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Analysis and Modeling of Wastewater Reuse Externalities in African Agriculture

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Abstract

Wastewater reuse has been identified to alleviate freshwater scarcity, improve crop yield and sustain the environment. This study analysed and modeled wastewater reuse externalities in the context of African agriculture. Data were retrieved from FAO-AQUASTAT (2015). Descriptive statistics and correlation analyses were performed to analyse the potentials of wastewater and determine the relationship between the environmental implications of treated effluent respectively. Cost-Benefit Analysis (CBA) and Stochastic frontier cost functions were modeled for estimating the economic/environmental trade-offs of wastewater reuse and costs of wastewater treatment. The descriptive results indicated that Northern Africa, which is the most vulnerable region, has the greatest potentials of wastewater reuse. The quantity of effluent from treatment plants was inversely proportional to the treatment capacity between Northern and Southern Africa. Correlation analysis results show that "area of land salinized" had a highly positive significant correlation with the quantity of treated wastewater used (r=0.69). CBA was modeled to account for treatment cost, health cost, cost of soil reclamation, aquifer damage cost, increased crop yield and aquifer recharge. A conceptual Stochastic Frontier Model (SFM) was also developed in this research as no previous studies took into account inefficiency parameters (negative externalities) accompanied with wastewater reuse. African regions living above *water-poverty line* must however not wait till when freshwater will become a limiting resource. The significance of salinity in this study calls for the use of appropriate agronomic practices to remediate saline soils. Stochastic frontier is recommended to be applied to empirical data for further studies considering the valuation of externalities. In conclusion, this study puts wastewater on the policy agenda by emphasizing its impacts in agriculture.

Keywords: Wastewater, Africa, Externalities, Cost-benefit analysis and Stochastic frontier model.

1. Introduction

Wastewater reuse is gaining importance for irrigation purposes in the world today (IWMI, 2014). This is often adduced to incessant drought associated with low annual rainfall, pollution of water bodies, health hazards from untreated wastewater, increasing demand for perishable food and nutrient supplementation potential of the water (SAI, 2010). These factors become more prominent in Northern areas of Africa especially in the semi-arid and arid regions where water consumption exceeds available water to meet increasing demand for industrial, domestic and agricultural needs at the expense of its ecological implications (Boelee, 2011).

There are both positive and negative externalities accompanied by wastewater reuse in agriculture. The positive externalities are environmental benefits due to reduced discharge of saline wastewater into natural bodies, increased agricultural productivity and reduced climatic risks. Negative externalities of wastewater reuse include: potential groundwater pollution, increased soil salinity and impairment of human health (Mekala et al. 2008).

Irrigation potentials in African agriculture have not been optimally explored. IFPRI (2010) reported that despite high determinants of wastewater reuse, food production in Africa is largely rain-fed. It also has the least irrigated area of the total cultivable area of land, amounting to about 6 percent compared with 37 percent for Asia and 14 percent for Latin America respectively (FAOSTAT, 2009). Likewise, more than 67 percent of existing irrigated area is concentrated in five countries - Egypt, Madagascar, Morocco, South Africa and Sudan - which have more than 1 million hectares of irrigated areas. There are also few countries in Africa like South Africa, Tunisia and Namibia with experience in planned reuse and a record of wastewater treatment plants producing safe effluents (Bahri et al. 2008).

However, there are evidences that wastewater is used either raw or partially treated due to high treatment cost and unconsciousness of danger attributable to unsafe wastewater utilization (Corcoran et al. 2010). Scarcity of water and the need to protect the environment and its natural resources is significant in considering wastewater treatment and reuse as an option. Despite the increasing reliance on wastewater reuse, only few studies have taken into account militating factors like high treatment cost of wastewater and poor awareness of people of the danger of unsafe wastewater utilization especially in developing regions of the world. Economic, institutional, health and environmental impacts that hamper the sustainable and safe recycling of wastewater need to be emphasized.

The broad objective of this research paper is to assess the potentials of wastewater reuse for irrigation; analyze the environmental implications of municipal wastewater treatment facilities and develop models that will be used to estimate the cost of wastewater treatment and its implications (economic, environmental and health impact) in African agriculture.

1.1 Estimation of Externalities in the Water Resource Context

Wastewater treatment has both environmental benefits (positive externalities) and associated threats (negative externalities). These externalities are sometimes difficult to ascribe monetary quantification because they have no market value. In spite of this, the monetary valuation of these externalities is necessary to justify the economic feasibility of wastewater treatment projects (Molinos-Senante et al. 2010). Studies had shown in the past that conventional methods like Hedonic Prices and Contingent Valuation Methods (CVM) were used to measure the monetary benefits and costs of wastewater reuse in terms of environmental and health benefits. Godfrey et al. (2009), Chen and Wang (2009) applied a Cost-Benefit Analysis (CBA) to a grey-water and wastewater reuse projects. Likewise, Travel-Cost Method (TCM) was used to determine the positive externalities arising from wastewater reuse in the context of a wetland restoration project (Segui et al. 2009). Moreover, TCM has been widely used in numerous practical applications related to water resources and considered a consolidated technique (Bergstrom et al. 2000; Bateman et al. 2006; Birol et al. 2006; Del Saz et al. 2009).

However, a valuation method was developed for undesirable outputs with no market value in 1989 by Fare et al. This is called the *concept of distance function*, a shadow price calculated for those goods arising from human and productive activities that have no market value but create substantial environmental impacts. This method has been applied empirically in papers like Coggin and Swinton (1996), Ha Nguyen Van et al. (2007) and Hernandez et al. (2010) etc. Shadow price valuation method represents the value of external effects that could damage the environment in the case of inadequate management. This is proportional to the value of the positive externalities associated with avoiding discharge of pollution into the environment. The strength of shadow prices is that, it could be used to determine income gained in case of centrally controlled resources, thereby using the information provided to set rates for the use of environmental services or to compare the current rates with the marginal revenue (Fare et al. 2001). It may also help the society to understand the benefits generated as a result of environmental improvement programs. So, Economists can further check into estimated measures of willingness to pay from alternative methods like CVM or Capitalization Methods (Fare et al. 2001). Shadow price method also has a very low costs compared to the cost incurred in surveying processes involved in other valuation methods. In spite of these advantages, shadow price valuation is limited in relations to other stated-preference methods such as CVM and Choice Experiment Method. In estimating the total economic value of use and non-use values, stated-preference methods can be more appropriate.

2. Methods

2.1 Study Area

This research focused on African countries most especially Northern and Southern Africa. These regions are predominant for the use of treated wastewater and operation of wastewater treatment facilities. Northern Africa comprises: Algeria, Egypt, Libya, Morocco, and Tunisia, while Southern African countries include: Botswana, Lesotho, Mozambique, Namibia, South Africa, Swaziland and Zimbabwe. Other regions in Africa are Sudano-Sahelian (Burkina Faso, Cape-Verde, Djibouti, Eritrea, Gambia, Mali, Mauritania, Niger, Senegal and Somalia), Gulf of Guinea (Cote d'voire, Ghana and Nigeria), Central Africa (Congo and Democratic Republic of the Congo), Eastern Africa (Ethiopia, Kenya, Uganda and Tanzania) and the Indian Ocean Islands (Mauritius and Seychelles). The map of these countries is shown in Fig. 1. Unlike Northern and Southern African countries, there is paucity of data on treated wastewater use for irrigation in most of the other parts of Africa according to FAO-AQUASTAT (2015). Fresh water supply may not have being a limiting resource, thus, necessitating little research on wastewater reuse in these areas.

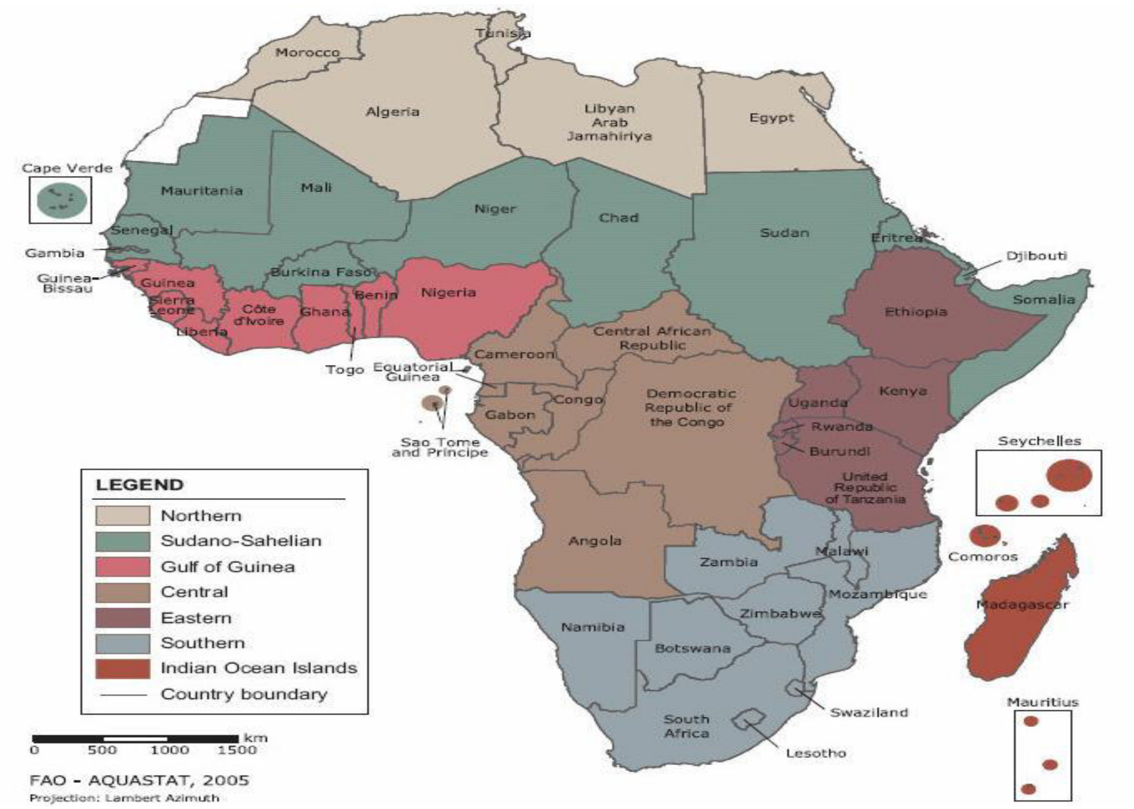

Figure 1: Regional Division of Africa (FAO-AQUASTAT, 2005)

2.2 Data Sources and Analytical Techniques

Data for this study were retrieved from Food and Agriculture Organization of the United Nations (AQUASTAT, 2015) in collaboration with the International Water Management Institute (IWMI). AQUASTAT is FAO's global water information system developed by the Consultative Group on International Agricultural Research (CGIAR) program on water, land and ecosystems led by IWMI and the land and water division. They provide regional data on countries in Africa, Asia, Latin America and the Caribbean.

Wastewater variables collected include:

i. Produced municipal wastewater (10^9m^3 per year)
ii. Collected municipal wastewater (10^9m^3 per year)
iii. Treated municipal wastewater (10^9m^3 per year)
iv. Number of municipal wastewater treatment facilities
v. Capacity of the municipal wastewater treatment facilities (10^9m^3 per year)
vi. Untreated municipal wastewater (10^9m^3 per year)
vii. Treated municipal wastewater discharge (secondary water) (10^9m^3 per year)
viii. Untreated municipal wastewater discharge (secondary water) (10^9m^3 per year)
ix. Direct use of treated municipal wastewater (10^9m^3 per year)
x. Direct use of treated municipal wastewater for irrigation purposes (10^9m^3 per year)
xi. Direct use of untreated municipal wastewater for irrigation purposes (10^9m^3 per year)
xii. Area equipped for irrigation by direct use of treated MWW (1000 ha)
xiii. Area equipped for irrigation by direct use of untreated MWW (1000 ha)
xiv. Area salinized by irrigation (1000 ha)
xv. Percentage of area equipped for irrigation salinized (%)
xvi. Area waterlogged by irrigation (1000 ha)
xvii. Population affected by water related disease (1000 inhabitants)

Descriptive statistics such as frequency distribution table, percentages and graphs were used to analyse the wastewater variables in line with its irrigation potentials. Correlation analysis was performed by using the Pearson's Product-Moment Correlation (PPMC) to determine the relationship between the environmental implications of treated municipal wastewater effluent.

PPMC is defined as:

$$\rho X_i, Y = (X_i, Y) = \frac{Cov\ (X_i, Y)}{\sigma X\ \sigma Y} = \frac{E[(X_i - \mu x)(Y - \mu y)]}{\sigma x\ \sigma y} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where:

X_i and Y are random variables with expected values $\mu x, \mu y$ and standard deviation $\sigma x, \sigma y$

$Y =$ Treated municipal wastewater $10^{9m^3}/year$

$X_1 =$ Area salinized by irrigation (1000 ha.)

$X_2 =$ Percentage of area equipped for irrigation (%)

$X_3 =$ Area waterlogged by irrigation (1000 ha)

$X_4 =$ Population affected by water related disease (1000 inhabitant.)

CBA and Stochastic Frontier Cost Function were modeled to specify the economic/environmental trade-offs of wastewater reuse and costs of wastewater treatment. CBA is represented as;

$$CBA = \frac{\sum \text{costs}}{\sum \text{benefits}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Costs considered in this study were;

a. Cost of soil reclamation (C1)
b. Aquifer damage cost (C2)
c. Health cost (C3)
d. Capital and operational cost of wastewater treatment (C4)

Benefits accruing to wastewater reuse in agriculture may be quantified by calculating the quantity of crop yield (B1) (kilogram or tons) and Aquifer recharge benefit (B2). All these can further be converted into monetary terms.

There are many underlying assumption that must be taken into consideration in CBA analysis of wastewater reuse trade-offs. In wastewater treatment, an economically feasible treatment implies that the benefits accruing from the treatment process is greater than its associated cost. CBA must however be expressed in the same unit (monetary term). Even if there are environmental externalities that are difficult to quantify, then shadow price for undesirable output in wastewater may homogenize CBA method. It should also be noted that monetary quantification of environmental benefits derived from wastewater treatment is more complex than calculating its cost, since benefits have no market value.

Stochastic Frontier Model (SFM) is specified according to Battese and Coelli (1995) based on the assumption that wastewater treatment is a production process;

$$\ln Ci = \alpha_0 + \alpha_i \ln X_i + (V_i + U_i) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where:

$Ci = costs$

α_0, α_i are parameters (efficiency variable)

$X_i =$ regressors

$V_i =$ efficiency model $(\ln Ci - U_i)$

$U_i =$ inefficiency model

$U_i = \delta_0 + \delta_i Z_i$

δ_0, δ_i are inefficiency parameters

The strength of using SFM to model wastewater treatment cost is that, it may improve on other existing models used by past researchers. SFM uses more factor variables, thus gaining an insight into the key role of the economies of scale. Also, it independently account for both efficiency and inefficiency parameters associated with wastewater treatment. This methodology has not been tried till date (2015), with exception to the work of Hernandez-Sancho et al. (2011) which uses Cobb-Douglas function to model the cost of wastewater treatment processes.

3. Results and Discussion

Northern region of Africa is the most vulnerable and explored the greatest potentials of wastewater reuse (Fig. 2). According to the descriptive statistics result (Table 1), the average quantity of treated municipal wastewater used in Northern Africa for irrigation (81.8 million m^3 per year) was higher than that of South African region (1.02 million m^3 per year) and Sudan-Sahelian region (0.01 million m^3 per year). Northern Africa produces about 1.9 billion m^3/year of municipal wastewater, while their treatment capacity is in the range of 1.3 billion m^3/year

(Table 1). This capacity is however not sufficient as this region has the largest untreated effluents' use (993 million m^3/year), followed by Gulf of Guinea (86 million m^3/year) and South Africa (324 million m^3/year). Moreover, in Northern Africa, Egypt has the highest (372) number of municipal wastewater treatment facilities compared to the whole countries in Africa. Algeria (138) and Tunisia (109) takes precedence in the number of treatment facilities acquired (Table 1). 9820 hectare of land area is equipped for irrigation by direct use of treated municipal wastewater in Northern Africa, and Southern Africa region accounted for about 629 hectare of land area equipped for irrigation. The problem of increased soil salinity was prevalent in the Northern part of Africa as this region has 135200 hectare of land area salinized by irrigation, followed by Gulf of Guinea (33827hectare), East Africa (20000 hectare), Southern Africa (14757 hectare) and Sudan-Sahelian (35 hectare).

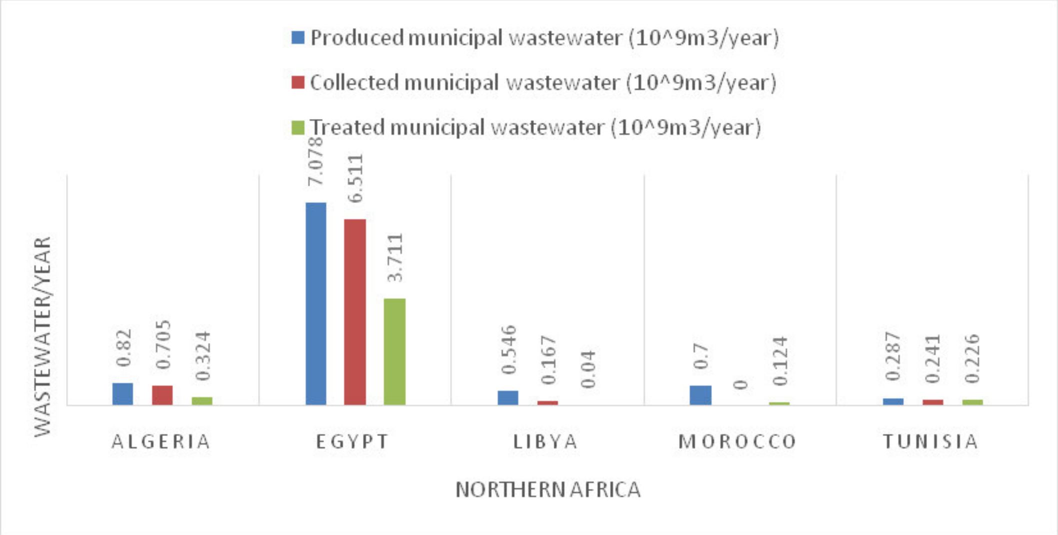

Figure 2: Quantity of Wastewater produced, collected and treated in Northern Africa (AQUASTAT, 2015)

Table 1: Descriptive statistics parameters of wastewater reuse in Africa

Variables (mean value)	*A*	*B*	*C*	*D*	*E*	*F*	*G*
Produced MWW (10^9m^3/year)	1.886	0.00418	0.093	0	0.00175	0.537	0.0044
Collected MWW (10^9m^3/year)	1.525	0.00024	0.0093	0	0.01175	0.396	0
Treated MWW (10^9m^3/year)	0.885	0.00031	0.0074	0	0	0.291	0.0195
Number of MWW treatment facilities	778.0	6.80	24.333	0	0	1060.0	0
Capacity of the MWW treatment facilities (10^9m^3/year)	1.284	0	0	0	0	0.346	0
Untreated MWW (10^9m^3/year)	0.993	0.0004	0.086	0	0	0.324	0
treated MWW discharged (Secondary water) (10^9m^3/year)	0.634	0.00001	0	0	0	0.044	0
untreated MWW discharged (Secondary water) (10^9m^3/year)	0.314	0	0	0	0	0	0
Direct use of treated MWW (10^9m^3/year)	0.168	0.00014	0	0	0	0.231	0.000003
Direct use of treated MWW for irrigation purposes (10^9m^3/year)	0.082	0.00001	0	0	0	0.0010	0
Direct use of untreated MWW for irrigation purposes (10^9m^3/year)	0.0117	0	0	0	0	0	0
Area equipped for irrigation by direct use of treated MWW (1000ha)	9.820	0	0	0	0	0.629	0
Area equipped for irrigation by direct use of untreated MWW (1000ha)	1.60	0.95	0.247	0	0.50	3.143	0
Area salinized by irrigation (1000ha)	135.2	0.035	33.827	0	20.00	14.757	0
Area waterlogged by irrigation (1000ha)	48.0	1.95	0	1.0	0	0	1.35
Proportion of area equipped for irrigation salinized (%)	14.532	0.048	11.483	0	6.783	3.292	0
Population affected by water related disease (1000 inhabitants)	0	1171.76	474.33	87.6	0	0.418	0

Source: AQUASTAT (2015). **MWW**=Municipal Wastewater, **A**=Northern Africa, **B**=Sudano Sahelian, **C**=Gulf of Guinea. **D**=Central Africa, **E**=Eastern Africa, **F**=Southern Africa &**G**=Indian Ocean Islands

The correlation analysis results (Table 2) show that, area equipped and waterlogged for irrigation and population of inhabitants affected by water-borne diseases were inversely correlated to the quantity of treated wastewater utilized in the study area. Area salinized by irrigation had a strong positive correlation with treated wastewater use.

Table 2: Correlation analysis results of environmental implications of wastewater reuse in Africa

Variables correlated	*n*	*r*	*Sig.*
Treated wastewater (Y) vs Area salinized by irrigation (*X1*)	33	0.685**	0.000
Treated wastewater (Y) vs Percentage area equipped for irrigation (*X2*)	33	-0.093	0.608
Treated wastewater (Y) vs Area waterlogged by irrigation (*X3*)	33	-0.045	0.805
Treated wastewater (Y) vs Population affected by water-related diseases (*X4*)	33	-0.092	0.611

Source: AQUASTAT (2015). ** Correlation is significant at 0.01 level (2-tailed). Y is Treated Wastewater (m^3/year), *n* is the number of observations and *r* is the correlation coefficient.

The average regional quantities of treated municipal wastewater use in Africa were proportional to the rate of collected and produced municipal wastewater (Table 1). The severity of water-stress encountered in Northern Africa resulted in the establishment of about 778 municipal wastewater treatment facilities, with Egypt having the highest (372), followed by Algeria (138) and Tunisia (109). The overall number of these facilities present in Northern Africa cannot be compared with those owned by the Southern African region, with South Africa alone having about 923 treatment plants and Zimbabwe, 137 treatment facilities. These results indicated that, the quantity of treatment plants had negative correlation with its treatment capacity between these regions (Northern and Southern Africa), as the former that had the least number of treatment facilities compared to the latter, produced the highest effluents (6.422 X 10^9 m^3 per year). This conforms to the suggestion of Tawfic

(2008), that in Northern Africa, an additional treatment capacity of 1.7 billion m^3 is targeted by 2017. Although the capacity increase is significant, it will not be sufficient to cope with the future increase in wastewater production from municipal sources and therefore, the untreated loads that will reach water bodies are not expected to decline in the coming years. Nevertheless, despite that Northern African region had functional wastewater treatment facilities, an average quantity of untreated municipal wastewater used for irrigation purpose by farmers was estimated to a whopping of 11.7 million m^3 per year. This posed serious environmental danger, as the average area of land equipped for irrigation by direct use of untreated municipal wastewater in Northern Africa was 5,719 hectares and Southern Africa, 1,886 hectares respectively. Notable environmental implication of treated wastewater use was increased soil salinity which had 69 percent correlation coefficient (Table 2). Water-related diseases were devastating in regions with low or zero usage of treated effluents, like the Sudano-Sahelian region having an average of about 1.2 million inhabitants affected by water-related diseases, Gulf of Guinea (0.48 million inhabitants), Central Africa (0.088 million inhabitants) and an infinitesimal number of people in Northern and Southern Africa affected by waterborne diseases (fig. 3).

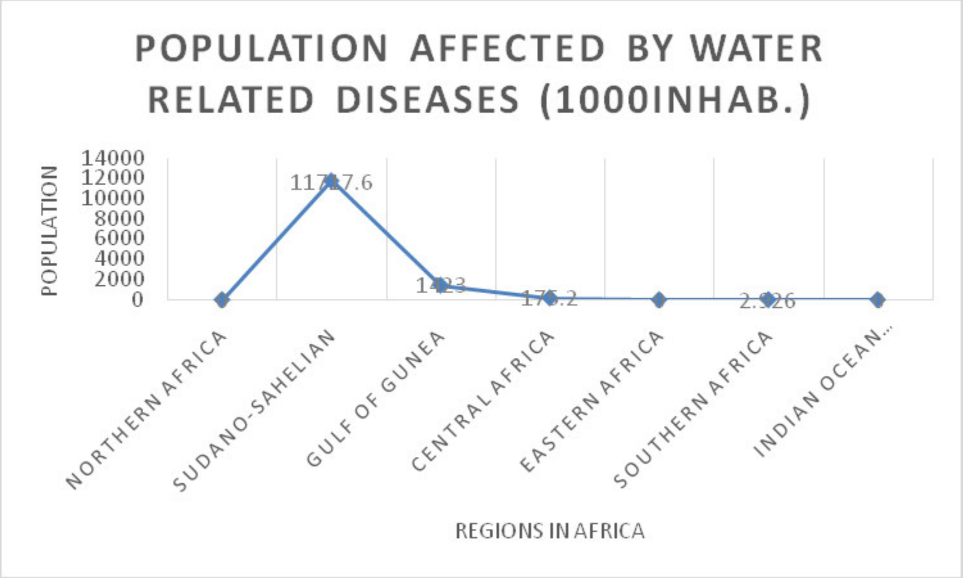

Figure 3: Population of inhabitants affected by water-related diseases in Africa (AQUASTAT, 2015)

According to the correlation analysis results (Table 2), "*area of land salinized*" had a highly positive significant correlation with the quantity of treated wastewater used (r=0.69). All the other independent variables (proportion of area equipped for irrigation salinized, area waterlogged by irrigation and population of people affected by water-related diseases) exhibited a weak negative coefficient (r=-0.093, -0.045 and -0.045 respectively) with treated wastewater use. This implies that, the higher the quantity of treated wastewater used, the lower the area equipped for irrigation salinized, decreased waterlogged area and reduced population of people affected respectively. The area salinized by irrigation was a major implication as it was significant at 0.01 level.

In modeling cost-benefit equation for estimating the economic and environmental trade-offs of wastewater reuse, costs taken into consideration were; capital and operational cost of wastewater treatment ($C1$), health cost ($C2$), soil reclamation cost ($C3$) and aquifer damage cost (C4). The benefits of using wastewater were adduced to increase in crop yield production ($B1$) and aquifer recharge benefit ($B2$). So the equation for the cost-benefit analysis (CBA) will be:

$$CBA = \{\frac{(C1 + C2 + C3 + C4)}{(B1 + B2)}\} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (4)$$

$C1$ depends on daily wastewater, its quality and technology employed. Following Tsagarakis (2003), the wastewater treatment cost follows the functional form:

$$C1 = aWW^b + t \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . . \dots . (5)$$

WW is the treatment plant capacity (m^3) which depends on the population of inhabitants, a & b are coefficients which have been used to express factors like land requirements, construction and operational costs; t is constant based on the type of technology used. According to the work of Molinos-Senante et al. (2010), $C1$ can be further decomposed into:

$$C1 \ = \sum X_i \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

Where:

X_1 is the energy cost which includes: the cost related to the fixed part of the energy consumption (power term)

and the variable part (energy consumption) of the installation.
X_2 is labour costs which reflect wages, social security charges, taxes, and social insurance.
X_3 is the term reagents which include the cost of the reagents required for water and sludge.
X_4 is waste costs which include the costs associated with waste and sludge management.
Finally, the cost of maintenance (X_5) is considered-including concepts such as equipment and machinery maintenance and depreciation.
C2 is quantified using equation modified from Guang (2000);

$$L = \{PT_i(L_i - L_{oi}) + Y_i(L_i - L_{oi}) + PH_i(L_i - L_{oi})\}M + A \ldots\ldots (7)$$

Where:
$L =$ value of lost health resulting from wastewater irrigation/year
$P =$ human capital (per capita value), US$/ year per person
$M =$ population of people exposed to wastewater and consumers of crops produced using wastewater (number of persons)
$T_i =$ Average annual loss of labor by patients suffering from wastewater *related diseases* (US$ / year)
$Y_i =$ Average medical and nursing expenses for patients sick with *wastewater related diseases* (US$ / year)
$H_i =$ Average annual work time lost by relatives accompanying family *members' sick with one*
$L_i, L_{oi} =$ respectively, the incidence of wastewater related diseases among *population exposed to wastewater reuse and consumption of crops;* and *clean areas (person* / 100,000 *person / year)*

Wastewater has negative impacts on the health of the farmers, the consumers and the environment exposed to wastewater irrigation impacts (Table 1 & 2).
C3 is necessary since wastewater irrigation has negative effects on the soil (salt accumulation causes soil infertility, loosen soil structure, heavy metal accumulation etc.); this results into yield loss in the long run and depreciation of market value of land. Measuring yield differentials may be biased to estimate *C3*, but a reliable way is to calculate the cost of resuscitating soil fertility (like cost of fertilizer, manure, lime etc.).
C4 is represented by seepage of harmful elements like nitrates below the root-zone contaminating groundwater. This is considered hazardous according to WHO (2006) recommendation when the level of nitrate exceeds 50 mg/l.
In estimating *B1*, we assume that a farmer produces Q_i which is the quantity of crop *i* produced, considering factors of production like, wastewater input (WW_i), fertilizer (F_i), labour (L_i), seeds (S_i) and other variable inputs (X_n). This is expressed as;

$$Q_i = f(F_i, L_i, S_i, WW_i, X_n) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (8)$$

B2 is the current value of water from contribution of irrigation to aquifer recharges. The price of the fresh water unit should be used in calculating the total benefit of groundwater recharge by irrigated wastewater. Where *CBA* is less than 1, it implies that the costs outweigh the benefits, but if greater than 1, then the benefits outweigh the costs, and it is worthwhile to consider the treatment of wastewater.
Recall from equation (3) that, Stochastic Frontier Model (SFM) was specified according to Battese and Coelli (1995);

$$\ln Ci = \alpha_0 + \alpha_i \ln X_i + (V_i + U_i) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

The SFM parameters is stated and explained as;
$Ci =$ *total cost of operation and maintenance of treatment plant / year*
α_0, α_i *are coefficient of efficiency variable* (X_i)
$X_i =$ *volume of wastewater treated* (m^3 *per year*)
$V_i =$ *efficiency model* ($\ln Ci - Ui$)
$U_i =$ *inefficiency model*
$U_i = \delta_0 + \delta_i Z_i$, δ_0, δ_i are coefficient of inefficiency variable (Z_i)
Z_i *are externalities, i.e. shadow prices of contaminants.*

These externalities have no market value and can be estimated using the stated-preference methods (like shadow pricing). This method suffers a drawback relating to bias in sample or responses when attempting to apply a valuation to some cost or benefit of a project. Also, the value of a good or impact resulting from a project when measured using shadow pricing may however differ from the market prices. Shadow prices in this case are the inefficiency variables (Z_i) associated with effluent production in SFM, unlike other models tried in the past, which doesn't take this into account. Wastewater treatment can however be considered a production process in which the needed output i.e. treated water, is obtained alongside with series of pollutants like organic matter, phosphorus, and nitrogen. Contaminants extracted from wastewater are considered undesirable outputs because if they were discharged in an unregulated manner, they would cause a negative impact on human and the environment.

Since wastewater treatment produces both the desirable and undesirable output, making this total output our dependent variable may not be justifiable since they vary in quality. Better still; the total cost of producing treated effluents will be our dependent variable. Multinomial logistic regression could have been a suitable model if we are to consider all the wastewater treatment outputs as our dependent variables, but these outputs (treated water and contaminants) are not mutually exclusive since the production of treated wastewater will definitely imply the production of undesirable outputs like sludge and other contaminants.

From equation 3, *C1* have been formulated, i.e. equation 5 and 6. This is the cost of operation and maintenance of wastewater treatment plant in US dollar per annum. X_1 is the volume of treated wastewater (m^3/year), Z_1 is the shadow prices of contaminants which will be removed during treatment i.e. suspended solids, chemical oxygen demand (organic matter/microbes), nitrogen and phosphorus (measured in kilogram per year). This indirectly signifies the benefit resulting from wastewater treatment. Shadow price valuation method is based on the *concept of the distance function* (Fare et al. 1989). This function provides the distance of a vector of outputs from the maximum output frontier and starts from a vector of constant inputs. Let us assume that the production process uses a vector of *N* inputs$x \in R_+^c$to produce a vector of *M* outputs $u \in R_+^{x_i}$ the distance function is defined as:

$$D_0(x,u) = Min\{\theta : (u/\theta) \in \mathrm{P}(x)\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Where:

$$\mathrm{P}(x) = vector\ output\ that\ are\ technically\ viable\ \&\ use\ vector\ of\ inputs\ x$$

$$(u/\theta) = output\ ratio\ in\ production\ frontier$$

$$\theta\ is\ a\ ratio\ between\ 0\ \&\ 1, i.e. D_0(x,u) \in [0,1].$$

$$Thus, D_0(x,0) = 0\ \& D_0(x,u) = 1$$

If *u* belongs to production frontier, i.e. the most efficient, this implies a production process using a minimum of inputs to produce a particular output. In this case, wastewater treated with a certain quantity will be placed on the production frontier (Hernandez and Sala, 2009).

For flexibility sake, the translog function is the most appropriate when considering a problem with *k* units, *n* inputs and *x* outputs. The formula can be illustrated as:

$$\begin{aligned}\ln D_0(x^k,u^k)^0 = \alpha_0 &+ \sum_{n=1}^{N} \beta_n \ln x_n^k + \sum_{m=1}^{M} \alpha_m \ln u_m^k \\ &+ \frac{1}{2}\sum_{n=1}^{N}\sum_{n^i=1}^{N} \beta_{nn^i} (\ln x_n^k)(\ln x_{n^i}^k) \\ &+ \frac{1}{2}\sum_{m=1}^{M}\sum_{m^i}^{M} \alpha_{m\,m^i} (\ln u_m^k)(\ln u_{m^i}^k) \\ &+ \sum_{n=1}^{N}\sum_{m=1}^{M} \gamma_{nm} (\ln x_n^k)(\ln u_m^k) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)\end{aligned}$$

α, β, γ can be calculated under empirical studies using Linear Programming.

$$MaxZ = \sum_{k=1}^{k} [\ln Do(x^k,u^k) - \ln 1] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

Subject to:

(i) $\ln Do(x^k,u^k) \leq 0$

(ii) $\frac{\partial \ln Do(x^k,u^k)}{\partial \ln u_m^k} \geq 0, (m = 1)$

(iii) $\frac{\partial \ln Do(x^k,u^k)}{\partial \ln u_{m^i}^k} \leq 0, \left(m^i = 2, 3, 4 \dots\dots\right)$

(iv) $\sum_{m=1}^{M} \alpha_m = 1; \sum_{m=1}^{M} \beta_{nn^i} = \sum_{ni=1}^{N} \gamma_{nm} = 0 \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (12)$

(v) $\alpha_{mm^i} = \alpha_{m^i m}; m = 1, \dots, M;\ m^i = 1, \dots, M$

$\beta_{nn^i} = \beta_{n^i n}; n = 1, \dots, N;\ n^i = 1, \dots, N.$

According to Shephard (1970) and Fare et al. (1993), simultaneity relationship between the distance and revenue function creates the link between relative and absolute prices. This is expressed as:

$$R(x,u) = \underset{u}{Max}\ \{ru : D_0\,(x,u) \leq 1\} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (13)$$

$$D_0(x,u) = \underset{r}{Max}\ \{ru : R(x,u) \leq 1\} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. \quad (14)$$

$R\ (x,u) = revenue\ function$

$r = output\ prices$

Assuming that both the distance and revenue function can be differentiated, the Lagrange multiplier method and Shephard's duality theorem make possible the calculation of shadow prices under empirical analysis.

4. Conclusions

As agriculture remain the major user of freshwater, strategies for improving water-use efficiency and identifying options are crucial for solving the problem of water scarcity and ensuring that water is available for use in other sectors where it has higher economic value. Nevertheless, there is still both economic and environmental justification irrespective of the cost of wastewater reuse. Beside the direct benefits of increasing water supply, safeguarding the environment from pollution and health effect of dumping wastewater does not only justify the allocated resources, but also supports sustainable development. This consequently averts the costs of pollution and the use of contaminated water by downstream users such as farmers, industries, other municipalities and even tourist industry. In this vein, wastewater is seen as an economic good in some regions in Africa like Northern and Southern Africa. Other regions living above *water-poverty line* must however not wait till when freshwater will become a limiting resource, because unvalued water may lead to an uncertain future. Investment in safe wastewater collection and treatment can remove a potential brake on economic activity in Africa. It is also important to be weary of the increased use of wastewater overtime and the vagaries of climate change.

Salinity was a major concern in wastewater reuse for irrigation in Africa, as it has a high positively significant correlation. Proper agronomic practices should be put in place to reduce the effect of salinity – Addition of Potassium, strip cropping, intercropping with salt resistant crops etc. This study also shows the variety of wastewater treatment qualities with the cost-benefit components to achieve acceptable irrigation practices. It should be noted that, lower levels of wastewater treatment might results into lower capital, operation and maintenance cost, but higher environmental/health cost. Soil reclamation and irrigation cost could also increase in the long-run and vice versa. Stochastic frontier model specified in this study is recommended to be applied to empirical data for further studies considering the valuation of externalities.

In conclusion, this study puts wastewater on the policy agenda by analyzing and modeling wastewater reuse externalities for irrigation in agriculture.

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