Article

Potential of Wind Energy Development for Water Abstraction Systems in developing country context: A case of Teso Sub-region of Uganda

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Abstract: Wind energy powered pumps could be an alternative to conventional fuel powered pumps for water abstraction because they rely on a free energy and they are environmentally friendly. The objective of this study was to assess the potential of wind energy to operate water abstraction systems in Teso sub-region of Uganda for livestock watering Daily mean wind speeds recorded at a height of 10 m for a period of ten years (2005-2015) were collected from Amuria and Soroti Meteorological stations in the study area. Data were analyzed using Weibull distribution to evaluate the annual wind speed frequency distributions and consequently assess their potential for water abstraction. The results indicated that warmer months (January, February and March) have higher mean wind speeds than the cold months (August, September and October). High wind speeds in the dry seasons corresponded to the periods of high water demand. The highest shape parameter (k) of 3.07 was registered in 2009 and scale parameter (c) of 3.78 in 2012. The highest wind power density of 43 W/m^2 was obtained the year 2012 while the lowest wind power density of 15.47 W/m^2 was obtained for Soroti district in the year 2009. The maximum power extractable in Amuria in 2012 was 324 W/m^2 which is potentially enough for water abstraction. Maximum discharges of 1.86 m^3/s and 1.52 m^3/s were obtained for Amuria and Soroti districts respectively at mean wind speeds of 5 m/s. Therefore, Teso sub region winds have potential for water abstraction and Amuria district better sites for livestock watering using wind energy.

Keywords: Wind energy; Weibull distributions; Water abstraction; Water stress; Water pumping

1. Introduction

Energy is vital for sustaining life on earth and plays a crucial role in human and economic development. As such energy poverty is one the injustices that call for human endeavor to address. Conventional energy sources (fossil fuels) are limited in nature, costly and when used cause greenhouse gas emissions [1-3] Global warming due to greenhouse gases contributed by us use of fossil fuels [4], calls for new strategies to utilize available renewable energy sources and wind energy is more promising [5-7]. However, accurate wind resource assessment is essential in the choice of a profitable location for harnessing wind power [8].

Teso sub-region in Northeastern Uganda is part of the cattle corridor and experiences water stress [9-11] regardless of the fact Uganda is endowed with abundant water resources [12-14]. Water scarcity in this region is largely driven by frequent and prolonged droughts, increasing livestock and human population growth leading to increasing water demand [15]. As a result, there is widespread of livestock diseases, increased nomadism and also social political conflicts. Interventions by Government of Uganda have focused on utilization of water resources for productive use through increasing storage volumes for water and exploitation of groundwater. Abstraction of water has relied on use of motorized pumps used at valley tanks, abstraction by gravity (used on dams), electric pumps and cattle ramp abstraction system. However, the systems have not been sustainable due to high operation costs of the conventional motorized pumps and limited access and high cost of electricity [16]. Only approximately 18.2 % of the total population in Uganda has access to the national power grid [17].

Wind energy powered pumps could be an alternative to conventional fuel powered pumps for water abstraction because they rely on a free energy source and are green-technology with an operational carbon-footprint of zero and thus environmentally friendly. However, its potential for water abstraction has not been assessed. The absence of reliable and accurate Uganda Wind Atlas, calls for further studies on the assessment of wind energy in potential areas in Uganda. Therefore, the overarching objective of this study was to assess the potential of wind energy to operate water abstraction systems in Teso sub-region of Uganda for livestock watering.

2. Materials and Methods

2.1 Description of Study area

The study areas within Teso sub region were Amuria and Soroti districts as depicted in Figure 1. Teso sub-region experiences a humid and hot climate, receiving bimodal rainfall with an annual average between 1,000 to 1,350 mm, much of which is received between March to May and Septembers to November. The main dry season begins in December and lasts till February. The climate of the sub-region is modified by the large swamp wetland area that surrounds it. Minimum and maximum temperatures are about 18ºC and 31.3ºC respectively. However, extremes usually occur in February, when the temperature can exceed 35°C. The vegetation is generally savannah. There are woodlands as well as forest plantations and reserves.

2.2 Data Analysis

According to the requirements for wind energy assessment, a representative year with maximum wind speed or peak is used to estimate the wind energy resource potential of a given study area [7].

2.2.1 Weibull distribution function

The Weibull probability distribution function, f_w as shown in Equation 1 of different wind speeds of any region predicts the wind energy potential corresponding to different possible wind speeds in a certain period of time [18]. Weibull distribution is a two parameter function characterized by scale parameter c (m/s) and shape parameter k (dimensionless).

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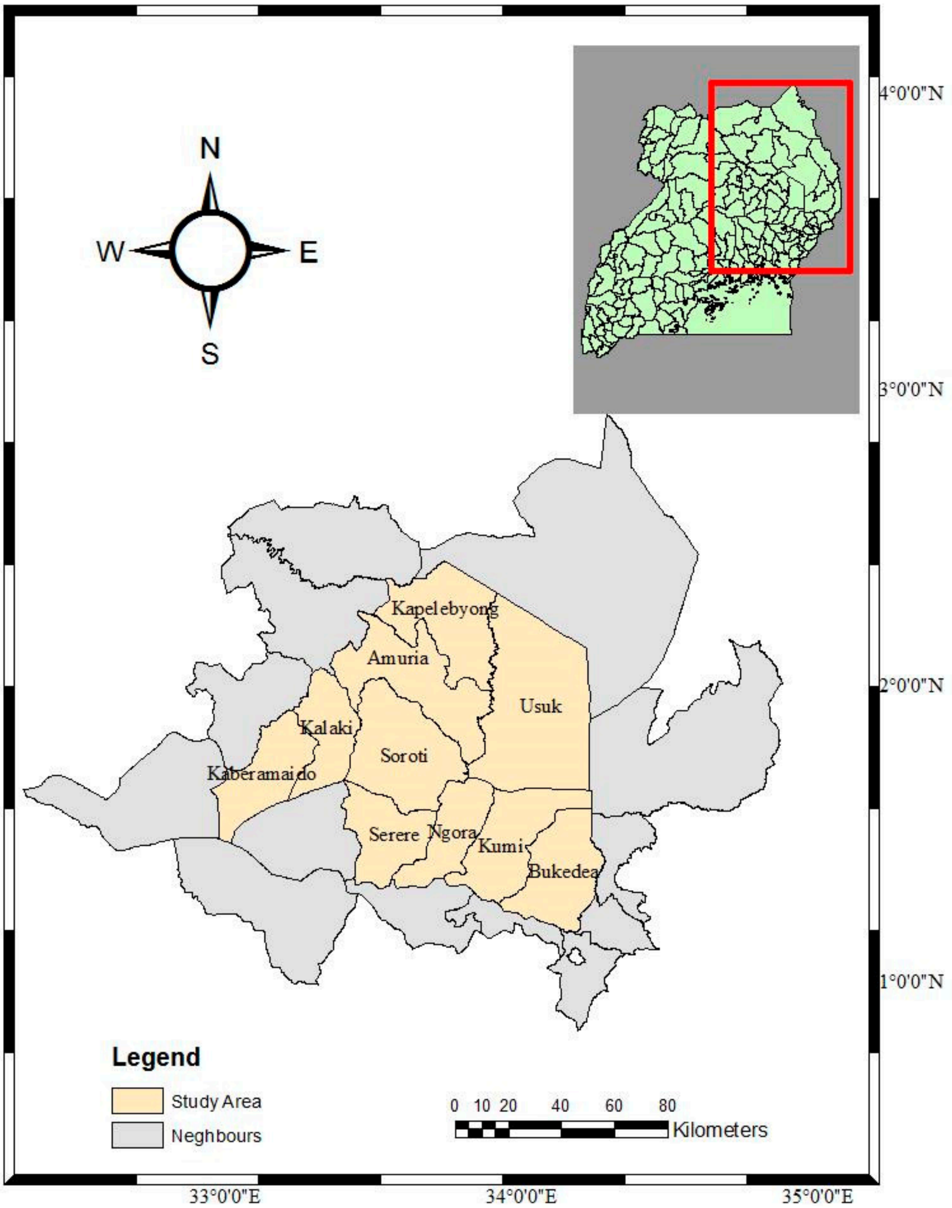

Figure 1. A map showing the locations of the study areas in Teso sub region.

$$f_w(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (1)$$

Where; k is the unit less shape parameter, c is the scale parameter in m/s and v is the Wind Speed

The cumulative distribution function (Equation 2) is used to predict time at which a installed turbine actively functions in a given area [19]

$$F_w(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (2)$$

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Weibull parameters (Scale factor k and shape factor c) for wind data analysis can be obtained using the Empirical method as given in the Equations 3 and 4 respectively.

$$k = \left(\frac{\sigma}{\bar{V}}\right)^{-1.09} \quad (3)$$

$$c = \frac{\bar{V}}{\Gamma\left(1+\frac{1}{k}\right)} \quad (4)$$

Where $\bar{v}$ is the mean wind speed and σ the variance of the known wind speed calculated using Equations 5 and 6 respectively and Γ is the gamma function and using the Stirling approximation the $\bar{v}$gamma function of (x) can be given as in Equation 7[19].

$$\bar{v} = \frac{1}{n}\left[\sum_{i=1}^{n} v_i\right] \quad (5)$$

$$\sigma = \left[\frac{1}{n-1}\sum_{i=1}^{n}\left(v_i - \bar{v}\right)^2\right]^{\frac{1}{2}} \quad (6)$$

$$\Gamma(x) = \int_0^{\infty} e^{-u} u^{x-1} du \quad (7)$$

2.2.2 Most probable wind speed

This refers to the most frequent wind speed for a given wind probability distribution Equation 8 [19].

$$V_{mp} = c\left(1-\frac{1}{k}\right)^{\frac{1}{k}} \text{ (m/s)} \quad (8)$$

2.2.3 Maximum energy carrying by the wind speed

The wind speed carrying maximum wind energy was calculated using Equation 9 [19].

$$V_{\max.E} = c\left(1+\frac{2}{k}\right)^{\frac{1}{k}} \text{ (m/s)} \quad (9)$$

2.2.4 Wind power density and Actual Power

Wind power density was determined to find a comparative measure of capacity of wind resource for the 2 districts (Amuria and Soroti). The power density was calculated using Equation 10 [20, 21].

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$$P_m = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right) \quad (10)$$

Where; P_m is the wind power density (W/m²), ρ is the air density = 1.225 kg/m³, v is wind velocity (m/s), c is Weibull scale Parameter, k is Weibull shape parameter and Γ(x) is the gamma function of (x).

The actual power was estimated using Equation 11 [22].

$$Power = \frac{1}{2}\rho A V^3 \quad (11)$$

And taking swept area, A = 1 m²

2.2.5 Wind energy density

Wind energy density was computed using Equation 12 which was derived from Equation 11 by adding the desired time T as in accordance to Islam [19]. Equation 12 was very useful when calculating the wind energy for any specific period when the achieved wind speed frequency distributions were different.

$$\frac{E}{A} = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right)T \quad (12)$$

2.2.6 Weibull Wind Power Density

The wind power density was assessed using Weibull probability density function (pdf) given by the expression in Equation 13 which have also been applied in similar studies [20, 21].

$$P_w = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) \quad (13)$$

Where: P_w is the Wind power Density, v is wind velocity (m/s), c is Weibull scale Parameter, k is Weibull shape parameter, Γ(x) is the gamma function of (x).

2.2.7 Pump discharges with maximum mean wind speed and Power requirements

A year with maximum mean wind speed was used to calculate the power requirement of the water abstraction system as well as coming up with the maximum pump discharges on a monthly basis. The power requirement was computed using Equation 14 [22].

$$P_u = 0.1A_r(V_{mean})^3 \quad (14)$$

Where: P_u is the useful power delivered in pumping the water (W), A_r is the swept area of rotor (m²) and V_{mean} is the mean wind speed (m/s).

Since the commonly used systems for water abstraction in the Teso region is the piston pump with a reciprocating motion, the instantaneous discharge Qvp of the system at any velocity V can be deduced as in Equation 15 [23].

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$$Q_{vp} = 2C_{pd}\eta(T,P)\frac{\rho_a \pi D_T^2}{\rho_w 4gH}V^3\left[1-K_o\left(\frac{V_1}{V}\right)^2\right]K_o\left(\frac{V_1}{V}\right)^2 \quad (15)$$

Where: C_{pd} is the power coefficient of the rotor at the design point, $\eta(T,P)$ is the combined transmission and pump efficiency, K_o is a constant taking care of the starting behavior of the rotor pump combination, ρ_a is the density of air (1.225 kg/m³), ρ_w is the density of water (1,000 kg/m³), H is the pressure head (approximately 5 m), V_1 is the different mean wind speeds and V is the actual mean wind speed of the study areas at reference height

2.2.8 Wind energy potential for water abstraction

Microsoft excel software was used to evaluate the potential of the energy for water abstraction. Minimum and maximum mean wind speeds for the study area were used as the input parameters to compute the volumes of water that can be extracted and the correspond number of cattle watered.

3. Results

3.1 Mean wind speed

Figure 2 shows variations between the mean wind speeds (2005-2015) for the two study areas. Overall, the mean wind speed for Amuria district was higher than that for Soroti district. The highest mean speed in Amuria district was 3.35 m/s and lowest was 2.42 m/s in 2006. Soroti district also registered high and low mean speeds in the same years as that of Amuria district. The lowest wind speed was 2.07 m/s and highest was 2.94 m/s. There was a gradual decrease in wind speeds for the two regions between 2005-2006 and then an exponential increase from year 2006 - 2012 where the peak was obtained, after which it reduced in year 2013 and remained almost constant with small variations between 2013 to 2015.

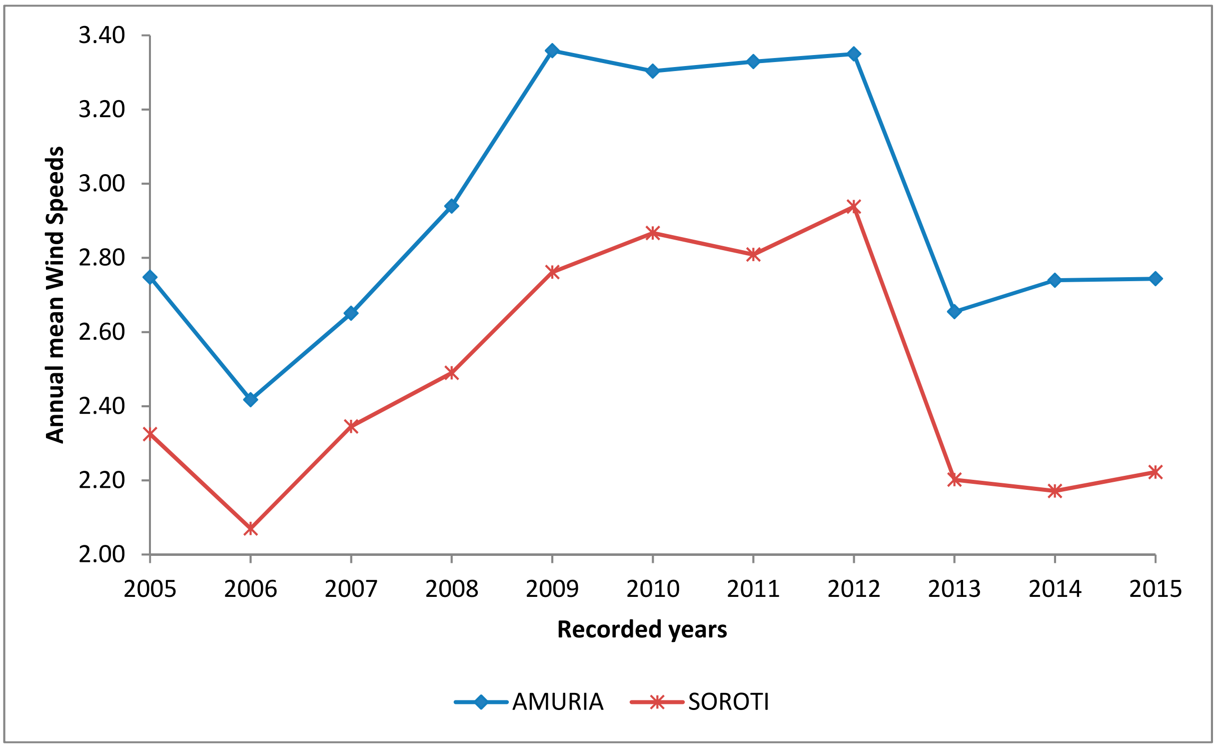

Figure 2. Annual wind Mean speeds for 10 year period

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Figure 3 shows the monthly mean wind speed for the year 2012 because in all the study areas, it's the year where the maximum wind speed or peak was achieved. For Amuria district, the highest mean wind speed (5.41 m/s) was in February and the Lowest (2.06 m/s) in September. Soroti district had the highest mean wind speed (4.23 m/s) in January and lowest (2.16 m/s) in September.

The mean wind speeds followed an exponential decreasing trend from January to June, then a slight increase in June – August, then a decrease between August and September, thereafter a sharp increase from September to December. The curves for the two study areas follow the same trend, where wind speeds decreases from January to June and increases slightly from June to August then reduces to September and increases again till December.

It is known that in the Teso region, dry months are January, February, June, July and December, and in these months there is an increase in wind speeds at the onset of dry seasons (Figure 3) and decrease in wind speed at the onset of cold seasons. The cold seasons in Teso region are March, April, May, August, October and November.

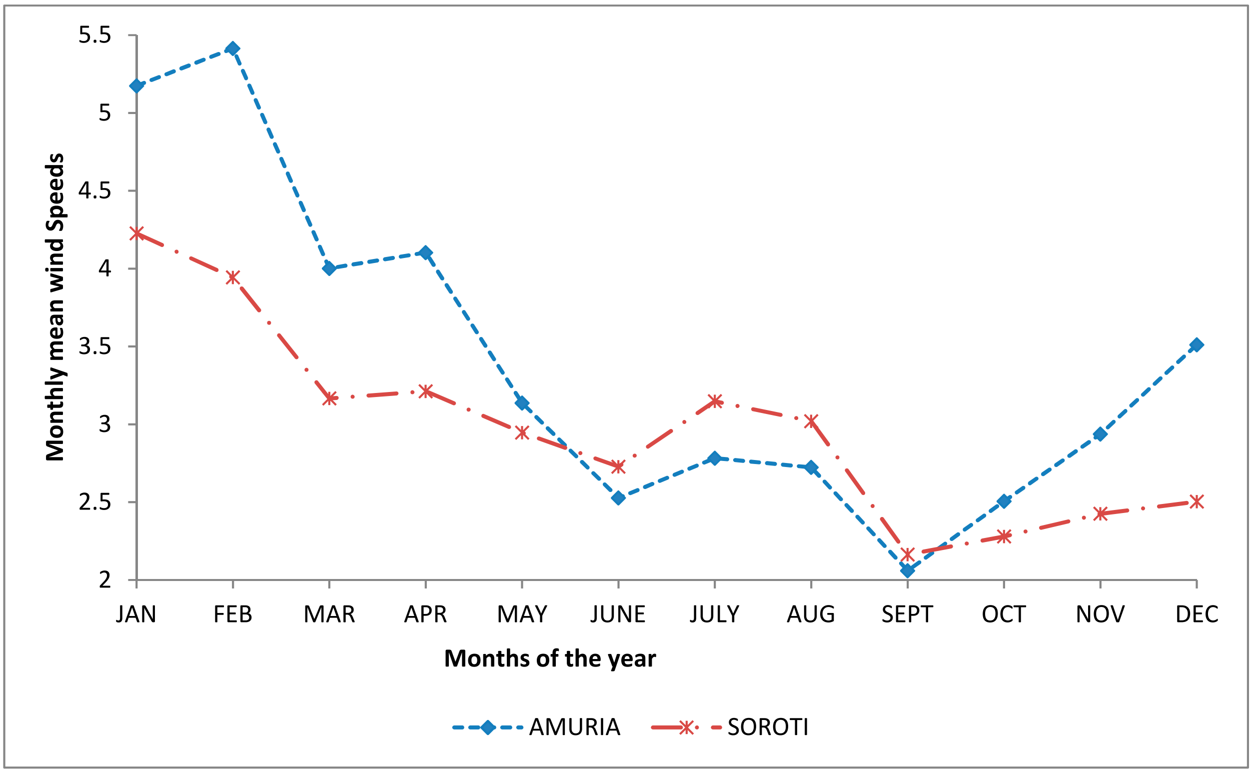

Figure 3. Monthly wind speeds for 2012

3.2 Weibull Distribution

Table 1 shows the variations of the standard deviation, shape parameter (k), and scale parameter (c) for four consecutive years (2009-2012) with the highest mean wind speeds for the study areas.

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Table 1. Annual mean wind speed, standard deviation, shape parameter (k), and scale parameter (c), Wind power density (Pm), Most Probable wind speed (Vmp) and maximum energy carried by wind (Vmax.E)

Parameters	AMURIA					SOROTI				
	2009	**2010**	**2011**	**2012**	**Average**	**2009**	**2010**	**2011**	**2012**	**Average**
$\bar{v}$ (m/s)	3.36	3.30	3.33	3.35	3.34	2.76	2.87	2.81	2.94	2.85
σ (m/s)	1.20	1.31	1.54	1.73	1.45	0.71	0.76	0.77	0.90	0.79
k	3.07	2.71	2.30	2.04	2.53	4.36	4.25	4.07	3.62	4.08
c (m/s)	3.76	3.71	3.76	3.78	3.75	3.03	3.15	3.10	3.26	3.14
P_m (W/m^2)	32.20	32.93	37.98	43.18	36.57	15.47	17.45	16.65	19.92	17.37
V_{mp} (m/s)	0.83	0.86	0.92	0.94	0.89	0.54	0.57	0.57	0.65	0.58
$V_{max.E}$ (m/s)	2.02	2.38	3.05	3.68	2.78	1.01	1.09	1.13	1.40	1.16

3.3 Monthly standard deviation, shape parameter (k), and scale parameter(c)

The monthly standard deviation ranged from 1.20 to 1.73 m/s in Amuria district whereas Soroti district had 0.71 to 0.90 m/s and one with the small difference in variation within standard deviation.

The range of variation of the shape parameters and scale parameters for Amuria is 2.04-3.07 and 3.71–3.78 m/s respectively and Soroti: 3.62–4.36 and 3.03–3.26 m/s respectively. The registered highest shape parameter (k) was in 2009 and scale parameter (c) in 2012 for both Amuria and Soroti districts.

3.4 Wind power density, maximum energy carried by wind and most probable speed

From Table 1, it was observed that the highest wind power density was 43.18 W/m^2 when the two study areas were compared, and this density was obtained in Amuria district in year 2012. The lowest wind density was 15.47 W/m^2 in Soroti district in 2009. The highest value of the wind speed carrying maximum energy and most probable wind speed were 3.68 m/s and 0.94 m/s, and all achieved in Amuria district in 2012.

At Amuria district in 2012, the maximum power extractable was equal to (0.598 x 43.18 W/m2 x A) where A is the Swept area of the wind turbine. The used water abstraction wind powered systems in Teso region have a swept radius of 2m, therefore area becomes, A = (πr2) = (3.14 x 22) = 12.56 m2. Finally the maximum power extractable at Amuria district if the peaks received are similar with hose achieved in 2012 is 324.32 W.

3.5 Weibull distribution and Cumulative distribution

The Weibull parameters: scale parameter c (m/s) and shape parameter k (dimensionless) have values computed on year basis (Table 1). For easy analysis, a year which registered peak mean wind speed as well as highest scale parameter and shape parameter was selected and this was 2012. A plot of probability distribution function, $f_w(v)$ against wind speed was developed (Figure 3) with two Study area – Amuria and Soroti districts found in Teso region.

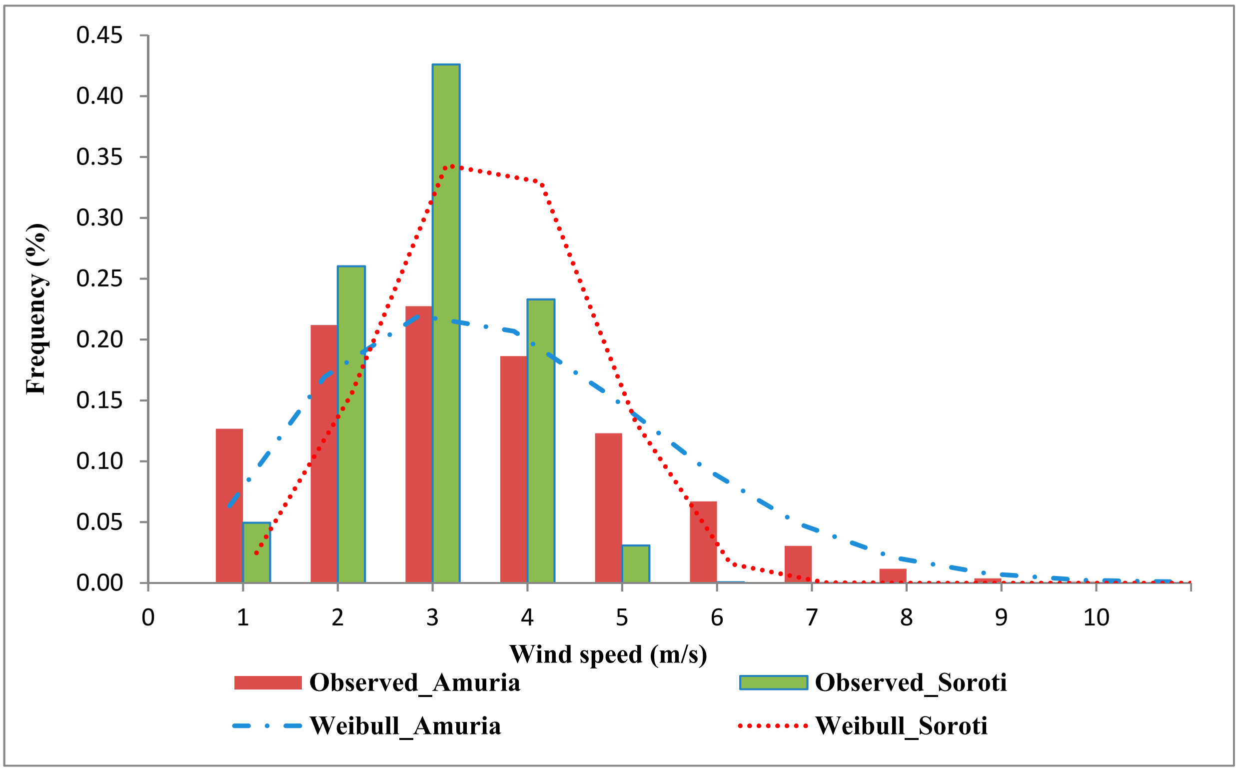

Figure 4. Weibull and Observed annual wind speed frequencies of Study areas in 2012

Figure 4 shows the annual variation of observed and Weibull wind speed frequencies for 2012 at Amuria and Soroti districts respectively. Maximum percentage error between Weibull and observed frequencies occurs at less than 3 m/s wind speed at 23% for Amuria district and 43% for Soroti district, and the maximum variation is 5% for all the study areas higher than 2 m/s.

3.6 Maximum discharge of the pump with mean wind speeds

Figure 5 indicates that maximum discharge is expected not beyond the mean wind speeds of 5 m/s, however according to the Weibull distribution the wind frequency is high at 3 m/s and therefore the discharge can be 1.86 m3/hr and 1.52 m3/hr for Amuria and Soroti districts respectively. The useful power delivered by the pump is 41.16 W for Amuria district and 25.57 W for Soroti district. Therefore, more useful power delivered by the pump can happen when situated in Amuria district because of the high mean wind speeds occurring in that region.

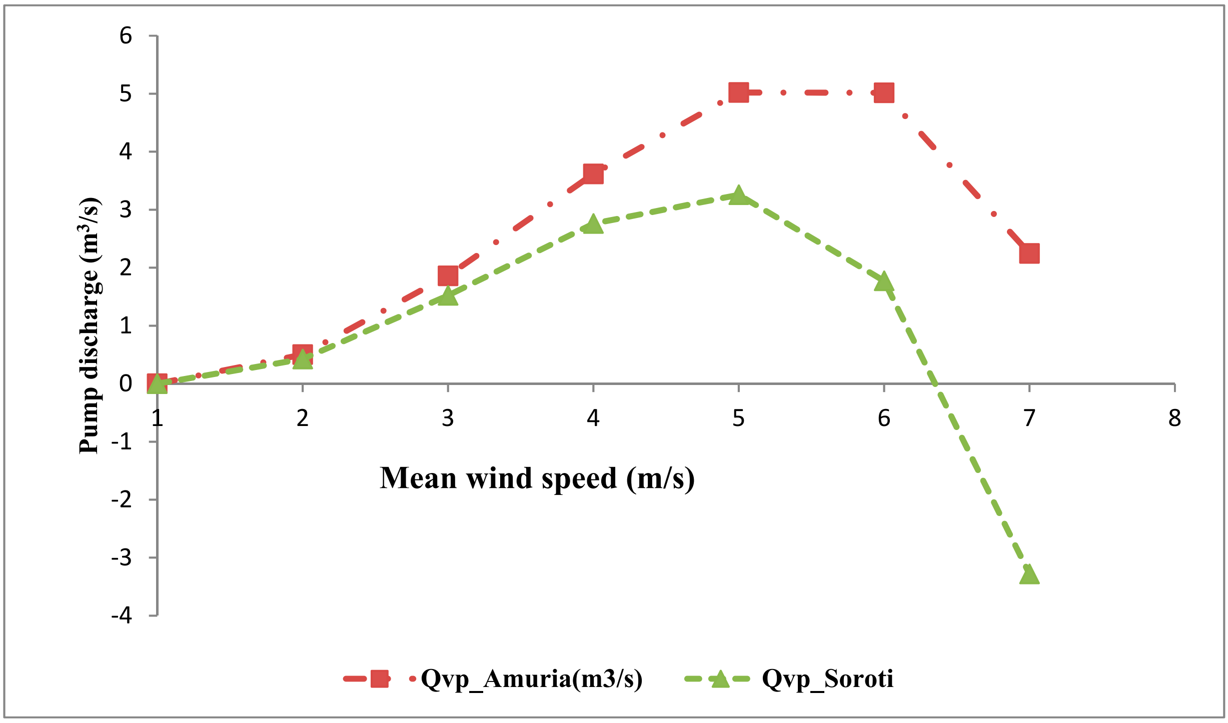

Figure 5. Maximum Pump discharge with different wind speeds

3.7 Wind energy potential for water abstraction

Results obtained from the computation of output power, discharge and the watered number of cattle is shown in Table 2. It presents output power, discharge and the watered number of cattle for the maximum and minimum speed among the series of 10 years data used for Amuria and Soroti districts.

For Amuria, the discharge from the observed maximum and minimum mean wind speed was 2.79 m^3/s and 2.01 m^3/s respectively. The discharge as a result of maximum and minimum wind speeds is able to water 1,743 and 1,255 heads of cattle respectively. For Soroti, the discharge from the observed maximum and minimum mean wind speed was 2.79 m^3/s and 2.01 m^3/s respectively. The discharge as a result of maximum and minimum wind speeds is able to water 1,743 and 1,255 number of cattle respectively considering a water demand of twenty (20) litres per day for local cattle.

Table 2. Wind energy potential for water abstraction

Parameters	Amuria (m/s)		Soroti (m/s)	
	Maximum speed	Minimum Speed	Maximum speed	Minimum Speed
Output power (W)	23.23	8.68	15.57	5.43
Discharge (m3/s)	2.79	2.01	2.44	1.72
No of animals (Heads)	1743	1255	1525	1074

4. Discussion

There were observed differences in the wind speeds between the two study districts as seen in Figure 2 and this could be attributed to a spatial climate variation [18]. Under a 'normal' climate

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pattern for the study area, the lowest mean wind speeds should be expected in September (cold season) and the highest to be in months of January-February (hot season). Because inside a hot season, the air density is less than air density in the cold season, the observed wind speeds which depend on air density were as expected. The increase in wind speed during the dry seasons corresponds to the periods of high water demand in the study areas especially Amuria district at which high performance wind powered water abstraction systems is expected. According to Kaldellis [24], for most wind conditions, k always varies from 1.5 to 3, whereas c ranges from 3 to 8 m/s. From Table 1, the average value of c is for the study areas (Amuria - 3.75 m/s; Soroti - 3.14 m/s) and the average value of k (Amuria – 2.53; Soroti – 4.08) were within the range observed by Kaldellis [24].

Since the shape parameter k determines the peak of the wind distribution, the analysis of this study shows that the wind distribution reaches the peak during dry periods of the year. Moreover, the ratio of k/c is a crucial factor in determining the peak frequency, and also predicting most probable speed with greater accuracy [18]. Authors Keyhani [2] suggested that the scale parameter c indicates how windy a location is whereas the shape parameter k indicates how peaked the wind distribution is. Applying this argument to the analysis of this study points out that Amuria district is windier whereas Soroti district has the highest peaked wind distribution. Despite experiencing peak wind distribution required for maximum power output, Islam [19] found out that it is impossible for any device to convert all the output power to a usable form and so a Betz relation assigns a power coefficient of 0.593 for the maximum extractable power from an optimum wind energy conversion system.

According to Manwell [22], there is a range of power densities (Pm) at which wind turbines can potentially function: If the Pm< 100 W/m2, it is deemed a poor potential and if Pm≅ 400 W/m2 , it is deemed a good potential and for Pm> 700 W/m2 , it is great potential. For this study, the computed wind power potential tends to a good potential enough for water pumping.

In scenarios where there is observed zero or very low wind speed (less than 2 m/s) (Islam [19], the Weibull distribution is insufficient to represent probabilities. For this study, the observed distribution was reasonably well in the higher wind speed range (greater than 2 m/s) where maximum percentage error between frequencies is below 25%.

Using the cumulative distribution function which predicts the fraction of time a wind speed is below a particular speed and where a potentially installed wind powered abstraction system can be functional [7], the study established that for the wind turbine system to be functional at model mean wind speed of 3 m/s in the study area of Amuria district, it will be below this speed 46% of the time and in Soroti district, it will below the model speed 52% of the time. Using the peak mean wind speed received for each of the study areas: 3.35 m/s for Amuria district and 2.94 m/s for Soroti district all in the year 2012, the cumulative distribution of Amuria district would then be approximately 50% and for Soroti district 48%. Therefore from Table 2, Amuria district is endowed with more wind energy potential for abstracting water than Soroti district due to its higher pick mean winds.

5. Conclusions

The obtained results clearly show that warmer months have higher mean wind speeds than the cold months in all study areas. Therefore, the increase in wind speed in the dry seasons corresponds to the periods of high water demand in the study areas especially Amuria district at which high performance wind powered water abstraction systems is expected. The cold seasons in Teso region are March, April, May, August, October and November, and hot seasons in January, February, April, July and December.

The annual mean wind speeds for Amuria district were higher than that of Soroti district at 10 m. The highest wind power density was 43.18 W/m2 obtained in Amuria district in year 2012 and the lowest wind density was 15.47 W/m2 in Soroti district in 2009. It is from the power density where maximum power extractable at Amuria district was achieved if wind speed peaks are received and occurred in 2012. The obtained power density was 324.32 W which is potentially enough to be used for pumping water.

The maximum discharge is expected not beyond the mean wind speeds of 5 m/s, however according to our Weibull distribution the wind frequency is high at 3 m/s and therefore the discharge can be 1.86 m3/s and 1.52 m3/s for Amuria and Soroti districts respectively. The useful power delivered by the pump is 41.16 W for Amuria district and 25.57 W for Soroti district. Therefore, more useful power delivered by the pump can happen when situated in Amuria district because of the high mean wind speeds occurring in that region.

Evaluation of the wind energy potential using the maximum and minimum mean wind speeds, results showed that discharges for both maximum and minimum speeds were high in Amuria than soroti. The discharge as a result of maximum and minimum wind speeds has the potential to water 1743 and 1255 number of cattle respectively. The findings about the wind potential in water abstraction systems in Teso region, can be the future reference for engineers designing the wind pumps or those planning to set up pumps in Teso region.

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