the Penman open water equation.

Month	T* (C)	RH*** (%)	Rs** (J/m2/d)	Rext (J/m2/d)	N (h)	u** (m/s)	z (m)	P (Pa)
Jan	23.3	58.6	22982400	32595696	11.73	5.1	470	95866
Feb	24.0	56.3	23155200	35073457	11.73	4.5	470	95866
Mar	25.7	56.8	25833600	37145163	11.95	4.0	470	95866
Apr	27.6	62.7	23500800	37888029	12.19	3.3	470	95866
May	28.6	58.0	21081600	37232316	12.39	3.9	470	95866
June	28.4	45.5	24364800	36482490	12.49	6.9	470	95866
July	27.9	43.1	24451200	36612305	12.45	7.9	470	95866
Aug	27.9	44.0	23500800	37250299	12.28	6.7	470	95866
Sep	28.4	49.7	26438400	37081618	12.04	5.4	470	95866
Oct	26.8	60.3	24451200	35421366	11.81	3.3	470	95866
Nov	24.7	59.0	23760000	33010488	11.60	3.7	470	95866
Dec	23.7	61.0	23414400	31730188	11.51	4.7	470	95866

* From FAO's Web LocClim, Local Monthly Climate Estimator
** From NASA's Global Land Data Assimilation System (GLDAS)
***From NASA's Surface meteorology and Solar Energy (SSE)

As expected the evaporation from the berkads has a similar pattern to that of the general evapotranspiration in the area. In both it is visible how the evaporation is the highest in the dry months, and it is exactly in those months that the collected water in the berkads is needed the most. Preventing it from evaporating is a significant gain.

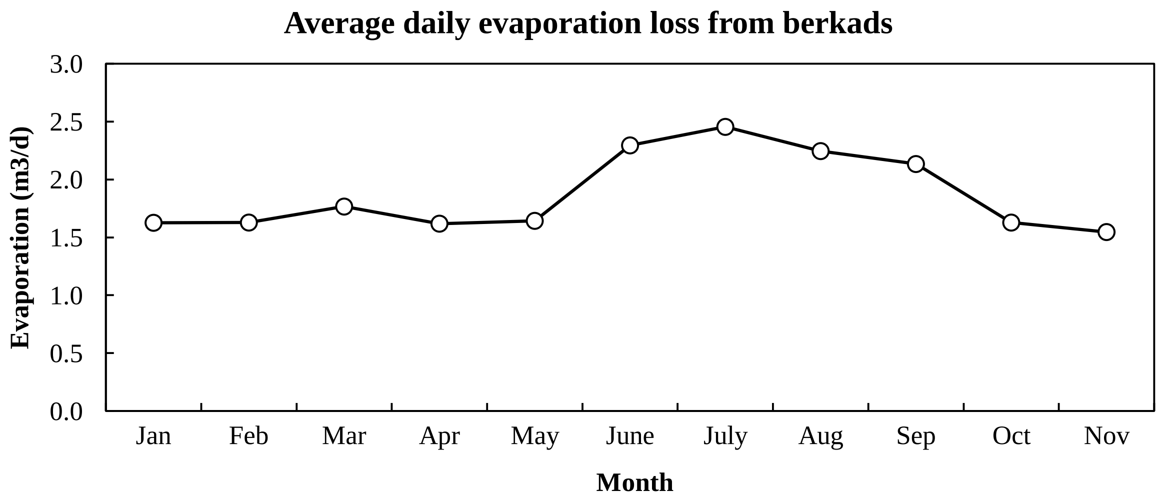

Figure 3. Daily evaporation loss from berkads (m^3/d).

Solar distillation systems

Solar water distillation is a simple, yet effective, technology that has long been used to provide potable water in many remote areas of arid and semi-arid developing countries (Hanson et al., 2004 and Flendrig et al., 2009). The first known use of solar stills dates back to the 16th century, when Arab alchemist used this system to distil water on a small scale (Malik et al., 1982). The first large-scale solar still plant was build at the end of the 19th century in Northern Chile, where a 4460 m^2 basin was providing 22.5 m^3d^{-1} of fresh water (Malik et al., 1982). After that the most significant step in the development of solar stills has been the design of a small scale inflatable plastic still used by the United States armed forces after World War II (Malik et al., 1982 and Howe and Tliemat, 1977). Since then, several solar distillation systems have been developed, patents have been granted and papers have been published (Kabeel and El-Agouz, 2011; Flendrig et al., 2009; Tiwari et al., 2003).

The principle

The basic principle behind solar distillation is simple and replicates the natural process of water purification (Badran, 2007). A solar still is an air tight basin that contains saline or contaminated water (*i.e.* feed water). It is enclosed by a transparent top cover, usually of glass or plastic, which allows incident solar radiation to pass through. The inner surface of the basin is usually blackened to increase the efficiency of the system by absorbing more of the incident solar radiation (Tiwari et al., 2003). The feed water heats up, then starts to evaporate and subsequently condenses on the inside of the top cover, which is at a lower temperature as it is in contact with the ambient air. The condensed water (*i.e.* the distillate) trickles down the cover and is collected in an interior trough and then stored in a separate basin (Al-Hayek and Badran, 2004 and Tiwari et al., 2003). This system is also known as passive solar still, as it operates solely on sun's radiation (Figure 4) (Kalidasa Murugavel et al., 2008).

From a radiative point of view the following happens inside the distiller unit: the part of the solar radiation that is not reflected nor absorbed by the cover is transmitted inside the solar still, where it is furthered reflected and absorbed by the water mass (Tiwari and Singh, 2004). The amount of solar radiation that is absorbed is a function of the absorptivity and depth of the water. The remaining energy eventually reaches the blackened basin liner, where it is mostly absorbed and converted into thermal energy (Tiwari and Singh, 2004). Some of this energy might be lost due to poor insulation of the sides and bottom (Tiwari and Singh, 2004). At this stage, the water heats up, resulting in an increase of the temperature difference between the cover and the water itself. Heat transfer takes then place as radiation, convection and evaporation from the water surface to the inner part of the cover. The evaporated water condenses and releases latent heat. This last one is then lost through convection and radiation together with the remaining convective and radiative heat (Tiwari and Singh, 2004).

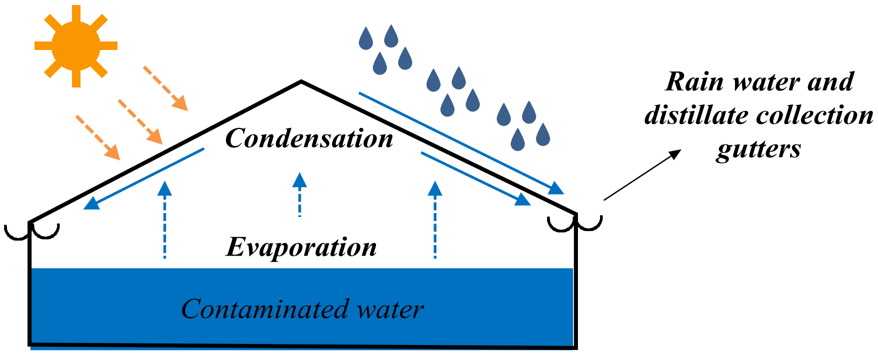

Figure 4. Solar still

Design

In the last decades, several designs for the solar stills have been proposed and investigated. The common objective behind these new designs is to maximize the output by increasing the efficiency of the system. It is possible to classify the passive solar stills as: basin, wick, diffusion or other type of stills (Fath, 1998). For this research, only the single basin horizontal solar stills are relevant, and will therefore be the only stills described and discussed. For more information about the present designs of solar stills it is advised to read Kabeel and El-Agouz (2011) and Tiwari et al. (2003).

There are numerous variations on the single basin still, but the two main categories are single slope and double slope stills (Fath, 1998 and Tiwari et al., 2003). The main difference between these two types of still is that the cover of the double-slope still is of a roof-type, while the single slope still presents just one inclined cover plate. Latitude is one of the factors that determine whether single or double slope still should be used. At latitudes higher than 20°, single slope stills with equator facing cover are recommended (Kalidasa Murugavel et al., 2008). For the study area, which is located at a latitude of 8.5°, both types of still can successfully be used. When the cover is placed with an inclination equal to the latitude angle, it will receive the sun rays close to normal throughout the year (Kabeel and El-Agouz, 2011 and Khalifa, 2010). In this way, maximum interception is achieved. However, fundamental in the design is that the distillate condenses on the top cover as a film rather than as droplets. Droplets might otherwise drop back into the feed water and represent a loss of output. To prevent this from happening, the cover should be set at an angle ≥10º (Practical Action).

Water yield/output

The productivity of solar stills is affected by numerous factors. It is proven that meteorological parameters like solar radiation, sky temperature, wind velocity and ambient temperature affect the performance of solar stills (Kabeel and El-Agouz, 2011; Tiwari et al., 2003 and Garg and Mann, 1976). Factors as the solar still design, the water depth, black dye injection, reduction of the side/bottom heat losses and operational techniques are also considered to affect the output of solar stills (Al-Hayek and Badran, 2004; Fath, 1998 and Tiwari et al., 2003). The output of a solar still has been measured to be on average 2-5 $l/d/m^2$ (Kalidasa Murugavel et al., 2008, Kabeel and El-Agouz, 2011). To estimate the output of a solar still, the following approximation can be used (Twidell and Weir, 2006; Practical Action and Badran and Abu-Khader, 2007):

$$Q = \frac{E \times G \times A}{\lambda} \tag{9}$$

Even though well maintained stills working under optimized operating conditions can reach efficiencies up to 50%, overall efficiencies of 30% are typical for single-basin solar stills (Kabeel and El-Agouz, 2011). The efficiency of a solar still implemented on a berkad, is expected to be equal or lower than 30% because:

- Single basins with a water depth of 0.02 m resulted to have the highest annual yield (Kabeel and El-Agouz, 2011and Tiwari and Tiwari, 2007). The water depth in the berkads can be up to 3.5 m during the rainy seasons (when the berkads are fully filled), which is not optimal. However the distillate output of a single basin solar still is inversely proportional to the water depth for basins with a depth up to about 0.1 m. At greater depths, the yield becomes almost constant (Tiwari and Tiwari, 2007 and Kabeel and El-Agouz, 2011).
- The preferred material for the top cover is glass with a thickness of 3 mm (Kabeel and El-Agouz, 2011). Glass has a higher solar transmittance and a longer lifetime compared to plastic, which is advised to be used for the short-term use only (Kalidasa Murugavel et al., 2008). At the same time, glass is more expensive and fragile. For these reasons it is assumed that the top cover will most likely be of plastic (or plexiglass), thus reducing the efficiency of the system.
- It is expected that it will be hard to minimize side and bottom heat losses as no insulation material will be used (since the solar stills will just be implemented above the already existing berkads). Vapour leakage is also expected to be difficult to minimize in this setting. All this reduces the efficiency of the system as energy that could be used for the evaporation of the water within the still will be lost.

Based on the above assumption s it is possible to state at a high confidence level that that the overall efficiency will be lower than 30%. With this theoretical approach it is however not possible to exactly define what the efficiency of the system will be and for this reason it has been chosen to calculate the output based on different efficiencies (Table 3).

Table 3: Estimated average output for one berkad with solar still, and number of berkads needed with solar still and rain water harvesting system.

Efficiency	**Output (l/m^2)**	**Output (l/d)**	**Output (m^3/yr)**	**No. of berkads needed**	**No. of persons per berkad**
5%	0.5	100	35	11	70
10%	1.0	195	70	7	100
15%	1.5	295	110	6	135
20%	2.0	390	140	5	165
25%	2.5	490	180	4	200
30%	3.0	590	215	3	230

The estimated output varies between 100 and the 590 l/d on average. Even though the production rate per square meter can be relatively low (Table 3), it still is an economical way to provide clean drinking water in such a remote area. Moreover, it is important to notice that the distillate produced is meant to be used solely for human consumption, implying that one berkad could satisfy the need of up to 230 persons (Table 3).

Above this, rainwater harvesting on the top cover of the still could take place (Figure 5). This would increase the yearly clean water available with about 40 m^3 of water.

As already said, the daily drinking water demand for Budunbuto is estimated to be 2.25 m^3, which equals to about 820 m^3 per year. This demand could be satisfied with 3 to 11 berkads with solar still and rain water harvesting system (Table 3). This is a realistic result for Budunbuto.

Assuming an efficiency of 15%, and thus a yearly output of 110 m^3/yr plus 40 m^3/yr of harvested rainwater, the drinking water tank should have a volume of 10 m^3. This tank would satisfy the drinking water demand of 130 people.

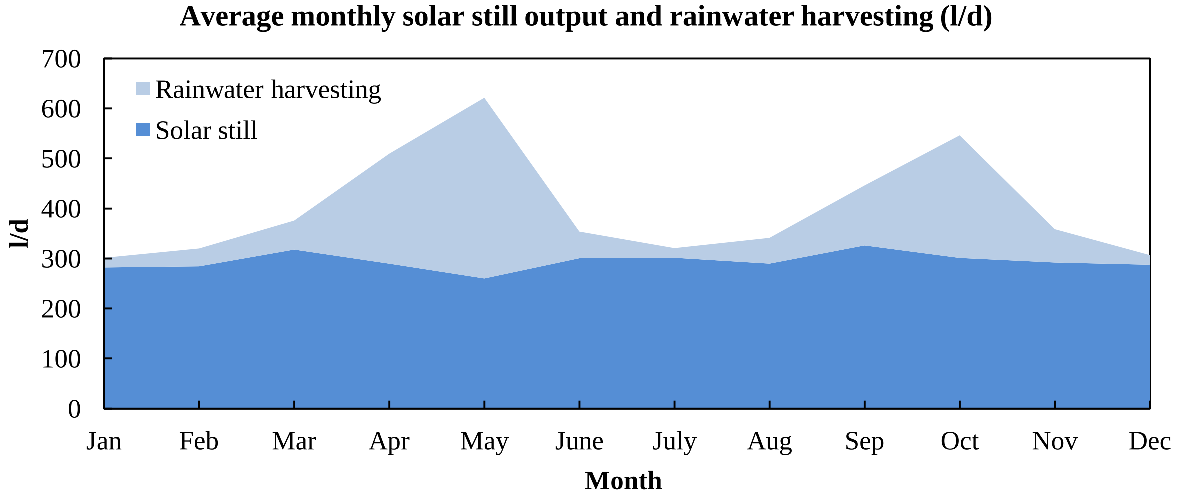

Figure 5: Average rainwater harvesting (l/d) added to the daily output of a solar still with an efficiency of 15%

Water quality

Little research has been done regarding the water quality of the water produced by solar-stills based on polluted or muddy water. However it is proven that nitrates, chlorides, iron, heavy metals and dissolved solids are completely removed by the solar still (Al-Hayek and Badran, 2004 and Zein and Al-Dallal, 1984). The process also proved to be effective in the destruction of microbiological organisms present in the feed water (Al-Hayek and Badran, 2004). The distillate is thus high purity water, which also lacks essential dissolved minerals. Drinking demineralised water can have serious health consequences, and it is thus of crucial importance that the essential minerals are added to the water before consumption (WHO, 2004b). The advised quantities of minerals where minimum or no adverse health effects are observed are shown are shown in Table 4.

Table 4: Advised mineralogical quantities (from WHO, 2004b)

	Total Dissolved Solids (mg/l)	Bicarbonate ion (mg/l)	Calcium (mg//l)	Magnesium (mg/l)	Hardness (mmol/l)	Alkalinity (meq/l)
Minimum	100	30	20	10		
Optimum	250-500		40-80	20-30	2-4	
Maximum						6.5

It is however believed that no addition of minerals will be required in this case as the still distillate will be stored in the same tank as the rain water will be, and also because the process will not be 100% clean. This will suffice as a natural re-mineralization of the water. If the water seems to be too low on certain minerals, it is possible to re-mineralise it in an affordable and simple way by dissolution of natural occurring minerals (Hasson and Bendrihem, 2006 and Ruggieri et al., 2008). Budunbuto is located in a limestone rich area. Running the distillate through a limestone bed can provide essential elements to the water (Hasson and Bendrihem, 2006 and Ruggieri et al., 2008). The process is as follows:

$$CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2HCO^{3-} \quad (10)$$

As a result the calcium, hardness and alkalinity concentrations are increased (Hasson and Bendrihem, 2006 and Ruggieri et al., 2008). Remineralisation rates can differ significantly based on the chemical and mineralogical composition and texture of the limestone used (Ruggieri et al., 2008). According to the European Norm EN 1018:1998, which assess the composition of limestone used for water treatment, the limestone should contain >85% of calcite.

Practical application

When implementing a solar still system on the berkads it is essential that the design is as simple as possible but still effective. Keeping in mind the economic and logistic aspects, affordable and local materials should be used whenever possible. Nevertheless, to guarantee a good functioning of the system, some parts need to be imported.

For Budunbuto, a single slope solar still is preferred above a double slope solar still, as having only one slope equals to having only one internal gutter which can be easily connected to the drink water storage tank. To increase the solar interception, the solar still needs an equator facing top cover, with the length therefore lined on an east-west axis (this might be problematic for already existing berkads, which might not be orientated properly). The top cover should be set at an angle of 10º, which is considered to be the most accepted angle for a single slope solar still at this latitude (Khalifa, 2010). It should be made either out of a 3-4 mm thick glass or a ultra-violet resistant polyvinyl chloride (PVC) sheet. As mentioned above, glass is the preferred material as it increases the efficiency of the solar still. When choosing for a glass cover, it is important that the structure of the still is build to carry the weight of the relatively heavy glass. The sides of the still should be closed in order to make the still airtight. This could be done by using the same material chosen for the top cover. At the inlet of the surface runoff water, a one way door should be placed (Figure 6). This would allow the surface runoff water to flow into the berkad during periods of rainfall, as the door would then open under the weight of the water, but it would remain shut during dry periods.

The condensed water should be collected in a gutter fixed along the lower edge of the cover. On the outer side of the cover a similar gutter should be placed for the collection of the rainwater. Both gutters should be placed on a small angle to let the water run towards the airtight pipes that connect it to the drinking water tank. Both gutters should also be made of a material that is not affecting the properties of the water and so should the airtight pipes be. Particular attention needs to be used when installing the rain water collection gutter, as factors as the weight of the water in the gutter and the wind effects should be considered. It is also advised to add a gutter screen (*e.g.* a simple mesh with a fine pattern), as debris from the roof may collect in the gutter, obstructing it.

The clean water storage tank should be placed in the immediate vicinity of the berkad and should be properly closed, preventing any light from entering. It is advised to place the drinking water tank in the ground (lower than the gutters), as in this way the water would flow under gravity towards the tank.

A hand pump should be used for the extraction of the drinking water from the tank, which should solely be used for human consumption. Another hand pump should be used for the extraction of the water from the berkad, which should be used for animal watering and other domestic use (washing, cooking, etc.).

Very important in the design of the system is that all the joints and fittings are accurately isolated to prevent heat loss. For this reason, a one way valve could be placed at connection point of the internal gutter and the pipe that goes to the drinking water tank.

This type of solar still systems requires little maintenance; however the following aspects should regularly be checked:

- The fittings and joints, in order to prevent colder air flow from outside into the solar still.
- The top cover, which should be checked for cracks and scratches which may reduce the solar transmittance. When using a PVC cover, it should be replaced after about 2 to 4 years.
- The waste product that is left over in the berkad at the end of the dry season should periodically be removed. It should be disposed outside of the catchment area of the berkads, to prevent it from re-entering the system.

The above described advisable design for the solar stills in Budunbuto is very simple and (thus) not optimally efficient. It has been chosen to keep the design simple because an increase in the efficiency and productivity of the still is usually coupled to an increase in cost, which is an undesirable result. With this design, the solar stills represent a low cost technology with low cost maintenance, which can be carried out by unskilled manpower (Tiwari et al., 2003).

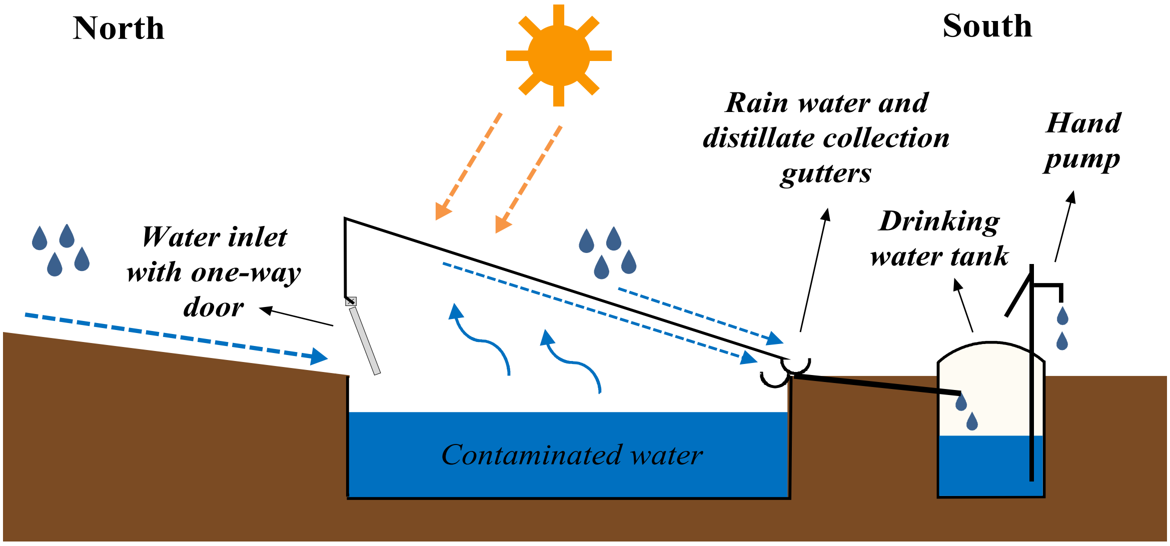

Figure 6: Simplification of a solar still on a berkad

Discussion and recommendations

The results presented above indicate that the implementation of a solar still on (already existing and new) berkads is a feasible measure for the improvement of the water quantity and quality in the village Budunbuto. Above this, it is generally agreed that solar stills are a good option in remote areas where the water demand does not exceed the 200 m^3/day (Tiwari et al., 2003 and Fath, 1998). However, the approach used is very theoretical and abstract, what inevitably may have lead to some inaccuracies:

- The *evaporation loss* has been calculated based mostly on remotely sensed data, which is available only at a large scale for the studied location. This is a source of inaccuracy within the results of the Penman open water evaporation equation. However, it is important to notice that due to the availability of this data it is actually possible to make estimates over an otherwise data scarce region.
- The actual *water consumption rate*, and thus the amount of berkads needed with a solar still system, might differ from what has been estimated. This because the water consumption rates and the number of inhabitants of Budunbuto are also an estimation based on the little information that is available.
- The theoretical approach used to estimate the *output from the solar still* is very abstract and might be inaccurate. On the other hand, this seems the most reasonable approach to use when estimating solar still output theoretically, as it is possible to make assumptions for the efficiency of the system and the remaining parameters are all known.
- The *solar still design* as described above resulted to be the most suitable for Budunbuto. However, as the approach used is very theoretical, it may not be the most functional design in practice. Therefore it is recommended to test various simple solar still designs during the pilot project. This could be done by constructing both single and double slope solar stills, using plastic and glass top covers.

Although the above described inaccuracies are present, the information of this report will provide a reliable guideline for the pilot project, during which the working of the system will be tested. It is expected that the actual production rate of the solar still will be within the range estimated and that the efficiency will most likely be around 15%. However, to satisfy the water demand for animal watering and domestic use (about 35.5 m^3/yr), more berkads are needed. These berkads obviously do not need a solar still system, as the water does not need to be within the mineralogical and bacteriological standard used for drinking water.

During the pilot phase of the project, it is advised to accurately measure both the quantity and quality of the water produced by the still. The electrical conductivity, pH, NO_3^- and the alkalinity of the water should directly be measured in the field. For the analysis of the major cations and anions, it is advised to take 10 ml samples filtered with a 0.45 μm membrane filter, which should then be sent to a water laboratory. Also the bacteriological content of the water should be analysed, to make sure that the bacteria and viruses are actually not present in the drinking water. These measurements would certainly contribute to increase the knowledge regarding the purification of contaminated water by using solar stills.

Once the working of the system has proven to be effective, it is important that the water users are well informed about the solar still in order to ensure its correct functioning and its sustainability. It is essential to emphasize that the solar still will only produce the expected output when it is fully airtight. This means that the water inlet should never be opened by the users to extract the water from the berkads as the hand pumps should solely be used for that. The same holds for the drinking water tank which should also never be opened. Another important point is that the maintenance of the berkads is regularly carried out and that possible leaks are immediately detected and repaired. Particular attention should be paid for the drinking water tank, which is positioned in the ground, what makes it difficult to detect possible leaks.

Conclusions

Even though there are uncertainties associated with the theoretical and abstract approach used in this research, the results indicate that the implementation of a solar still on berkads can be a feasible measure to reduce evaporation loss and to improve the drinking water quality in Budunbuto.

The production rate of distillate water is estimated to be between 100 and 590 l/d per berkad depending on the efficiency of the system. Above this, rain water harvesting on the top cover of the still can contribute to increase the water available with about 40 m^3 a year. This implies that Budunbuto would need between 3 and 11 berkads to fully satisfy the drinking water demand of the village, which is a very realistic result. However, more berkads (without solar still) are needed to satisfy the remaining water demand for animal watering and domestic use (about 35.5 m^3/yr).

The water extracted from the drinking water tank is expected to be within the bacteriological and mineralogical advised quantities where no adverse health effects are observed. The distillate is expected to be partially re-mineralized during the mixing process with the harvested rain water. However, accurate monitoring and analysis of the water quality is advised during the pilot project.

Based on the available information and based on the estimates made, the recommended design for the still is a single slope solar still, with an equator facing top cover placed at a 10º angle. The top cover should (preferably) be a glass top cover. Assuming an efficiency of 15% for the solar still, the drinking water tank should have a capacity of 10 m^3.

To conclude, the implementation of a solar still on (existing) berkads seems to be a good option in Budunbuto, as with a low cost technology with low cost maintenance, it is possible to improve the quantity and quality of the available water.

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