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Full Length Research Paper

Potential of harvesting atmospheric water over urban cities in Kenya

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Most urban areas in Kenya are facing water crisis due to rapid population growth, industrialization and climate change. This study investigates potential of harvesting water from fog and air humidity over urban cities in Kenya. Daily air temperature, dew point temperature, wind direction and speed were used. Parameters including atmospheric water vapor pressure, saturated vapor pressure and the absolute and relative humidity of the atmosphere were derived. Air temperatures ranged between 18.2 and 27.6°C in urban areas. Mean annual foggy days was higher at Jomo Kenyatta International Airport (JKIA) with a maximum of 17 foggy days compared to other stations. However, mean annual harvesting days was higher at Moi International Airport (MIA) with a maximum of 350 days. Based on device efficiency of 10%, stations in Nairobi city (JKIA/Dagorretti Corner/Wilson Airport) indicated maximum water harvesting potential of 3.2/1.4/2.9 litres/m^2/day in direction d6 (225 -270°) while Kisumu station showed highest potential of harvesting water (2.2 litres/m^2/day) in direction d5 (180-225°). In Mombasa, the MIA and Lamu stations showed potential of harvesting 4.4 litres/m^2/day and 3.9 litres/m^2/day in direction d6 and d5 respectively. Based on monthly distribution of potential monthly water, harvesting from fog and air humidity was classified into either coastal or non-coastal/continental regions. The urban cities in Kenya have high potential of water harvesting from fog and air humidity presenting an alternative sustainable low cost approach to augmenting available fresh water sources and alleviating existing water stress. This will enable achievement of Kenya's long term development footprint (Vision 2030) and Millennium Development Goals.

Key words: Vision 2030, urbanization, water stress, fog water harvesting.

INTRODUCTION

Urban and suburban centers are observed to grow as a result of increased population (Garcia et al., 2009). Water significantly influences the quality of human life (Karkee, 2005; Levin and Cotton, 2009). Increasing population coupled with rapid urbanization and climate change puts tremendous pressure on available natural resources increasing the need for exploration of every possible technology and adoption of integrated water resource approach in planning.

The rapid urbanization exacerbates the existing water stress. According to Sharan (2006), water harvesting from atmospheric resources could provide a clean, convenient and relatively reliable water supply in areas lacking good alternative water resources. Since 1960s, different countries have included the issue of water harvesting in their agenda. In Chile and Peru, Sharan (2006) studied water harvesting potential over the coastal areas with cold oceanic flows resulting to scanty rainfall. According to the study, cold oceanic wind flows saturated the air with moisture and formed fog in more than 200

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Figure 1. Fog harvesting equipment at Olteyani, Kajiado County of Kenya (ORSAM, 2013).

Figure 2. Map of Kenya showing the positions of Nairobi, Kisumu and Mombasa.

days of the year and thus high potential in water harvesting from fog. According to Devtalab et al. (2013), when relative humidity (RH) is equal or higher than 68%, the conditions are appropriate for water harvesting. The situation is favorable for fog formation when RH is from 90 to 98%. These processes were considered as thermodynamic processes which were used for water harvesting and fog formation (Esfandyar et al., 2009).

According to Schemenauer and Cereceda (1994), the relative size of water drops for rain (0.5 to 5 mm), drizzle (40 µm to 0.5 µm) and fog (1 to 40 µm) corresponded to fall velocities of 2 to 9 m/s, 0.05 to 2 m/s and 0.01 to 0.05 m/s respectively. Since all of these fall velocities were quite low, the angle of fall of the drops would be influenced by horizontal winds of even few meters per second. In the case of fog droplets, the fall speeds were almost horizontal.

The fog water collection technology is very simple, and demand less operation and maintenance works (Karkee, 2005). A fog collector screen made up of polypropylene mesh is mounted vertically on two or more posts (Figure 1). According to Kenya Meteorological Department (KMD), the Olteyani fog collector costs about $300 (ORSAM, 2013).

Most urbanized centers in Kenya are experiencing rapid urbanization growth just like many other developing countries in Africa (UN Habitat, 2008; Ongoma et al., 2013). Kenya is classified as water scarce with its renewable fresh water per capita estimated at 647 m^3 against UN recommended 1000 m^3 (GOK, 2007). Rainfall which is the main source of water remains highly variable in both space and time, limiting the country's socio-economic development in key sectors such as agriculture and energy (Muhati et al., 2007). Failure in these key sectors hinders the realization of Kenya's Vision 2030 and Millennium Development Goals (MDGs). The aim of this paper is to assess the possibility of harnessing the non-conventional water resources not only for use but also improve visibility over fog dominant urbanized environment.

METHODOLOGY

Scope of study

Kenya is located in the Eastern part of Africa (5°N, 4°40'S and 33°53'E, 41°55.5'E) and has a total area of 582,646 km^2. The study focused on the three Kenyan cities: Nairobi, Mombasa and Kisumu (Figure 2). Nairobi, Kenya's capital city is located within 1° 9'S, 1° 28'S and 36° 4'E, 37° 10'E and covers an area of 684 km^2 and has a population of 3.1 million people (KNBS, 2010). According to Opijah et al. (2007), the predominant easterlies over Nairobi are associated with precipitation occasioned by moisture inflow into the country from the Indian Ocean. During December to February, the Northeast monsoons are common, and to an extent, the Southeast monsoons in June to August, are generally associated with depressed rainfall conditions. Mombasa is Kenya's second largest city, located on the south eastern coast of the country, along the Indian Ocean (3°80', 4°10'S and 39°60' and 39°80'E). The city has an area of 295 km^2 and a population of 939,370 people (KNBS, 2010). Kisumu is a port city (0°6'S, 0.1°S and 34°45', 34.75°E) with a population of 968,909 people (KNBS, 2010). It is the third largest city in Kenya. The city covers an area of approximately 417 km^2, of which 297 km^2 is dry land and approximately 120 km^2 under water.

Data

In order to investigate the water harvesting potential from

Table 1. Meteorological stations.

Station	Altitude	Longitude	Latitude
Dagoretti	1798	36.75	-1.30
Wilson Airport	1615	36.92	-1.32
JKIA	1615	36.92	-1.32
Kisumu Airport	1149	34.58	-0.10
Mombasa	5	39.62	-4.03
Lamu	6	40.9	-2.27

the fog and air humidity, 6 synoptic stations distributed over Kenyan cities were selected (Table 1). Daily wind speeds and direction was sourced from the KMD for the period of 1995 to 2010 while daily air temperature and dew point temperature was downloaded from the National Climate Data Center (NCDC) website (ftp://ftp.ncdc.noaa.gov/pub/data/gsod).

Research procedure

Absolute humidity M_t is one of the main parameters for determining the water harvesting from fogs and air humidity. The parameter was extracted using Equation 1 (Alizadeh, 2002):

$$M_t = \frac{217 * e}{T + 273.3} \qquad (Eqn\ 1)$$

where *e* is the air vapor pressure (mb) and T is the air temperature (°C). In this study, the three hour air temperature and the relative humidity (RH) were available. The air vapor pressure was calculated from air temperature (Equation 2). The vapour pressure was used to compute:

$$e_s = 6.11 * \exp\left(\frac{17.27 * T}{T + 273.3}\right) \qquad (Eqn\ 2)$$

$$RH = \left(\frac{e_s}{e}\right) * 100 \qquad (Eqn\ 3)$$

The relationship between T, dew point T_d and RH was calculated using Equation 4. This conversion can be used as long as RH is above 50% (Lawrence, 2005):

$$RH = 100 - 5(T - T_d) \qquad (Eqn\ 4)$$

The air humidity flow could be determined by knowing the absolute air humidity and wind velocity and direction. Esfandyar et al. (2009) determined that the appropriate humidity for fog formation would be around 98% but the humidity required for water harvesting would be around 69%. Therefore by knowing the wind direction suitable for supplying the air humidity and the speed of supplying the humidity, the water harvesting could be calculated using Equation 5:

$$\left\{\begin{matrix} if\ RH \geq 69\% \Rightarrow WH_3 = (24 * M_t * U_2 * E_{eq} * 3.6) \\ if\ RH < 69\% \Rightarrow WH_3 = 0 \end{matrix}\right\} \qquad (Eqn\ 5)$$

where WH_3 is the potential water harvested through air humidity during 24 h, E_{eq} is the device efficiency which is around 10-30% depending on the device type and the climatic conditions of the region. U_2 is the wind velocity at 2 m height; however, wind velocity in synoptic stations is obtained 10 m from the surface and thus the wind power law is used in calculating the wind velocity in 2 m (Alizadeh, 2002) (Equation 6):

$$\frac{U_z}{U_o} = \left(\frac{Z}{Z_o}\right)^{0.5} \qquad (Eqn\ 6)$$

where, U_z and U_o is the wind velocity at 10 and 2 m height respectively while Z and Z_o is the height at 10 and 2 m respectively.

For efficient water harvesting, the direction of the device was assumed to be in the direction of dominant wind in the region as it provided air humidity. In this study, the best direction was for receiving humidity from the air calculated using Equation 4 by including 8 directions. These included between 0-45° as d1, 45-90° as d2, 90-135° as d3, 135-180° as d4, 180-225° as d5, 225-270° as d6, 270-315° as d7 and 315-360° as d8. The device could receive the humidity in any direction from an angle of 45°. The efficiency of the device was considered at 10, 20 and 30%. Therefore, in each station, 24 conditions were calculated by considering the device efficiency and the wind directions.

RESULTS AND DISCUSSION

Water harvesting conditions

In order to determine the existing conditions for water harvesting over the 16 year period, the number of foggy days (RH greater than 90%) as well as the number of days with more than 69% RH in each station were considered with the corresponding air temperature during the same period (Table 2).

The mean annual foggy days were higher at JKIA compared to other urban stations with a maximum of 17 foggy days (Table 2). However, mean annual harvesting days (potential number of days for water harvesting where RH was equal to or above 69%) was noted to be higher at MIA with a maximum of 350 days. This number varied from 144 days at Wilson Airport located in Nairobi

Table 2. Water harvesting potential conditions over urban cities in Kenya.

Station	Mean annual foggy days	Mean annual harvesting days	Air temperature
Kisumu	3	194	23.2
Jomo Kenyatta International Airport (JKIA)	17	296	19.1
Dagorretti Corner	14	178	18.2
Mombasa International Airport (MIA)	15	350	26.4
Wilson Airport	10	144	19.6
Lamu	9	186	27.6

Table 3. Average potential annual water harvesting from air humidity with an efficiency equal to 10% (Litres/m^2/day).

Station	Wind Direction							
	d1	d2	d3	d4	d5	d6	d7	d8
Kisumu	0.8	1.2	1.7	2.1	2.2	1.8	-	-
JKIA	1.4	1.9	1.3	1.7	-	3.2	-	-
Dagorretti Corner	0.5	1.0	1.0	0.8	1.4	1.4	-	-
Mombasa	2.3	2.3	2.5	2.8	3.2	4.4	-	3.0
Wilson	1.2	1.6	1.3	1.6	1.9	2.9	-	-
Lamu	1.3	2.6	2.4	3.4	3.9	3.0	-	-

Table 4. Average potential annual water harvesting from air humidity with efficiency equal to 20% (litres/m^2/day).

Station	Wind Direction							
	d1	d2	d3	d4	d5	d6	d7	d8
Kisumu	1.6	2.4	3.3	4.1	4.5	3.5	-	-
JKIA	2.8	3.9	2.7	3.4	-	6.3	-	-
Dagorretti Corner	1.1	2.0	2.1	1.7	2.8	2.8	-	-
Mombasa	4.5	4.7	5.0	5.6	6.4	8.9	-	6.0
Wilson	2.3	3.1	2.6	3.2	3.8	5.8	-	-
Lamu	2.6	5.1	4.8	6.8	7.8	6.0	-	-

region to 350 days at MIA located at the coastal Kenya. Air temperatures in the urban cities ranged between 18.2 and 27.6°C.

Water harvesting potential from fog and air humidity

Based on 10, 20 and 30% device efficiency, the potential maximum water harvesting for eight wind directions were computed (Tables 3 to 5).

Tables 3 to 5 show that the water harvesting potential varied based on the direction of the device. Based on device efficiency of 10%, stations in Nairobi city which included JKIA, Dagorretti Corner and Wilson Airport indicated the maximum water harvesting of 3.2, 1.4 and 2.9 litres/m^2/day respectively in direction d6 with an angle equal to 225-270°, while Kisumu station showed that direction d5 had the highest potential of harvesting water (2.2 litres/m^2/day) from fog and air humidity. In Mombasa, direction d6 (4.4 litres/m^2/day) in MIA and direction d5 (3.9 litres/m^2/day) showed the potential of harvesting the highest water amount. Generally, increasing the efficiency of the device resulted to increased amount of water harvested over all stations as noted in Tables 4 and 5 for the 20 and 30% device efficiency.

By taking account of all the directions, the annual water harvesting potential from air humidity at 10% would range from 0.8 to 2.2 litres/m^2/day, 1.8 to 3.7 litres/m^2/day and 1 to 2.5 litres/m^2/day in Kisumu, Mombasa and Nairobi cities respectively. The amount of water harvested was comparable to other existing water harvesting projects as

Table 5. Average potential annual water harvesting from air humidity with efficiency equal to 30% (litres/m^2/day).

Station	**Wind Direction**							
	d1	**d2**	**d3**	**d4**	**d5**	**d6**	**d7**	**d8**
Kisumu	2.4	3.6	5.0	6.2	6.7	5.3	-	-
JKIA	4.2	5.8	4.0	5.0	-	9.6	-	-
Dagorretti Corner	1.6	2.9	3.1	2.5	4.2	4.2	-	-
Mombasa	6.8	7.0	7.5	8.4	9.6	13.3	-	9.0
Wilson	3.5	4.7	3.9	4.7	5.7	8.8	-	9.0
Lamu	3.9	7.7	7.3	10.2	11.7	9.1	-	-

Table 6. Average potential annual water harvesting from air humidity with efficiency equal to 30% (litres/m^2/day).

Project Name	**Harvested Water**
Eltofo-Chile	3.1
Haiti	5.5
Coastal South Africa	2.5
Mari Peskop South Africa	11.0
Peru	6.3
Haja- Yemen	4.5
Chonkongo-Chile	3.0
Khorasan- Iran	3.3

Source: Devtalab et al. (2013).

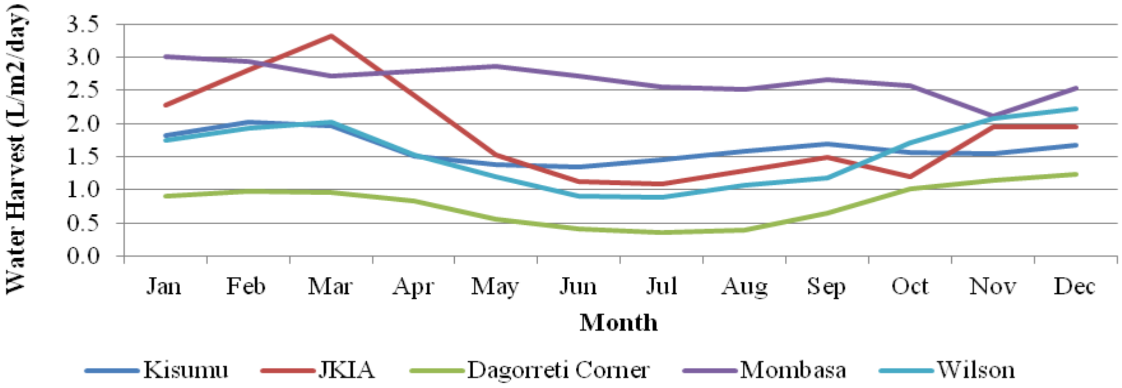

Figure 3. Trend of monthly potential water harvesting from air humidity for 10% device efficiency.

indicated in Table 6. For instance, in the Coastal South Africa, the amount of water harvested is 2.5 litres/m^2/day.

Monthly variations of water harvesting

The monthly variations of water harvesting potential for each of the stations considered for the study are presented in Figures 3 and 4 for the 10% and 30% device efficiency respectively.

The potential maximum amount of water harvested using a 10% device efficiency over JKIA, Mombasa, Wilson, Kisumu and Dagorretti Stations was about 2.4 (March), 3.0 (January), 2.2 (December), 2.0 (February) and 1.2 (December) litres/m^2/day respectively (Figures 3 and 4). Increasing the efficiency of the device to 30% resulted to increased amount of water harvested to 7.3 (March), 9.0 (January), 6.7 (December), 6.0 (February) and 3.7 (December) litres/m^2/day in JKIA, Mombasa,

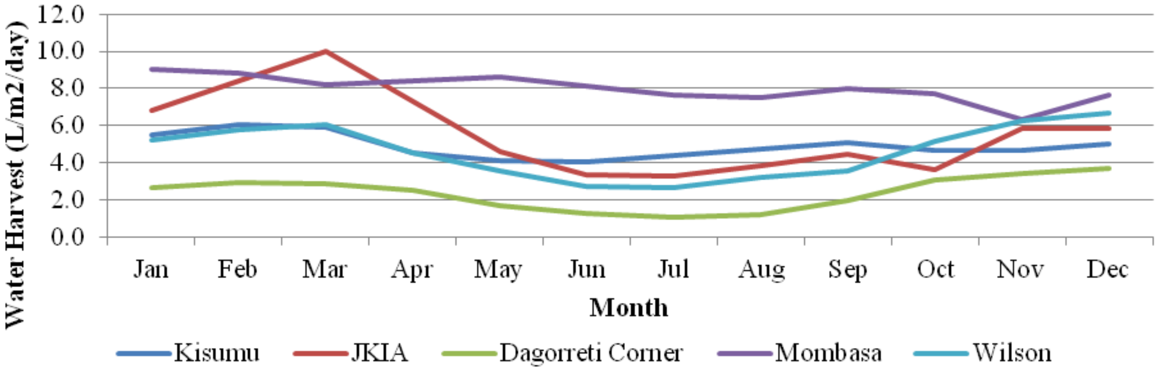

Figure 4. Trend of monthly potential water harvesting from air humidity for 10% device efficiency.

Wilson, Kisumu and Dagorretti Stations respectively. Moreover, Figures 3 and 4 indicate that the distribution of potential monthly water harvesting from air humidity could be classified into types as either coastal or non-coastal/continental regions. In the continental regions, the maximum potential water harvesting occurs in the warm months while the minimum occurs in the cold months. This could be attributed to considerable increase in air humidity through evapo-transpiration by increased air temperature due to not only the position of the Inter-tropical convergence zone (ITCZ) present within the vicinity of the equator during this period but also the Congo air mass that accounts for moisture over the region. Dagorretti Corner, JKIA, Wilson Airport and Kisumu Stations are amongst these stations. In the coastal regions, potential water harvesting undergoes slight variations with the maximum potential water harvesting occurring in the warmer months of January - February while the minimum occurring during the cold season attributed to considerable increase in air humidity through water evaporation from the sea by increase in air temperature. Mombasa and Lamu stations are amongst these stations.

Conclusions

The study shows that most urban cities in Kenya have high potentiality of water harvesting from fog and air humidity. In case the amount of water harvested is much more than portable water required, the exceeding amount could be used for irrigation in urban and peri-urban farms. Moreover, water harvesting from fog would not only increase fresh water availability but also enhance visibility in areas such as Jomo Kenyatta International Airport and Kinungi along the Nairobi Nakuru–highway where fog has been associated with flight cancellation of deviation and road accidents respectively. Therefore, water harvesting from fog and air humidity is a sustainable low cost approach to augmenting available water resources and alleviate the existing water stress due to overdependence on the existing fresh water sources and thus realization of the country's Vision 2030 and overall achievement of MDG of ensuring water for all by the year 2015.

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