Investigation of productivity and efficiency of a passive solar desalination technology for brackish water in North-Central Namibia

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Brackish groundwater exists in the ground as part of a major stock of water on earth. This water can be considered as a source of drinking water in Namibia. Attempts have been made in north-central Namibia in recent years to produce safe drinking water from groundwater, using various technologies. These include the plant at Okashana trial which produced drinking water of good quality using solar-powered desalination systems (von Oertzen & Schultz, 2008). In spite of efforts to produce and supply drinking water countrywide, many rural communities in north-central Namibia are less likely to get access to safe drinking water. There are several factors that contribute to the shortage of drinking water; the issue of scarce surface waters, lack of alternative water supply technologies and the challenges related to the distribution of the rural population. Population in northern Namibia is around 922 065 people distributed sparsely in five regions (Namibia Statistics Agency, 2011). Around 8.59% of the northern population live in five towns, while 91.41% is scattered in rural areas.

Namibia Water Corporation (Namwater) treats and distributes drinking water countywide including water supply in northern regions. Due to the scattered distribution of rural populations, some communities in remote settlements are not supplied with water by the Namwater distribution network (Liehr, Papangelou, Brenda, Urban, & Kluge, 2015). As a result, some communities rely heavily on brackish water of poor quality supplied from hand-dug wells and active boreholes with salinity around 2000mg TDS/l and beyond. Water with salt content greater than 2000 mg/L total dissolved solids (TDS) is too salty to drink (National Research Council, 2008). Perhaps, the greatest hindrance of water distribution in Namibia is the issue of limited perennial rivers in the interior. Non-perennial surface water bodies in north-central Namibia occur during rainy seasons in Oshana and drain toward the Etosha Pan where it evaporates completely before summer. Groundwater aquifers in north-central Namibia are mostly brackish with salinity ranging between that of fresh and seawaters, making it unsuitable for human and livestock consumption.

Although research is clear on the suitability of water desalination using solar stills, further studies are needed to explore the potential of small scale desalination technologies for the supply of safe drinking water in remote settlements. A passive solar still is a technology suitable for purification of brackish water in remote settlements. This article describes a study conducted with passive solar stills in order to produce drinking water from brackish groundwater. The aim of the study was to determine the productivity and efficiency of passive solar desalination units (SDU). Samples of brackish groundwater collected from remote settlements were distilled using passive solar stills. The results provided insights regarding the design, productivity and efficiency of passive solar desalination units in regions with high solar radiation. The findings revealed the efficiency, productivity, quantity, quality and capacity of the units to produce safe drinking water. Recommendations are made for the removal of all important contaminants, for post-treatment and mineral enrichment of distillate, and for improvement in the design of the condensing cover of the units.

1. Background

The rural populations of northern Namibia are the most affected by drinking water scarcity and is hampered from economic activities such as crop production. Such activities have economic potential (Alexandra & Cedric, 2009). 59% of the rural population in northern Namibia have no access to safe drinking water in the form of pipes inside or outside their dwelling whilst about 13% of the rural population depends on drinking water from unprotected wells (Namibia Statistics Agency, 2011). This lack of access to safe drinking water contributes to poverty which is high among those who drink from rivers, dams, Oshana and public taps (Namibia Statistics Agency, 2012). Moreover, 47,7% of the poor population in Namibia use drinking water from unsafe sources. Thus, additional water supply in northern Namibia has the potential to promote domestic food supply and the formation of an additional source of income (Alexandra & Cedric, 2009). The production of additional water can be achieved with water supply technology such as solar stills. In a recent study, (von Oertzen & Schultz, 2008), summarised critical issues in relation to various desalination technologies in Namibia. The study found desalination with solar stills technology more favourable when factors such as capital costs, operating costs, maintenance cost, energy and technical requirements are combined. Other researchers also found desalination costs low enough to make it an attractive option for safe drinking water supply (National Research Council, 2008).

In contrast to earlier forms of desalination, recent water policies have been dominated by efforts to identify new, untapped sources of water supply. This resulted in the growth of the desalination capacity of approximately 37 million m^3/day both globally and nationally (National Research Council, 2008). Current studies have reported an estimated 90 million m^3 of desalinated water per day, produced by around 18,500 desalination plants worldwide. Saudi Arabia, the United States, the UAE and Kuwait share the globe's highest desalination capacities (B2B Connect UAE, 2018). Reverse osmosis and other membrane systems account for nearly 96% of online desalination capacity in the United States (National Research Council, 2008). In Namibia, operating desalination plants use Reverse Osmosis (RO) (von Oertzen & Schultz, 2008; Mansour, 2016). The earliest form of desalination was accomplished by boiling salt water, cooling and condensing it as fresh water (Mansour, 2016; von Oertzen & Schultz, 2008) This article, investigated desalination of brackish groundwater using solar stills. It focused on design, quality, capacity, productivity and efficiency of solar desalination units (SDU) used in the study.

2. Desalination technologies in Namibia

Commonly used desalination technologies in Namibia include reverse osmosis (RO), multistage flash, multiple effect distillation (MED), vapour compression (VC), the freezing method, submerged tube evaporator (STE), chemical desalination and solar stills (von Oertzen & Schultz, 2008; Mansour, 2016). Reverse osmosis is a membrane separation process in which pure water passes from the high-pressure water side of a semi-permeable membrane to the low-pressure permeate side of the membrane (von Oertzen & Schultz, 2008; Mansour, 2016; Salinas-Rodriguez, Schippers, & Kennedy, 2016).

Multistage flash (MSF) and multiple-effect desalination (MED) are thermal processes suited to high salinity. The MSF process generates vapour in a multistage which is condensed and channelled into fresh water containment. The heat generated during the condensing process is used to pre-heat additional feed water resulting in enhanced efficiency (von Oertzen & Schultz, 2008). Multiple effect distillation uses the steam produced by boilers to successively feed water in a series of steps called effects. According to recent studies, thermal desalination processes are energy intensive compared to membrane technologies, with MSF being more energy-hungry requiring up to 80kWh of thermal energy for every cubic metre of water to be desalinated, followed by MED, using about 70kWh/m^3. RO is reported as the most energy efficient membrane desalination technology in common, used today, with a total equivalent electricity 17.5kWh/m^3, about one quarter that of MED and one-fifth of that used by MSF (B2B Connect UAE, 2018). Contrary to the energy requirement of most common used desalination technology, passive solar stills use only solar energy falling onto the unit. In active solar stills, an external thermal energy source can be added to the unit to aid heat addition to the salty or brackish water (Lienhard, Antar, Bilton, Blanco, & Zaragoza, 2017). Solar stills can also operate in hybrid mode, whereby solar radiation and other energy can be provided in combination for operation beyond the daily sun-shine periods (von Oertzen & Schultz, 2008).

3. Procedures and methods

3.1 Water sampling procedures and testing

Rural communities in remote settlements with drinking water scarcity were identified for the study. Study areas were initially identified in 11 national demarcated water basins which were later reduced to only basin as a result of the selection criteria used to select the final study area and sampling points. Criteria used for the selection of suitable study areas included; population affected by water shortage in water basins, groundwater salinity and water supply, solar radiation, and accessibility of sample points (boreholes or hand dug-wells). The researchers sought to include only boreholes and hand dug-wells with water declared unfit for human consumption due to its salinity and thus they used a purposive sampling procedure to select boreholes and hand dug-wells identified within a sample location. This process resulted in the Etosha water basin being the only suitable study area due to its groundwater salinity level, see Figure 1. Four sampling locations were identified in the Etosha water basin for the study see Figure 1. Samples were collected from sample points using 25 litre sampling containers. Containers were transported to the Namibia University of Science and Technology (NUST) Laboratory in Windhoek, and stored in laboratory controlled conditions. The water samples collected from boreholes in sample location K were the most reliable for the analysis. Apart from the reliability of samples from the rest of the sample points, access to these points was also an issue which could not be resolved during the research period. Water analysis was carried out by an accredited water laboratory. A representative sample from each container was analysed using various methods to determine the physical and aesthetic quality of raw water and to assess its classification in drinking water. Desalinated water was analysed using the same methods to determine the quality of the final water. The water quality test included, Salinity, Alkalinity, Total hardness, Chloride, Iron, Manganese, Nitrate, Fluoride, Sulphate, Conductivity, Colour and pH, before and after desalination, see Table 1.

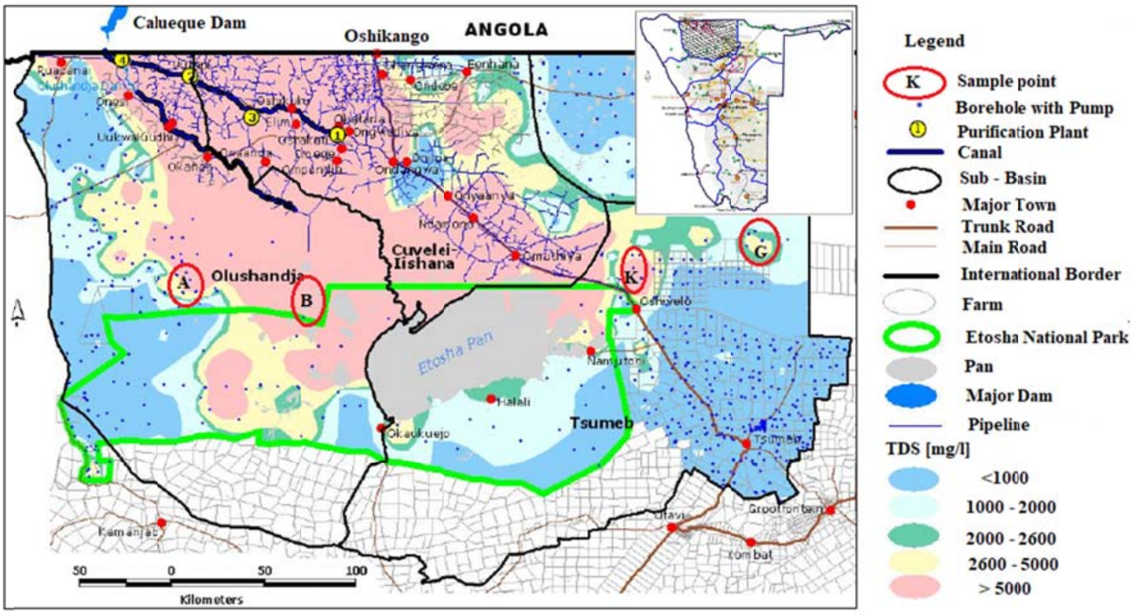

Figure 1: Sample points in Etosha water basin, map by (Bittner Water Consult CC, 2004) modified

3.2 Design and performance enhancement

Figure 2: Experiment set-up

Solar still technology has been used successfully for many decades. Yet, no mandatory guideline or standard has been adopted for the evaluation of productivity, efficiency and performance of passive solar stills. There is also no mandatory standard for the design and construction of solar stills. The scope of solar still construction material is extensive and somewhat unlimited according to recent studies. Various considerations including techniques of energy augmentation were considered for construction of stills to improve the quality, quantity and efficiency of SDU and to increase the yield. A 3mm thick Aluminium sheet was chosen for the construction of an evaporation basin after the analysis of various materials. Figure 2 shows the experimental setup of the solar desalination unit (SDU) used for the study. Basins with an area of 1.1 m^2 fitted with glass covers inclined at 19 degrees were used. Research suggests various solar stills such as, double, vertical, conical, inverted absorber, multi-effect and multistage (Lienhard, Antar, Bilton, Blanco, & Zaragoza, 2017). Several angles of inclination ranging from 15 to 45 degrees were considered in a study by (Singh, Dev, Hasan, & Tiwari, 2011). 20 litre storage tanks attached to a steel frame above the solar stills were used to supply feed water through plastic pipes. A gate valve attached to the bottom of each feed water tank was used to control the flow of feed water. Water condensing on the glass was collected in a plastic gutter connected to the trough inside the stills. Desalinated water was collected from the trough with plastic pipes. The brine water was collected from the stills using a plastic pipe attached to the bottom of the box. Brine water was recycled to improve the efficiency of stills. The temperature was measured using thermometers. Distilled water was collected using metering cylinders. The inclination of the condensing cover was considered taking into account the project research location. Literature suggests an angle of inclination around 10 degrees in summer and 60 degrees in winter. In the study by (Singh, Dev, Hasan, & Tiwari, 2011) single slope solar stills inclined at 45^0 were used. The minimum distance between the evaporation basin and the condensing cover was used to maximise the distillate yield and to improve the efficiency of the units. An increase in the depth of water was observed to elevate the heat capacity of water for prolonged distillation.

The surface area was improved with mattress cubes placed on top of gravels at the bottom of the unit to enhance heat storage and improve the evaporation rate and the yield.

4. Results and discussion

Typical results of water quality test before and after desalination is shown in Table 1. The results show improvement in permeate quality, with significant purification achieved in the removal of salts. Raw water was classified in group D of drinking water category be purification. Group D indicates water which is bacteriologically unsuitable for human and livestock consumption. Purified water was found to meet the drinking water criteria of group B, and group A in some cases. Insignificant depletion in some minerals was observed. The permeate can be enriched with minerals using post-treatment or the simple addition of minerals. Further research is needed to determine what post-treatment methods will increase mineral contents of permeate. A drastic improvement in the quality of the final water indicates the reliability of the passive solar desalination method. Although the permeate was not tested to determine inorganic constituents, it can be categorised in group B of drinking water in terms of its aesthetic and physical determinants. The results provided insights for desalination of brackish water using passive solar stills. The findings are a step toward better understanding what determinants could be distilled and what quality of permeate can be achieved using passive solar stills. Research on the practical application of water desalination using passive solar stills in poor rural communities in Namibia is very limited. Further research is needed to determine the quality of brackish water at remote settlements affected by water scarcity in the Etosha water basin which is beyond the scope of the current study.

Table 1: Typical water quality test before and after desalination

Determinants	Units	AKK26 Onalufipa		BKK29 Ondjamba		CKK22A Chamuchamu	
		Before	After	Before	After	Before	After
Colour	mg/l Pt**	20	20	20	20	20	20
pH	pH-unit	8.66	8.1	8.91	8	7.9	8.1
Turbidity	N.T.U.***	0.8	0.5	0.8	0.5	0.7	0.5
Salinity	mg/l	1541	0.05	7839	0.07	13400	0.08
Conductivity	mS/m 25^{0}C	2300	0.075	11700	0.01	20 000	0.119
Alkalinity	mg/l $CaCO_3$	>10 000	0.1	>10 000	0.09	>10 000	0.07
Chloride	mg/l Cl	3523	8	3674	8	3703	9
Total hardness	mg/l $CaCO_3$	156	156	164	140	163	146
Manganese	µg/l Mn	17	5.0	20	5.0	19	5.0
Nitrate	mg/l N	0.5	0.4	0.5	0.3	0.5	0.3
Iron	µg/l Fe	1280	50	1160	50	1290	40
Fluoride	mg/l F	1.92	0.01	1.97	0.01	1.95	0.01
Sulphate	mg/l SO_3	>800	1.0	>800	1.0	>800	1.0

** Pt = Platinum Units.

*** Nephelometric Turbidity Units.

The variation in the water level of the evaporation basin was studied to analyse the effect of still water depth and the depth of the SDU on its performance see Figure 3. Two prototypes were used; Prototype1- (80mm deep still with 50mm deep tray), Prototype2 - (150mm deep still with 100mm deep tray). The level of raw water in the evaporation basin was found to influence distillation efficiency and performance of the SDU. A good balance in the level of evaporation tray and depth of stills resulted in a good performance. Analysis revealed that evaporation in the shallow stills is faster as compared to the deeper stills. Figure 3 shows the comparison of prototypes. Although both prototypes show comparable results, Prototype1 produced a high yield per day. The water basin level influences its yield, with water depth being inversely proportional to the still productivity. The effects of productivity studies (Abed, Kassim, & Rahi, 2017) using three water depths (5, 7.5, 10 mm) produced similar trends. Increase in the depth of stills has a direct influence on the evaporation rate. Additionally, as brine depth increases, the volumetric heat capacity of the stills is reduced resulting in a decrease in water temperature for a given solar irradiation. A summary of the effects of depth on productivity in a study conducted by (Ayoub & Malaeb, 2012) also revealed similar decreasing trends in productivity with increasing brine depth. Moreover, water depth was found to be inversely proportional to productivity during daylight but reverse for overnight production. Additionally, more yield is obtained during off-shine hours as compared to daytime for higher water depths due to heat storage effects, this finding was also observed by (Ayoub & Malaeb, 2012; Badran & Abu-Khader, 2007).

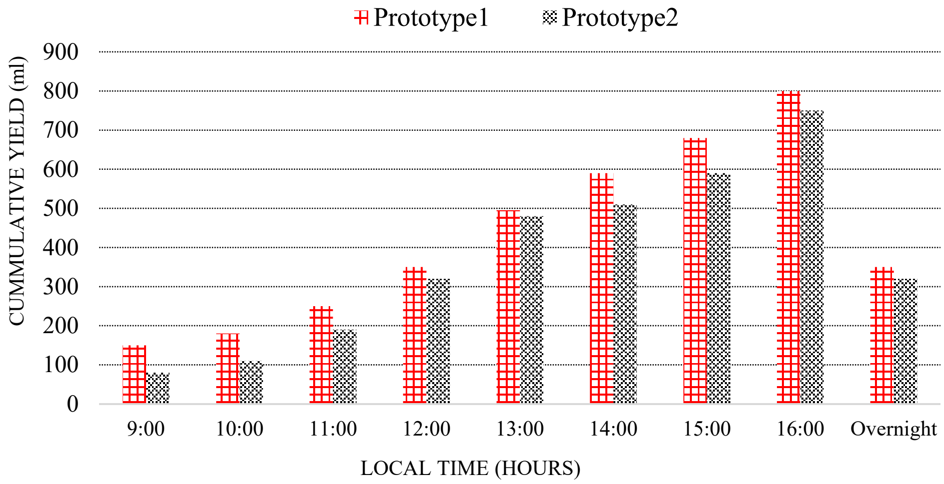

Figure 3: Effects of still depth on performance

In addition to the analysis of the effects of still depth on solar still performance, two approaches were taken to study the effects of surface area on solar still productivity. This analysis compared the productivity of a conversional solar still without mattress cubes, against a solar still with mattress cubes in the evaporation basin. Sponge cubes were used to increase the surface area. An increase in the yield of about 1.51Litres/m^2/day was obtained. This is about 20% greater than the basin without sponges. The addition of sponges increased the surface area in the desalination basin, which resulted in an increased evaporation area. The effect of absorbing materials on the productivity of solar stills have been studied by other researchers using various approaches. A 15% increase in productivity of solar stills with sponges was also reported by (Ayoub & Malaeb, 2012; Lienhard, Antar, Bilton, Blanco, & Zaragoza, 2017)

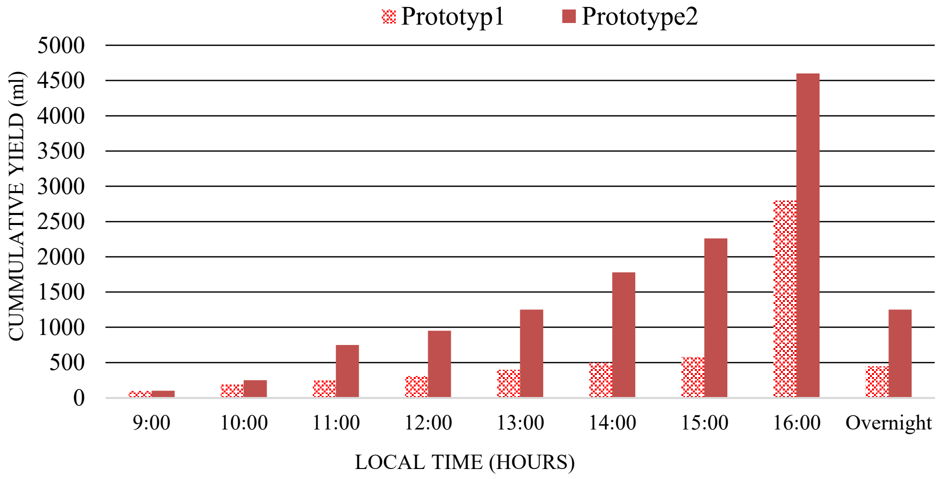

Figure 4: Effect of heat storage on still performance

The effect of heat storage materials on performance and productivity of solar still was studied using two prototypes; a conventional solar still (Prototype1) and a prototype filled with 3kg 19mm gravels and mattress sponge cubes (Prototype2). As seen on the results shown in Figure 4, the addition of gravels combined with sponge cubes enhanced the daily productivity to reach a value of 4.5 litres/m^2/day with daily efficiency reaching 37.8%.

The conventional prototype achieved daily productivity of 2.8 litres/m^2/day with a daily efficiency of 30%. Additionally, the prototype with heat storage materials showed enhanced performance overnight. The conventional prototype achieved a maximum efficiency of around 40.5% compared to the 58.59% of prototype2. These results were found in other studies, for instance, (Lienhard, Antar, Bilton, Blanco, & Zaragoza, 2017) also found a significant increase in the productivity of solar stills with heat storage materials. The addition of black rubber or black gravel materials also improves solar still productivity according to (Badran & Abu-Khader, 2007).

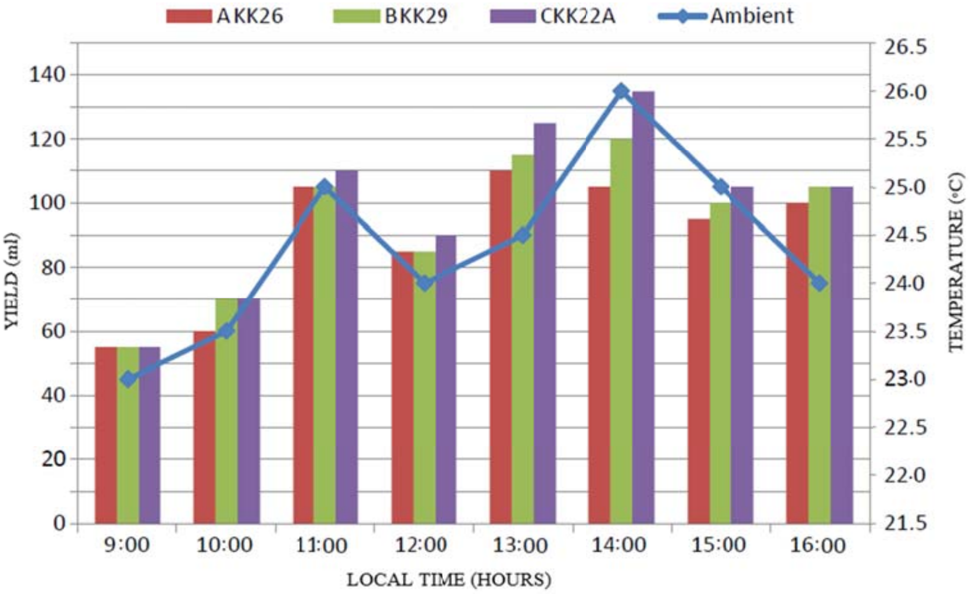

Figure 5: Effect of temperature on still performance

The performance of the solar still with temperature variation was analysed using a conversional solar still prototype. Results of this analysis are shown in Figure 5. Results show the increase in the yield until midday. High temperatures at midday combined with warm air in the atmosphere prevent the condensing cover to cool down, resulting in less yield. The rapid increase in the weight of the condensate on the condensing cover also contributes to the decline in the yield as more water droplets fall back in the evaporation basin before reaching the collection trough. The productivity of solar still with an increase in temperature follows a similar pattern of solar irradiation profile, increasing until midday and then decreasing until sunset. A similar finding was also observed by (Lienhard, Antar, Bilton, Blanco, & Zaragoza, 2017).

5. Conclusion

Research on solar-still technology is well documented (von Oertzen & Schultz, 2008; Driessen, 2013; Abed, Kassim, & Rahi, 2017; Badran & Abu-Khader, 2007; Singh, Dev, Hasan, & Tiwari, 2011), but there remains little comprehensive information on productivity and efficiency of passive solar desalination technology for small scale application in poor rural communities in Namibia. This study was an initial step to gain a better understanding of productivity and efficiency of small scale desalination technology, using passive solar stills. Several conclusions can be obtained from this study. Firstly, the addition of gravels as heat storage material combined with sponge cubes can enhance daily productivity to reach 4.5 litres/m^2/day with an average efficiency of about 37.8%. Conventional prototype achieved daily productivity of 2.8 litres/m^2/day with an average efficiency of about 30%. The addition of heat storage materials was found to have a positive effect on the yield of the prototype for daytime and overnight production. The design was found to be functional with maximum energy efficiency ranging from 41% to 58.8%. The applied technique of energy intensification was found to be very effective. Secondly, a daily capacity at rates between 6.5 and 7.06 litres/day using two solar desalination unit of about 1.1 m^2 was found to be sufficient to supply drinking water to an average household in a rural area. The average yield of litres/m^2/day of a single-stage solar still assuming a still efficiency of 40%, based on average daily yield data is more than 3.9 litres/m^2/day in northern and north-central Namibia, see Figure 6. The sizes of a household in most rural areas in northern and north-central Namibia is around 4.3 and 5.6 since 2011 (Namibia Statistics Agency, 2011). A study conducted by (Abed, Kassim, & Rahi, 2017) found comparable freshwater production capacity of 4.94 litres/m^2/day but with high distillation efficiency of 84%. Another study conducted by (von Oertzen & Schultz, 2008) also highlighted important conclusions from small scale desalination plants in northern Namibia considering actual performance using solar radiation as the only energy source.

Thirdly, passive solar desalination technology has the potential to address water scarcity in rural communities in regions with high solar radiation and abundant brackish groundwater. Desalination with solar stills technology requires low capital and operating cost, low maintenance costs and low technical requirements (von Oertzen & Schultz, 2008). Suitability and practical application of passive solar still technology in northern and north-central Namibia is made possible by its low capital and technical requirements, but also by the availability of brackish water and sufficient solar radiation in access of 6 kWh/m^{2}d. In addition, production of safe drinking water using desalination technologies driven by renewable energy systems should be considered not only in the context of safe drinking water supply but also eradication of poverty.

Although the design was found to be functional, further research is needed to determine what post-treatment methods will increase the mineral contents of permeate and whether the final water will indeed meet criteria of group A drinking water. Mineral enrichment could be achieved through chemical addition or addition of natural minerals. It is worth pointing out that future studies could also consider post-treatment using alternative natural stones containing high mineral contents. The findings of this study have nonetheless provided useful insights for the desalination of brackish water using passive solar stills. They are a beginning step toward better understanding what determinants could be distilled and what quality of permeate can be achieved using passive solar stills. Research on the practical application of water desalination using passive solar stills in poor rural communities in Namibia is very limited. Further research is needed to determine the quality of brackish water at remote settlements affected by water scarcity in the Etosha water basin. The efforts will reveal further insights on the quality of groundwater in the entire basin and will be useful for future studies and deployment of passive water desalination technology. Finally, further research is needed to determine whether current designs of solar stills are suitable for regions with very high temperatures and what efficiency and productivity can be achieved in such regions. The problems of rapid increase in the weight of condensate on the condensing cover and its effect on the yield require a new design approach to improve the yield at midday. The approach can include efforts to investigate the addition of multiple collection troughs attached to the condensing cover. This will prevent condensate droplets from dropping back in the evaporation basin and will improve productivity and increase the yield. This should be considered for inclusion in future studies.

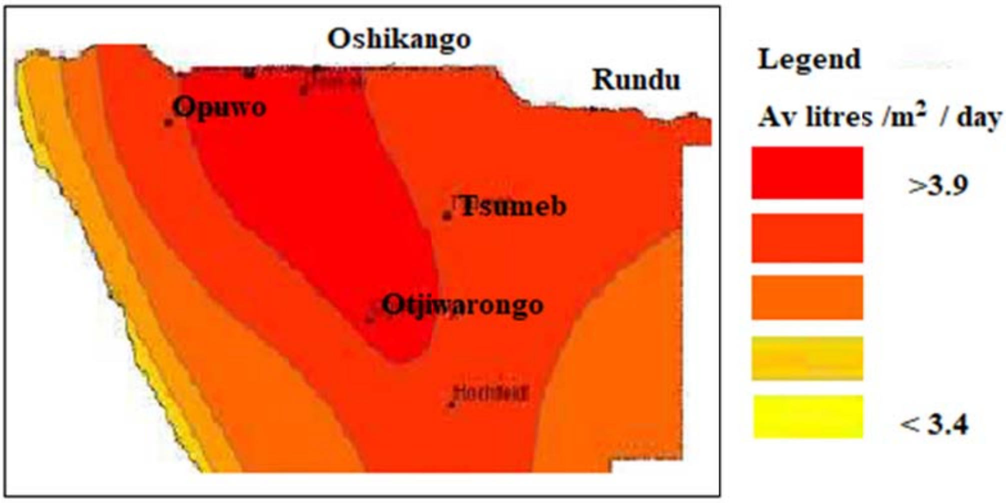

Figure 6: Average daily yield litres/m²/day of single-stage solar still with 40% efficiency (von Oertzen & Schultz, 2008) modified

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