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Table of Contents: Volume 9 Number 1 January 2017

ARTICLES

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Full Length Research Paper

Comparative assessment of soil and nutrient losses from three land uses in the central highlands of Ethiopia

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Land use/land cover change drive changes in several ecosystem processes over short and long terms. In Ethiopia, the main land use/land cover change involves conversion of natural ecosystem into cultivated land. However, a recent change also involves conversion of cultivated and grazing land into *Eucalyptus* woodlots. This study was conducted to analyse the effects of such land use/land cover change on soil and nutrient losses. Three land use/ land cover types (cultivated land, grassland and *Eucalyptus* woodlot) were selected for a comparative assessment. A total of twelve runoff plots, each with 43.3 m^2 area and with four replications, were installed. Rainfall depth, runoff volume and sediment samples (500 ml) were collected from each plots every morning and evening for 91 days (from 4th July to 2nd October, 2015) in the main rainy season. The sediment samples for ten consecutive days were stored in separate containers and composite sediment concentration samples were weighed after being filtered and oven dried for 24 hours at 105^{o}c. From the samples taken at the end of the rainy season, separate composite a sample before filtration of one litre was analysed in the laboratory for nutrient losses. The effect of land use/land cover on soil and nutrients losses was statistically tested using analysis of variance. The study found that soil loss significantly differed between the land use/land cover types. Soil loss from cultivated land (16.8 ton/ha) was significantly higher than loss from grassland (7 ton/ha) and *Eucalyptus* stand (8.1 ton/ha). The soil and nutrient losses were positively correlated with runoff volume. There was higher nutrient (N and P) loss from cultivated land than grassland and *Eucalyptus*. From the results, it can be concluded that soil and nutrients losses are above tolerable limit, and perennial land covers including *Eucalyptus* stand reduce soil and nutrient losses significantly. This re-affirms the multi-purpose nature of *Eucalyptus* not only for socioeconomic benefit but also for soil erosion control when planted in appropriate locations.

Key words: Cultivated land, grassland, runoff, sediment concentration, runoff plot.

INTRODUCTION

Land use/ land cover (LULC) changes are occurring throughout human history (Briassoulis, 2000; Lambin et al., 2003; Kindu et al., 2015; Wubie et al., 2016). Among the major changes, the shift from natural ecosystem to cultivated land by involving deforestation is the most common (Zeleke and Hurni, 2001; Bewket, 2002; Dwivedi et al*.,* 2005). Contrary to this process, a recent phenomenon in the Ethiopian highland is the conversion of land back from cultivated to *Eucalyptus* stand (Fisseha et al*.,* 2011; Jenbere et al*.,* 2012; Chanie et al*.,* 2013, Jaleta et al*.,* 2016a).

Eucalyptus has been acclaimed to have social, economic and ecological benefits (Lemenih, 2010; Kebebew and Ayele, 2010; Bekele, 2015). Farmers are continuing planting *Eucalyptus* converting their farm plots due mainly its positive economic benefits (Mekonnen et al*.,* 2007; Adimassu et al*.,* 2010). However, the uncontrolled expansion of *Eucalyptus* also is raising controversies with respect to the alleged ecological effect of the species (Jagger and Pender, 2003; Chanie et al*.,* 2013; Jaleta et al*.,* 2016b). *Eucalyptus* is considered to consume higher water and nutrients and it has allopathic effect on undergrowth vegetation (Nigatu and Michelsen, 1993; Fikreyesus et al., 2011; Chanie et al*.,* 2013). It is also considered as less desirable species for soil-water conservation (Chanie et al*.,* 2013), which has led to banning of its plantings, once in Tigray region, which was latter lifted (Jagger and Pender, 2003).

Soil and nutrient losses from the highlands of Ethiopia is a major environmental challenge owing to high rate of soil erosion (FAO, 1998; Tekele and Hedlund, 2000; Amsalu et al*.,* 2007). The current expansion of *Eucalyptus* is also feared to intensify the problem. Therefore, it is essential that studies are conducted to assess the effect of *Eucalyptus* on soil erosion and nutrient loss to help informed decision making for policy makers as well as plantation developers. The objective of this study was therefore to quantify soil and nutrient losses from under *Eucalyptus* stand in comparison with two other LULC types namely cultivated land and grassland, at Meja River watershed in Central Ethiopia.

MATERIALS AND METHODS

Description of the study area

Meja River watershed, where this study was done, found at Jeldu district, in West Shewa, central Ethiopia. Tiki and Sochoa sub catchment of the watershed were selected to install the runoff plots for the study. The catchments are located 114 km west of the capital, Addis Ababa, Ethiopia. The study sites is located within 9° 02' to 9° 15' N and 38° 05' to 38° 12' E, altitude ranging from 2400 to 3200 m above sea level (Figure 1). The mean annual temperature ranges from17 to 25°C. The rainfall is bi-modal with the short rainy season from February to May and long rainy season from June to September. The mean annual rainfall is 1400 mm. The site is characterized by a mixed crop-livestock system. Wheat (*Triticum vulgare*), potato (*Solanum tuberosum*) and Enset (*Ensete ventricosum*) are the crops mostly grown. The watershed is known for *Eucalyptus* expansion in the central Ethiopia. *Eucalyptus* woodlots are abundant in the Meja River watershed replacing cultivated land and marginal grazing lands. *Eucalyptus globulus* is the main species of *Eucalyptus* growing in the study area. The soil is characterized as Pellic Vertisol.

Experimental design

The runoff plot (43.3 m^2) was constructed in three LULC types with four replications in two adjacent sub catchments. The LULC types are cultivated land, grassland and *Eucalyptus* woodlot. The cultivated land covered by wheat and the species of *Eucalyptus* growing is four years old *Eucalyptus globules*. The grassland was grazed highly before the instalment of the runoff plots. The details of each runoff plots characteristics were given in Table 1. Two rain gauges were installed to record daily rainfall depth in the two sub catchments. The three LULC types at each site were adjacent and share other biophysical conditions. The runoff and the rainfall depth were registered twice daily: at every morning (6:00 am) and evening (6:00 pm).

Data collection and data analysis

Runoff sample of 500 ml was collected every morning and evening from each runoff plots during the study period (from 4th July to 2nd October, 2015). Samples of each plot were separately stored for 10 consecutive days in a plastic container, which were then composited per plot at end of the 10th day. The composite samples were filtered by Whatman (0.42 µm) filter paper. The filtered material was oven dried by 105°C for 24 h, weighed and converted to dry mass in milligram per hectare (mg/ha) to yield sediment load. Soil loss (ton/ha) was then calculated from the volume of runoff and sediment load (Adimassu et al*.,* 2014).

From each runoff plots, at the end of the rainy season, composite runoff sample of one litre was taken for nutrient analysis in the laboratory. Thoroughly stirred samples were kept for 5 h in the laboratory for sedimentation. Then the topmost water in each container was collected for runoff related nutrient analysis. Total dissolved solid, electric conductivity, pH, ammonia (NH_3)-N, Nitrate (NO3)-N and Phosphate (PO4)-P were analysed at Ethiopian Water Works Design and Supervision Enterprise Water laboratory. The total runoff related nutrient losses of each plot were calculated by multiplying the average concentration of each nutrient in the runoff with the total runoff volume. Dissolved Ammonia was analysed by Phenate method using spectrophotometer, modele Eleco SL-160 double beam ultraviolet (Patnaik, 2010). Dissolved Nitrate and Phosphate was analysed by spectrophotometer, modele Eleco SL-160 double beam ultraviolet (Patnaik, 2010).

Data analysis was done using Genstat 15th edition statistical software. Analysis of variance was used to test the effect of LULC changes on soil loss and nutrient loss statistically significant at $p < 0.05$. Least significant difference (LSD) was tested to compare the mean values at $p < 0.05$. The runoff and soil loss mean values regressed among themselves to see the runoff- soil loss relationships.

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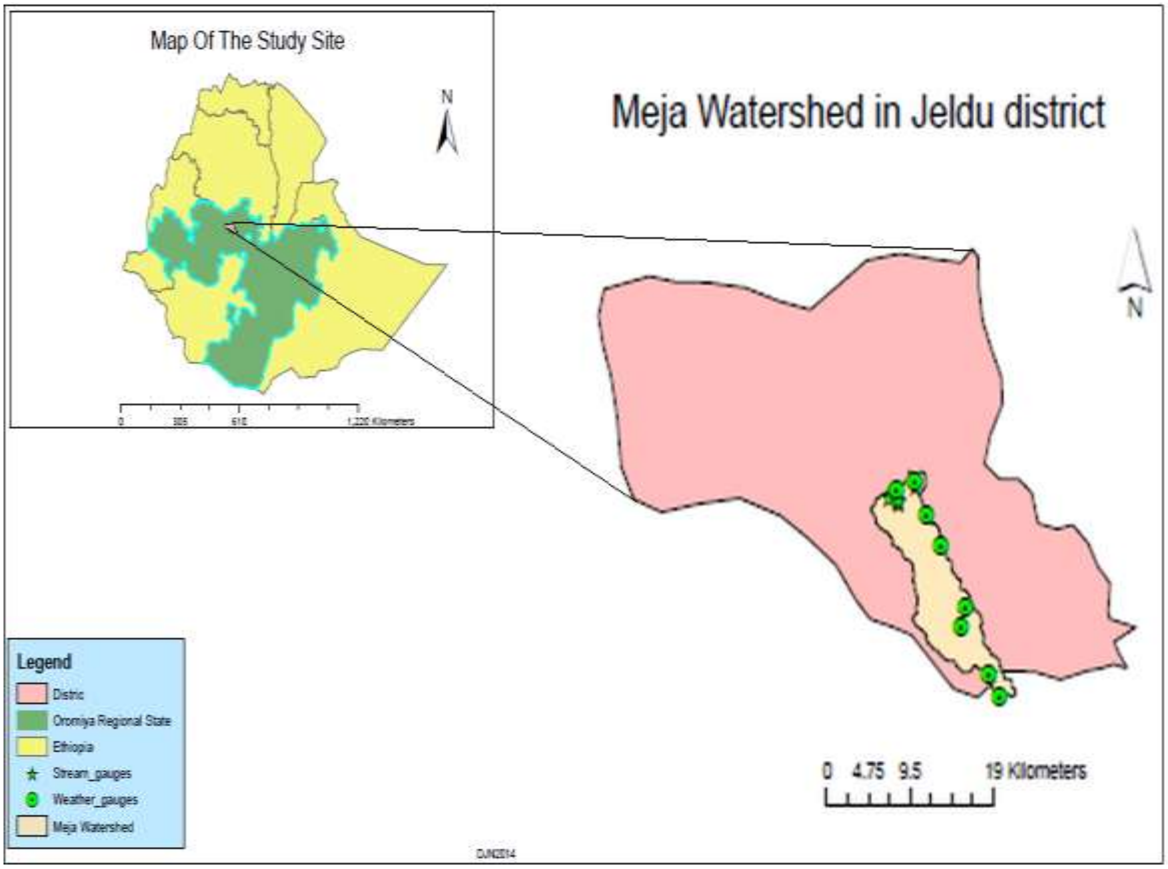

Figure 1. Map of the study area.

Table 1. Biophysical conditions of the runoff plots.

Plot code	Moisture content (%)	EC (μS/m)	Soil temp. (°C)	Slope degree	Stone Cover (cm)			Ground cover			Crown cover (%)
					Low	Middle	Up	Weed	Stubble	Organic residues	
C3	7.49	0.82	28.65	10	_	_	_	75	233	5	-
C4	10.86	1.01	27.5	10	_	_	3	67	396	11.5	-
G3	13.99	1.61	25.9	12	_	_	_	34	Grass	27.5	-
G4	17.72	1.85	26.7	12			_	25	Grass	22.5	-
E3	14.09	1.31	25.9	11	8	23	_	129	-	621	55
E4	17.47	1.6	24.05	11	_	7	_	40	-	482	55
C1	13.03	1.09	26.5	8	_	_	_	65	261	2.5	-
C2	7.04	1.04	24.11	8	2.5	8	9	95	315	0	-
G1	14.27	1.31	25.05	9	_	_	_	38	Grass	4	-
G2	18.73	1.53	22	9	_	_	_	34	Grass	3	-
E1	12.06	0.91	23.7	8	_	_	_	93	-	241	40
E2	12.76	1.18	28.2	8	_	_	_	84	-	196	42

RESULTS AND DISCUSSION

The runoff volume collected within the study period differed significantly between the LULC types. The mean runoff harvested from the cultivated land is 30% higher than that of grassland and 17% higher than that of *Eucalyptus* stand (Table 2). There was slightly higher runoff volume generated from *Eucalyptus* field

Table 2. Total runoff collected from each LULC types within study period.

Replication	LULC types		
	Cultivated land (mm)	Grassland (mm)	*Eucalyptus* (mm)
1	194.91	156.44	159.78
2	202.21	154.06	158.27
3	183.97	143.61	148.88
4	186.52	137.20	149.07
Mean	**191.90**	**147.83**	**154.58**

Table 3. Means of soil loss within study period at each LULC types.

Land use	Soil loss (ton/ha) per study period
Cultivated land	(14.80±1.19) [a]
Grassland	(7.08±0.48) [b]
Eucalyptus	(8.53±0.69) [b]
LSD (5%)	1.8

Table 4. Means of some nutrient loss from runoff at each LULC types.

Land use	TDS	Ec (μ S/cm)	pH	Ammonia (mg/l)	Nitrate (mg/l)	Phosphate (mg/l)
Cultivated land	75.25	122.00	6.43	4.33	0.39	0.75
Grassland	97.50	166.25	6.62	3.26	0.22	0.75
Eucalyptus	70.50	112.50	6.63	3.51	0.29	0.48
LSD (5%)	36.79 [ns]	61.25 [ns]	0.29 [ns]	3.12 [ns]	0.34 [ns]	0.41 [ns]

ns – no significant difference at $p < 0.05$ least significant difference.

(154.8 mm) than the grassland (147.8 mm).

Similarly, there was significant difference between in soil loss among the land uses/land cover types. The soil loss from cultivated land was significantly higher than the other two LULC types (Table 3). There was no significant difference in soil loss between the grassland and *Eucalyptus* field. The soil loss from the cultivated land was greater than the maximum tolerable amount of soil loss which is 10 ton/ha per year in Ethiopia (Hurni and Messerli, 1981; Hurni, 1985). The soil loss from cultivated land recorded in this study matches with the recorded amount from different part of the country (Haile et al., 2006; Girmay et al., 2009; Adimassu et al., 2014). The volume of soil loss has shown the reducing trend as the crop grown fully in cultivated land and resulted comparatively less difference in the final weeks of the experiment on the study area.

Total dissolved solids (TDS), pH, Electric conductivity (Ec), dissolved Ammonia (NH_3), dissolved Nitrate, dissolved Phosphate were checked for the significance difference at $p < 0.05$. The Nitrogen and Phosphorus level in the runoff was analysed indirectly in the form of dissolved Ammonia, Nitrate and Phosphate respectively. The two above listed nutrients and others were essential to show the land quality of the area. There is no significant difference in nutrient loss among the three land uses in the study site (Table 4). One reason for this might be the sample collection time effect, which was collected at the end of the rainy season, when the soil loss amount was very low due to crop cover increment.

The nutrient analysis from the runoff has indicated that essential nutrients are washed away from the land through runoff. The amount of dissolved ammonia and nitrate lost in runoff was higher in cultivated land than the other two LULC types (Table 5). Total dissolved solids and electric conductivity were higher in grassland than the other two land use. The amount of phosphate lost from *Eucalyptus* field was lower than cultivated land and grassland.

There is significant correlation between land use and runoff at $p < 0.01$. There is also significant correlation at $p < 0.05$ between LULC types and soil loss (Table 6). There is positive correlation between soil loss and runoff in the study area (Figure 2).

Similar to this study Adimassu et al. (2014) has observed that the soil loss from cultivated land reduces

Table 5. Means value of runoff, ammonia, nitrate and phosphate per hectare.

LULC types	Total Runoff (l/ha)	Ammonia (kg/ha)	Nitrate (kg/ha)	Phosphate (kg/ha)
Cultivated land	44329.48	18.86	1.73	3.37
Grassland	34148.15	11.15	0.76	2.59
Eucalyptus	35574.00	12.57	1.02	1.78

Table 6. Correlation between LULC types, runoff and soil loss.

Correlation	LULC types	Runoff	Soil loss
LULC types	1	-	-
Runoff	-0.75**	1	-
Soil loss	-0.70*	0.96**	1

** Correlation is significant at 0.01; *Correlation is significant at 0.05.

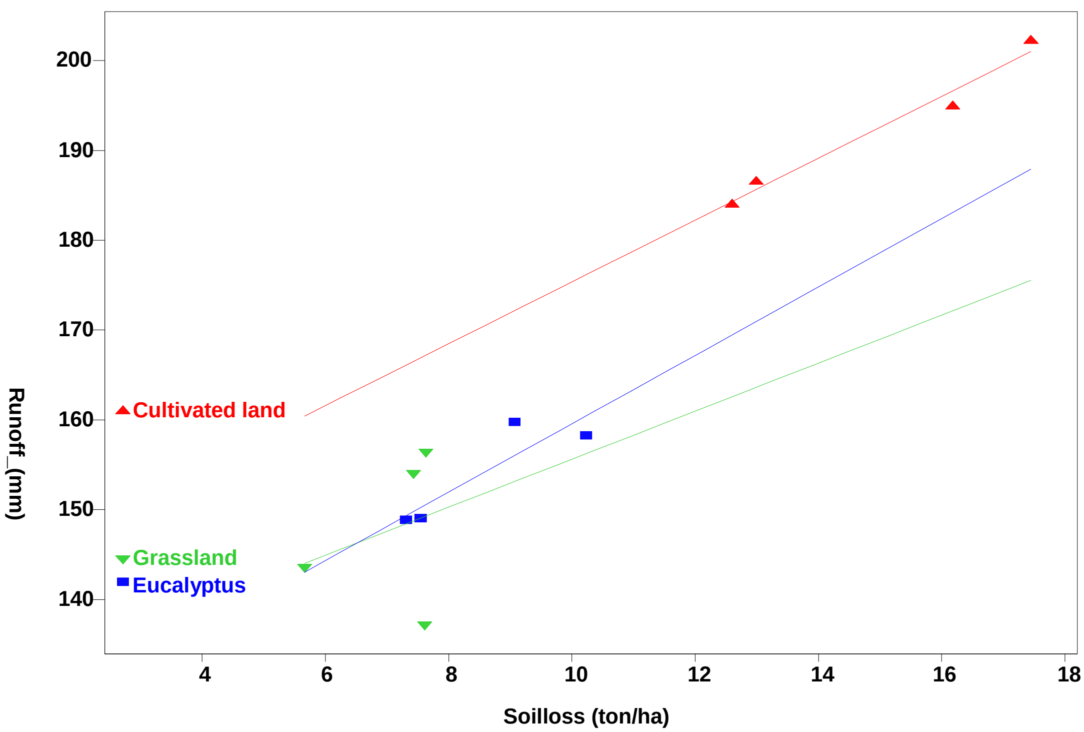

Figure 2. Runoff and soil loss relationship for the study period.

overtime due to the effect of direct rainfall on bare land reduced as the crops grown and cover the land. In different part of Ethiopia soil loss studies have found highly variable annual soil loss from 3.4 ton/ha per year (Walle et al., 2006) to 56.7 ton/ha per year (Gebreegziabher et al., 2008) in non-conserved cultivated land. Others found within the range given above from cultivated land (Haile et al., 2006; Nyssen et al., 2008; Girmay et al., 2009; Adimassu et al., 2014). Further exceptional soil loss was also registered up to 212 ton/ha per year in *Andit Tid*, Ethiopia (Haile et al., 2006). The soil loss from cultivated land has reached up to 300 ton per hectare per year in Ethiopia (Hurni, 1993; Herweg and Stillhardt; 1999; SCRP, 2000). The extent of previous soil erosion, rainfall characteristic, plot size and other variables could be mentioned as causes for variation soil loss in the country.

The annual sediment yield in cultivated land is higher than grassland, plantation, and conservation area in Tigray, North Ethiopia (Girmay et al., 2009). Oppositely, Nyssen et al. (2008) has found less mean soil loss from arable land (9.9 ton/ha/year) than rangeland (17.4 ton/ha/year) in Tigray, Ethiopia. Adimassu et al. (2014) has found greater soil loss from un-conserved cultivated land comparing with cultivated land conserved by soil bund. According to Hurni (1993) the average amount of soil loss from cultivated land was 40 ton per hectare per year in Ethiopia, which is higher than this study, Girmay et al. (2009) and Adimassu et al. (2014). Defersha and Mesele (2012) have also found higher soil loss from cultivated land than other LULC types. The soil loss study, from sub catchments in the same experiment sites with this study, has found lower sediment loss (2.4 ton/ha) and this is due to some sediment might be deposited on its way before reaching the outlet. It could be the reason of reduction of the value of soil loss (Erkossa et al., 2015).

Similar to this study, Girmay et al. (2009) has found no significant difference in soil loss among grassland, exclosure and plantation sites. Grassland has lower soil loss than cultivated land and bare land (Defersha and Mesele, 2012). Similar to the study by Girmay et al. (2009), this study confirms that soil loss from the cultivated land and other degraded land can be significantly reduced when lands are converted into plantation and especially exclosure.

There was no significant difference on nutrient loss from runoff associated P and K observed on cultivated land under different land management practices (Adimassu et al., 2014). The nutrient loss, specially the N and P losses, from the catchment were strongly related to the soil loss. This emphases that where there is high soil loss, there is also high nutrient loss; for instance N (9.7 kg/ha) and P (4.7kg/ha) losses were observed from catchments (Erkossa et al., 2015). Similar to the above, this study has found that higher nutrient loss where there is high soil loss in cultivated land. On contrary to the above, Girmay et al. (2009) has stated that nutrient loss was not only dependent on the sediment loss, but the soil condition of the land where nutrients losses can also influence. Soil and nutrient losses significantly reduced by application of land management practices such as soil bund on cultivated land (Adimassu et al., 2014). According to Haileslassie et al. (2006) nutrient loss rates vary between the land use types and the land management practices.

CONCLUSION AND RECOMMENDATIONS

This study has investigated that the effects of LULC change specially *Eucalyptus* expansion on soil and nutrient losses from runoff (N and P). The study has found that soil loss from each LULC types significantly varied. Cultivated land has contributed the major soil loss in the catchments. The soil loss from cultivated land is higher than the tolerable average soil loss limit given in the country. There was no significant effect on soil loss by changing from grassland to *Eucalyptus* plantation or vise verse. In other words, planting *Eucalyptus* on degraded land could reduce soil loss from the land. There was no significant difference in nutrient loss from runoff at each LULC types. However, the mean amount of soil nutrients loss from cultivated land is higher than other LULC types. Even, greater than the value given by Food and Agriculture Organization (FAO) for nutrient loss from cultivated land. The study has found that the negative correlation between LULC change and soil and nutrient losses in the study area. Similarly, it has found that strong correlation between the volume of soil and nutrient losses from the plots. In summary, cultivated land in the site needs land management practices such as physical and biological soil conservation measures to reduce the soil and nutrient losses beyond the tolerable limit. This study, along with other studies, which have been done in different part of the country on the effect of plantation on erosion, has proved that reduction of soil loss in plantation sites. *Eucalyptus* plantation or woodlot can reduce the soil and nutrient losses through soil erosion. This implies that apart from the socioeconomic benefits, *Eucalyptus* can also be used as biological soil erosion conservation measures on selected sites. Further studies of *Eucalyptus* need to be done in diversified agro ecological zones by considering its effect on soil and nutrient losses from runoff with spacing, long term erosion controlling effect, species and topographic effect. To this extent, this study recommends the policy makers and the experts to consider *Eucalyptus* as one of erosion conservation option where there is land degradation reached the climax and where there is limitation of conservation trees in the area.

Conflict of Interests

The authors have not declared any conflict of interests.

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Impact of climate change on hydrological responses of Gumara catchment, in the Lake Tana Basin - Upper Blue Nile Basin of Ethiopia

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Predictions of the impacts of climate change on the intensity, amount, and spatial and temporal variability of rainfall and temperature are required. The aim of this study was to assess the status of climate change and hydrological response to climate change for Gumara River sub-basin. Statistical Downscaling Model (SDSM 4.2) was used to downscale HadCM3A2a and HadCM3B2a predictors into finer scale resolution. To estimate the level of impact of climate change, climate change scenarios of precipitation and temperature were divided into four time windows of 25 years each from 2001 to 2099. The Soil and Water Assessment Tool (SWAT) was used to simulate the hydrological response. The results showed that the SWAT calibration and validation reveals a good agreement with R2 = 0.9 and NSE = 0.89 during calibration and R2 = 0.89 and NSE = 0.86 during validation. Annually, both precipitation and temperature showed increasing trends in all future time horizons in which precipitation increases up to a maximum of 13.7% (2076 to 2099) and temperature increases by 1.010c (2076 to 2099). The change in average flow volume due to climate change mainly corresponds to the change in precipitation. The average annual flow volume for the future increases by 17.8% (2076 to 2099). Overall, it appears that climate change will result in an annual increase in flow volume for the Gumara River. The increase in flow is likely to have considerable importance for local small scale irrigation activities. Since the flow volume increases in small rainy season (Belg) and main rainy season (Kiremit), due attention is also needed to prevent flood hazards. Generally, results presented in this study can provide valuable insight to decision makers on the degree of vulnerability of Lake Tana Basin to climate change, which is important to design appropriate adaptation and mitigation strategies.

Key words: Gumara river, climate change, SDSM, SWAT model.

INTRODUCTION

Climate change associated with rising atmospheric concentrations of greenhouse gases has been recognized in the Earth's atmosphere and simulations of its possible future course suggest substantial potential consequences

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for human societies and natural systems (Michael et al., 2004). Intergovernmental Panel on Climate Change (IPCC, 2007) point out that water and its availability and quality will be the main pressures on, and issues for societies and the environment under climate change. Climate change has greater implication on water resources systems. Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (Bates et al., 2008).

Predicting the impacts of climate change on the intensity, amount, and spatial and temporal variability of rainfall and its responses on stream flow regime are required for design and management of water resource systems (Boosik et al., 2007). Climate change effects may include the magnitude and timing of runoff, the frequency and intensity of floods and droughts, rainfall patterns, extreme weather events, and the quality and quantity of water availability and these changes, in turn, influence the water supply system, power generation, sediment transport and deposition, and ecosystem conservation (Tao et al., 2007).

Moreover, according to Chong-Yu (1999) the impacts of future climatic changes will be on changes in regional water availability. Such hydrologic changes will affect nearly every aspect of human well-being, from agricultural productivity and energy use to flood control, municipal and industrial water supply, and fish and wildlife management. The tremendous importance of water in both society and nature underscores the necessity of understanding how a change in global climate could affect regional water supplies.

The heavy reliance of the Ethiopian economy on rain fed subsistence agriculture makes it particularly vulnerable to hydrological variability (Dile et al., 2013). Most climate change studies in Ethiopia have been done at River basin scale (Kim *et al.,* 2008; Elshamy et al., 2008; Taye, 2010; Rizwan et al., 2010; Kigobe and Griensven, 2010) and results from these studies are highly aggregated and have little importance in informing the impact of climate change at smaller catchment scale. This research assesses the impact of climate change for Gumara River, one of the tributaries of the Lake Tana – the source of the Upper Blue Nile River, based on statistical downscaling model (SDSM).

Gumara River and the Lake Tana are important for various socio-economic purposes. However, due to climate change and variability, the water level in the lake fluctuates. The study extended to understand the implications of climate change at the hydrology of Gumara River by applying a process-based hydrological model (ArcSWAT model) with finer temporal and spatial resolution and potentially provide valuable insight to decision makers, planners and stockholders on the local vulnerability of the Gumara River flows and the Lake Tana regarding future change in rainfall and temperature because of climate change.

MATERIALS AND METHODS

General

Gumara watershed, drained by Gumara Rivers, is part of the Abay Basin and more particularly part of Lake Tana sub-basin which is situated on the North Eastern side of Lake Tana and contributes significant inflows to the Lake Tana. The climate of the LakeTana sub-basin is dominated by tropical highland monsoon with most of its rainfall (70 to 90% of total rainfall) occurring between June and September (Dile et al., 2013). The major rivers feeding the Lake Tana are Gilgel Abay, Gumara, Rib, and Megech. These Rivers contribute more than 93% of the flow (Setegn et al., 2009). The gauged part of Gumara watershed covers 1394 km^2. The geographical location of the watershed is between 11°34' 41.41" N and 11°56' 36" N latitude to 37°29' 30" E and 38°10' 58" E longitude. The elevation of the watershed ranges from 1800 m.a.s.l. at the lake to 3704 m.a.s.l. at the highlands. Based on the data obtained from Ethiopian Meteorological Agency, the mean annual rainfall is 1528 mm while the maximum (minimum) temperature are 27.02°C(9.51°C) respectively (Figure 1).

Land use land cover

The dominant land use of the watershed is rain fed agriculture and cultivated land is in a various forms including intensively cultivated, cultivated land with scattered trees, cultivated land with trees and shrubs and seasonally cultivated lands. More than three quarter of all land in the watershed has already been brought under cultivation. The major crops grown in the watershed are Teff, maize, Barley, Wheat and other cereals. Teff is the main staple food crop in the area. Bush or shrub land, grazing land, forest/wood land and wetland/swap are other land cover types in the watershed. Wetlands/swamp areas are commonly existent on the lower banks of Rivers, mainly of River and near Lake Tana. As it can be shown in Figure 2, the majority of the catchment is covered by crop land (cultivated), while the remaining are covered by leafy forests, shrubs, grasses and some are bar land and wet land.

Soil type of the study area

Soil data information as per FAO soil group is available at the Ministry of Water, Irrigation and Energy GIS department. The data was compiled during master plan study of the Abay River basin. Based on the data acquired and as per FAO soil classification, the catchment is dominantly covered by haplic luvisols, eutric vertisols, eutric fluvison, eutric leptosols and chronic luvisols (Figure 3).

Climate of the study area

There are some meteorological stations within the study area and its surroundings such as Bahir Dar, Debre Tabor, Amedber, Woreta, Amde Genet, Nifas Mewucha, Wanzaye and Gassay which are monitored by Ethiopian Meteorological Agency. Out of which Bahir Dar and Debre Tabor are first classes while others are second and third class stations. The annual climate may be divided into two, rainy and dry season. The rainy season may be divided into a minor rainy season in March to May (Belg) and a major rainy season from June through September (Kiremit). The dry season occurs between October and February (Bega). The four wettest

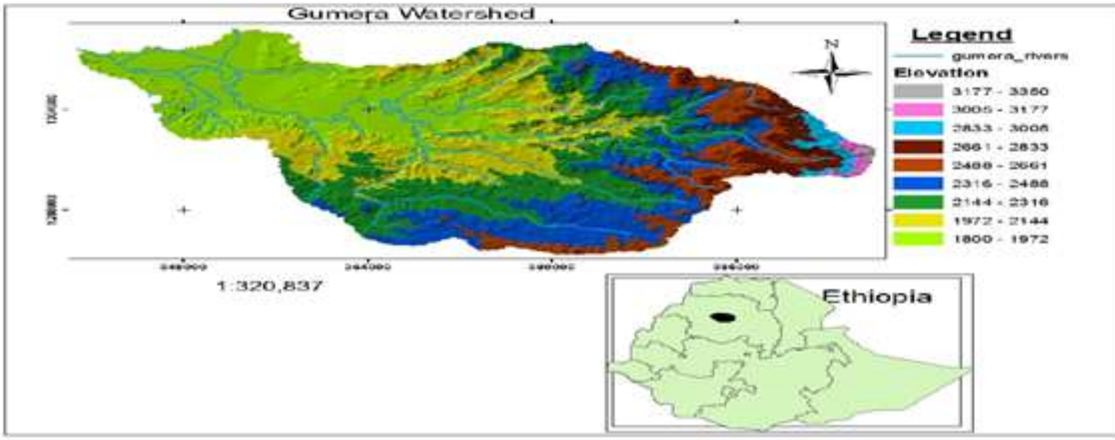

Figure 1. Location Map of Gumara Watershed.

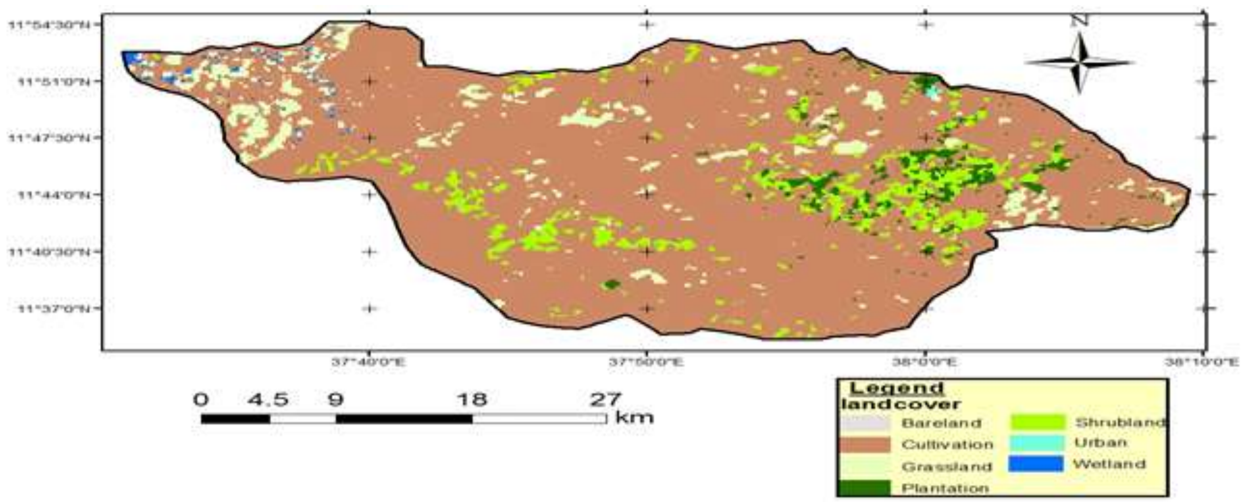

Figure 2. Land cover map of Gumara catchment.

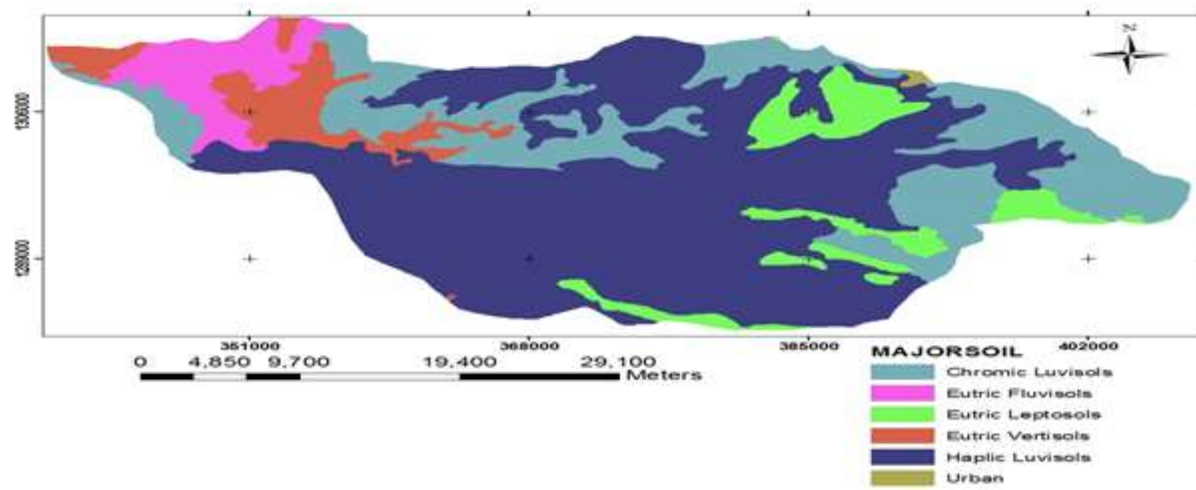

Figure 3. Major soil groups for Gumara w atershed.

months cover largest percent of the total annual rainfall. While the remaining months, being from October to May lowest rainfall. The mean annual rainfall and temperature of the area varies spatially from station to station. Based on the data obtained from Ethiopian Meteorological Agency, the mean annual rainfall is 1528 mm (1976 to 2005) at Debre Tabor station, 1288mm (1992-2008) at Woreta and 1279 mm (1986-2005) at Bahir Dar station while the maximum (minimum) temperature are 27.02°c(9.51°c), 27.5oc(9.6°c) and 27.95oc(11.97°c) at Debre Tabor, Bahir Dar and Woreta stations respectively.

Hydrology

Gumara is one of the major Rivers which contributes significant amount of inflow to Lake Tana. For this reason, the Ethiopian ministry of water, Energy and Irrigation installed gauging station downstream of the River. The gauging station is located at 11°50' 0" N and 37°38' 0" E and measures daily instantaneous flows of the River since 1959 and covers the area of 1394 km^2. Based on the recorded flow data obtained from Ethiopian ministry of water, Energy and Irrigation, the average daily flow of the River is 34.12m3/s (1976 to 2005).

Modeling approach

Climate change modeling approach

Global Circulation Model (GCM) derived scenarios of climate change were used for predicting the future climates of the study area based on criteria proposed by the Intergovernmental Panel on Climate Change (IPCC). There are different GCM outputs used for impact studies. Using the average outputs of different GCMs can minimize the uncertainties associated with each GCMs and can result in plausible future climates for impact studies (Lijalem, 2006). However, as this study was carried out within a very short period of time, only the HadCM3 model was selected for the impact study.

The HadCM3 GCM output was chosen since the model is widely used for climate change impact assessment in the upper Blue Nile basin (Kim et al., 2008; Rizwan et al., 2010; Dile et al., 2013), and the results of HadCM3 can be easily downscaled using SDSM (Dile et al., 2013). In addition, HadCM3 has the ability to simulate for a period of thousand years, showing little drift in its surface climate (Zulkarnain and Sobri, 2012). A2a (medium-high) and B2a (medium-low) scenarios were used for inter-comparison studies because the computing cost of all scenarios in GCM is too expensive.

GCMs are restricted in their use fullness for local impact studies by their coarse spatial resolution (typically of the order 50,000 km^2) and inability to resolve important sub-grid scale features such as clouds and topography (Wilby et al., 2001). Statistical downscaling method (SDSM 4.2) was used to relate large scale atmospheric variables (predictor) to local-scale surface weather (predictands), that is, precipitation and maximum and minimum temperature for this study, based on multiple linear regression techniques.

According to Wilby and Dawson (2007), statistical downscaling methods have several practical advantages over dynamical downscaling approaches in situations where low–cost, rapid assessments of localized climate change impacts are required and it was freely downloaded from http://www.sdsm.org.uk. Further, the SDSM is the first downscaling tool offered to the broader, less specialized climate change com-munity (that is, conservation authorities or private consulting companies). Comparisons between the SDSM and other statistical downscaling methods have demonstrated that the SDSM is a useful downscaling technique, capable of reproducing observed climatic variability. Numerous studies have also assessed the SDSM for downscaling GCM output to be used in many hydrological applications (Khan et al., 2006).

The downscaling of GCMs data using SDSM was done following the procedures suggested by Wilby and Dawson (2007). The required large scale predictor data that represents Gumara watershed were freely downloaded from the African window using the nearest average location of Gumara watershed from the web address of http://www.cccsn.ec.gc.ca/?page=pred-hadcm3. The predictor data files downloaded from the grid of interest consists of NCEP_1961-2001, H3A2a_1961-2099 and H3B2a_1961-2099. The predictand variables used were precipitation and maximum and minimum temperature obtained from the Ethiopian Meteorological Agency. Even though different weather stations are found in and around Gumara watershed, only the precipitation and maximum and minimum temperature at Debre Tabor station were used for downscaling since it has long-term and high-quality data. Moreover, since all stations in the drainage basin are located within the same grid box, the climate projection results from Debre Tabor station were assumed to represent other stations in the drainage basin.

Quality control checks in SDSM were used to identify gross data errors, specification of missing data codes and outliers prior to model calibration. Screening of predictors which have high correlation with the observed precipitation, maximum and minimum temperature at Debre Tabor station was done to select appropriate downscaling predictor variables for model calibration. The Conditional and unconditional processes was specified before the analysis takes place. In case of daily temperature where the predictand-predictor process is not regulated by intermediate process unconditional process was used, whereas for daily precipitation where the amounts depend on the occurrence of wet-day, the conditional process was chosen. Significance value is used to test the significance of predictor–predictand correlations and it was set as the default of ($p<0.05$ (5%).

The National Center for Environmental Prediction (NCEP_1961 to 2001) reanalysis data were used to calibrate and validate the SDSM model. The station data obtained from Ethiopian Meteorological Agency from 1986 to 1995 were used for calibration whereas from 1996-2000 they were used for validation at a monthly model type in order to see the monthly temporal variations. Though, ensemble sizes of up to a maximum of 100 are possible, the default ensemble size (20) was taken, and the mean of ensemble members were used even though individual ensemble members were equally plausible. The extent to which ensemble members differ depends on the relative significance of the deterministic and stochastic components of the regression models used for downscaling (Wilby and Dawson, 2007).

The regression weights produced during the calibration process were applied to the time series outputs of the GCM model based on the assumption that the predictor-predictand relationships under the current condition remain valid for future climate conditions. Twenty ensembles of synthetic daily time series data were produced for each of the two SRES scenarios for a period of 139years (1961 to 2099). Finally the mean of the ensembles for the specified period were produced for maximum and minimum temperature and precipitation. The period from 1976 to 2000 were considered as a base period against which comparisons were made for future periods (2001 to 2099). The future periods were divided into four time horizons from 2001 to 2025, 2026 to 2050, 2051 to 2075 and 2076 to 2099, and analyses were made for each time periods on seasonal and annual basis.

Bias correction was adapted to compensate for any tendency to over– or under–estimate the mean of conditional processes by the downscaling model. Linear Scaling (LS) method was adapted to correct the model errors due to its simplicity and the objective of the study mainly focuses on mean differences. Precipitation is typically corrected with a multiplier and temperature with an additive term on a monthly basis and the bias behavior of the model does not change with time that is, the transfer function is time independent and thus applicable in the future (Hagemann et al., 2011).

Thus to obtain the bias corrected future precipitation and temperature, the climate signal (difference between future and baseline climates) was first removed before the correction is adjusted. Then the future simulated results were added (temperature) and multiplied (precipitation) with the changing factor obtained in the baseline correction for each month. Then, initially removed climate signal is added back to create a bias corrected precipitation and temperature scenario for the future.

Hydrological modeling approach

Soil water assessment tool (SWAT) model was selected to assess the hydrological responses of climate change on Gumara catchment. SWAT is a River basin scale, continuous time, a spatially distributed model developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long period of time. The model can be used to simulate a single watershed or a system of multiple hydrologically connected watersheds (Neitsch et al., 2009).

The main reasons for the selection of SWAT model for this study was due to the model's moderate input data requirement, ability to simulate the major hydrological processes and its availability. The model is physically based, spatially distributed, and belongs to the public domain. SWAT can also simulates hydrological outputs based on a changed climate if the changes in the climate parameters are given as an input to the model. Moreover, SWAT has previously been applied in the highlands of Ethiopia and has given satisfactory results in the Lake Tana basin and upper Blue Nile basin of Ethiopia (Setegn et al., 2009; Easton et al., 2010; Betrie et al., 2011).

The first step in SWAT simulation process is delineating the watershed. Gumara watershed was delineated based on the automatic procedure using 30m digital elevation models (DEM) data into sixteen hydrologically connected sub-watersheds for use in watershed modeling and the final outlets found at the gauging station was used for comparison of measured and predicted flows. After watershed delineation of Gumara watershed was completed, the Hydrologic Response Units (HRU) were defined in ArcSWAT by overlaying soils, land use and slope classes. Hydrologic Response Units (HRU) HRUs are lumped land areas within the sub-basin that are comprised of unique land cover, soil, and management combinations that enables the model to reflect differences in evapotranspiration and other hydrologic conditions for different land covers/crops and soils which increases (Neitsch et al., 2009) the accuracy of load predictions and provides a much better physical description of the water balance.

SWAT requires daily values of precipitation, maximum and minimum temperature, solar radiation, relative humidity and wind speed. The weather data collected from seven stations in the study area have; however, missing data. Among the seven stations, daily rainfall, temperature, wind speed, solar radiation and relative humidity data, from three stations namely Bahir Dar, Woreta and Debre Tabor weather stations were used as an input to calculate statistical monthly weather generator parameters which are calculated by Weather parameter calculator program. Using thus three stations the SWAT model generates representative weather variables for Gumara watershed and fills the missed values.

Surface runoff was estimated using Soil Conservation Service (SCS) curve number method (USDA-SCS, 1972) and Penman-Monteith method was applied for Gumara watershed to estimate potential evapotranspiration. SWAT simulates the runoff for each HRU. Two options are available to route the flow in the channel networks; the variable storage and Muskingum methods. Both are variations of the kinematic wave model. The variable storage method uses a simple continuity equation in routing the storage volume, whereas the Muskingum routing method models the storage volume in a channel length as a combination of wedge and prism storages. For this study variable storage method was selected to rout the flow of water in the channel.

The sensitivity analysis was undertaken by using a built-in tool in SWAT that uses the Latin Hypercube One-factor-At-a-Time (LH-OAT) design method to minimize the number of parameters to be used in the calibration step and select the most sensitive parameters largely controlling the behavior of the simulated process. After running the sensitivity analysis, the mean relative sensitivity (MRS) of the parameters were used to rank the parameters, and their category of sensitivity were also defined based on the Lenhart et al. (2002) classification that is, small to negligible ($0 \leq MRS < 0.05$), medium ($0.05 \leq MRS < 0.2$), high ($0.20 \leq MRS < 1.0$), and very high ($MRS \geq 1.0$). Based on these classifications, sensitive parameters with mean relative sensitivity value of medium to very high were selected for calibration of the simulated flows for Gumara River.

The daily River flows at Gumara River gauge station obtained from Ethiopian Ministry of Water, Energy and Irrigation were used for calibration and validation of the simulated flows and climate change impact analysis. Measured Stream flows at Gumara River gage station from 1991 to 2000, were used for calibration of SWAT model including the first two years warm up period. Refsgaard and Storm (1996) distinguished three types of calibration methods: the manual trial-and-error method, automatic or numerical parameter optimization method; and a combination of both methods. According to Refsgaard and Storm (1996) the first method is the most common, and especially recommended for the application of more complicated models in which a good graphical representation is a prerequisite. Automatic calibration on the other hand relies heavily on the optimization algorithm and the specified objective function (Gan, 1988) in which only few optimized parameters may be used for calibration.

For this study, SWAT model was calibrated manually by adjusting sensitive parameters that affect surface runoff which were identified during sensitivity analysis until a satisfactory objective function was achieved (that is, percent difference (D) < 15%, correlation coefficient (R^2) > 0.6 and sutcliffe simulation efficiency (E_{NS}) > 0.5). Validation was done with an independent data set without making further adjustments of the calibration parameters. Model validation confirmed the applicability of the watershed-based hydrologic parameters derived during the calibration process. Measured Stream flows at Gumara River gage station from 2001-2005 were used for the validation process to evaluate the model accuracy.

RESULTS

SDSM calibration and validation

The calibration was done at a monthly model type in order to see the monthly temporal variations. Monthly precipitation, maximum temperature, and minimum temperature values were generated based on the selected predictor variables of the NCEP data (Table 1). The first step in the downscaling procedure using SDSM was to establish the empirical relationships between the predictand variables (minimum temperature, maximum temperature, and precipitation) collected from stations and the predictor variables obtained from the NCEP re-analysis data for the current climate. It involves the identification of appropriate predictor variables that have strong correlation with the predicted variable. Predictors

Table 1. List of predictor variables that have better spatial and temporal correlation with the predictands at Debre Tabor station at significant level of less than 0.05(p<0.05).

Predictands	Predictors (NCEP reanalysis data)	Notation	Partial r
Precipitation	Surface meridian velocity	ncepp_vaf	-0.053
	850 hpa divergence	ncepp8zhaf	+0.118
	Relative humidity at 850 hpa	ncepr850af	+0.348
Maximum temperature	Mean temperature at 2 M	nceptempaf	+0.383
	Surface specific humidity	ncepshumaf	+0.109
	Surface Vorticity	ncepp_zaf	+0.303
Minimum temperature	Mean temperature at 2 M	nceptempaf	+0.444
	Surface specific humidity	ncepshumaf	+0.300
	500hpa geo-potential height	ncepp500af	+0.109
	850 hpa meriodinal velocity	ncepp8_vaf	+0.014

The partial correlation coefficient (r) shows the explanatory power that is specific to each predictor. All are significant at p = 0.05, hpa – is a unit of pressure, 1 hPa = 1 mbar = 100 Pa = 0.1 kPa.

Table 2. Cal. and val. statistics before and after bias correction at Debre Tabor Station with the NCEP data.

Predictands	Uncorrected		Bias corrected	
	R^2		R^2	
	Calibration	Validation	Calibration	Validation
precipitation	0.70	0.62	0.99	0.99
Maximum temperature	0.69	0.65	0.98	0.99
Minimum temperature	0.72	0.77	0.99	0.99

with better spatial and temporal correlations are shown in Table 1.

The calibration and validation results of the SDSM showed that the downscaled NCEP precipitation, maximum and minimum temperature have good agreements with the observed values at Debre Tabor station before bias correction as shown in the Table 2. Due to the conditional process (dependent on other intermediate processes like on the occurrence of humidity, cloud cover, and/or wet-days) and high spatial variability of precipitation, the calibration and validation results are comparatively less than the maximum and minimum temperature (Lijalem, 2006; Habtom, 2009; Dile et al., 2013). However, for this study a good agreement between generated and observed precipitation was resulted (Table 2) and this might be due to less spatial variability of precipitation on Gumara watershed.

Hence the SDSM model resulted in satisfactory multiple regression equation parameters for precipitation, maximum and minimum temperature. Thus, it may be inferred that the SDSM model is able to generate weather variables which resembles the observed values at the station level and able to generate future scenarios under a given emission scenarios using the assumptions that the predictand-predictor relationship under the present condition are also valid for the future. Even though the correlation results showed good agreements before bias correction, the SDSM model over estimates in some months and under estimate in some other months. To compensate for any tendency to over– or under–estimate the mean of conditional processes by the downscaling model, bias correction was applied and it perfectly matches the observed predicts and with generated values.

The calibrated model was used to generate ensemble members of synthetic daily weather series giving daily atmospheric predictor variables from the HadCM3 A2a and B2a scenarios. The regression weights produced during the calibration process were applied to the time series outputs of the GCM model based on the assumption that the predictor-predictand relationships under the current condition remain valid for future climate conditions.

Climate change projections for the future periods

Maximum temperature

The results of the statistical downscaling model on annual bases for mean maximum temperature showed

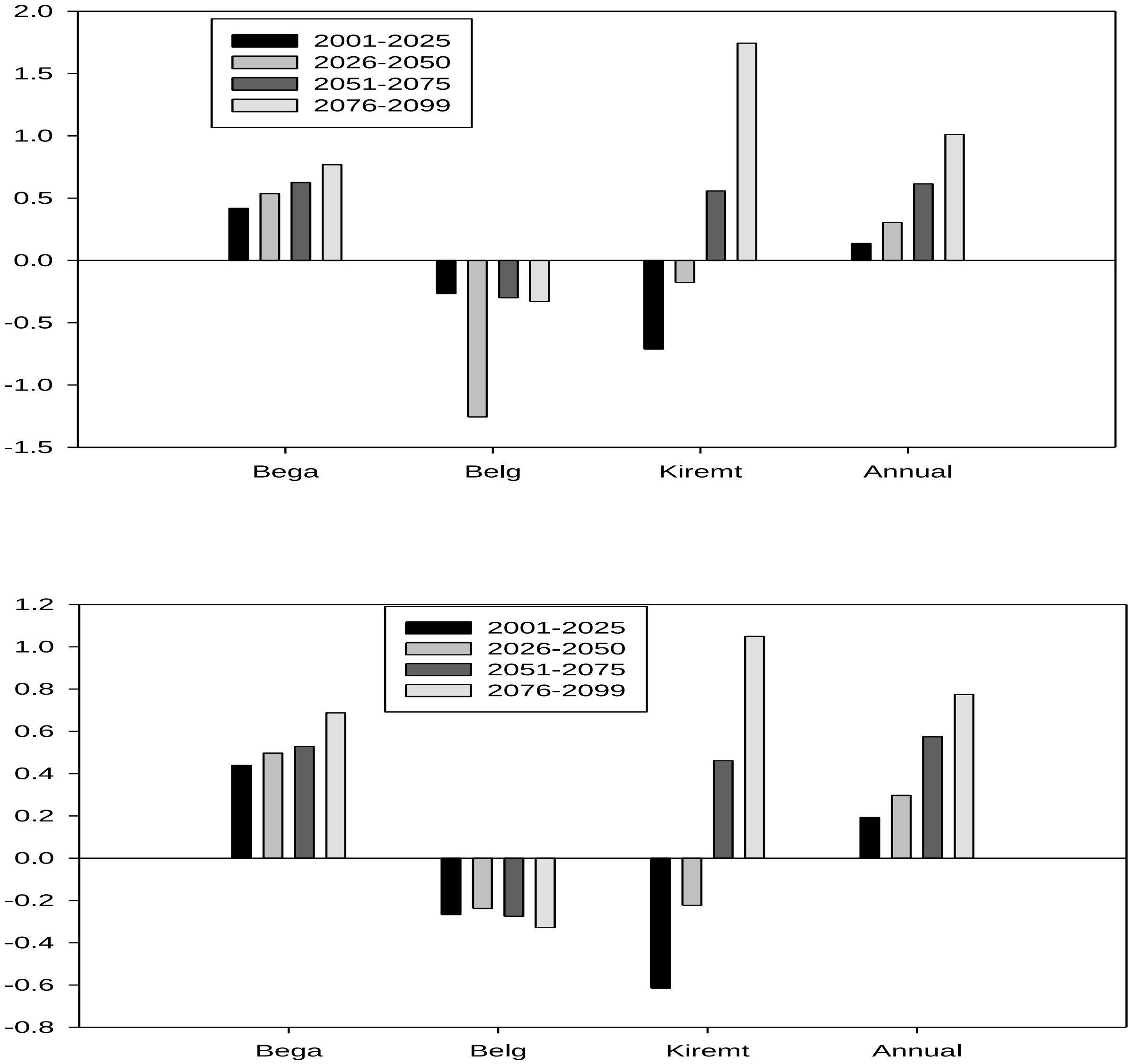

Figure 4. Change in average seasonal and annual maximum temperature in the future (2001 to 2099) for A2a scenario (a) and B2ascenario (b) as compared to the base line period (1976 to 200). (Bega season = October–February, Belg season = March–May, and Kiremit season = June to September).

an increasing trend (Figure 5) for both A2a and B2a scenarios for the future period (2001 to 2099) as compared to the base period (1976 to 2000) in which the increment ranges between 0.14°C (2001 to 2025) and 1.01°C (2076 to 2099) for A2a emission scenarios while for B2a emission scenario, it ranges between 0.2°C (2001 to 2025) and 0.77°C (2076 to 2099). Seasonally, maximum temperature does not show clear trends for both A2a and B2a scenarios. For A2a scenario the maximum increment of maximum temperature reaches up to 1.74°C (2076-2099) in Kiremit (JJAS) season and the maximum reduction reaches up 1.26°C (2026 to 2050) in Belg (MAM) season while for B2a scenario, seasonal increment of maximum temperature reaches up to 1.05°C (2076 to 2099) in Kiremit (JJAS) season and reduced by 0.62°C in Kiremit (JJAS) season (Figure 4).

Minimum temperature

Similar to maximum temperature, seasonal variation of minimum temperature due to climate change does not show clear trends. For A2a scenario, seasonal minimum temperature for the future period increases by a maximum of 1.05°C (2076 to 2099) in Kiremit (JJAS) season and decreases by 0.83°C (2076 to 2099) in Belg

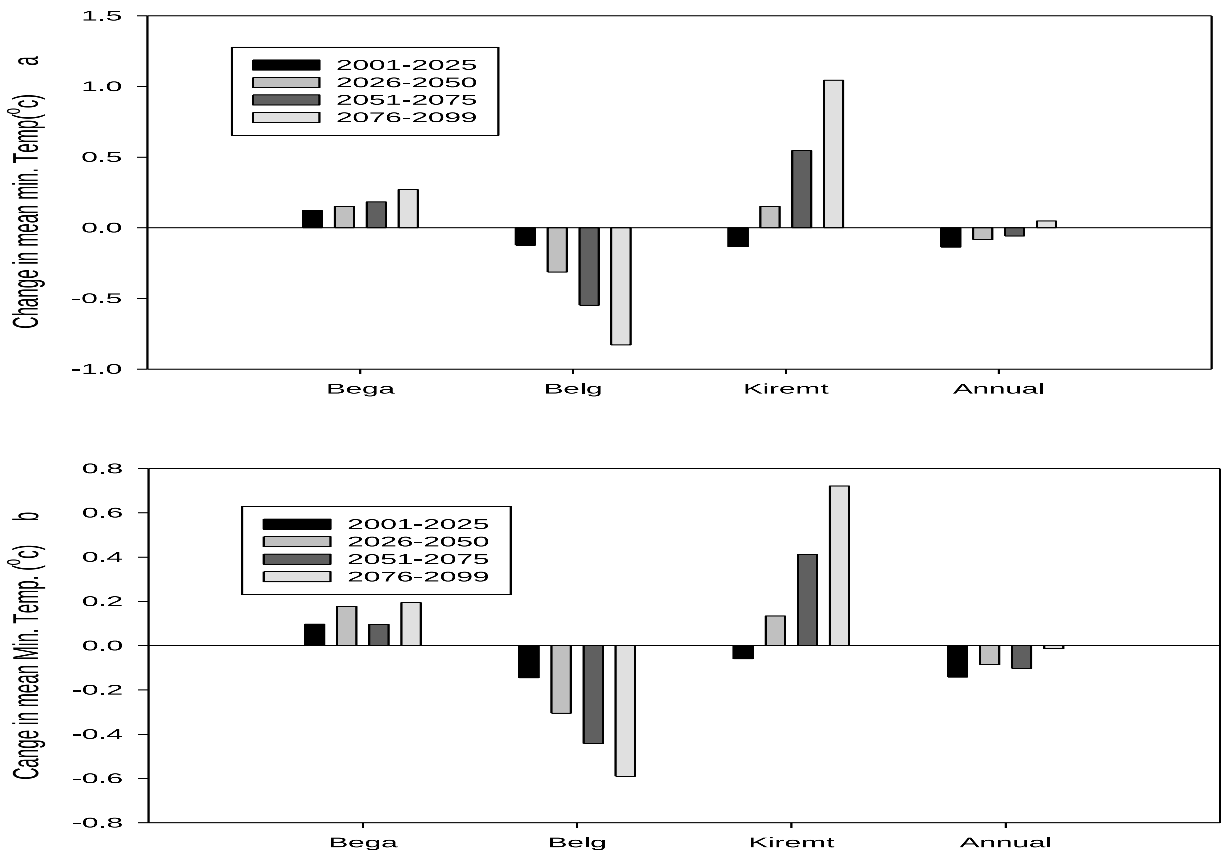

Figure 5. Change in average seasonal and annual minimum temperature in the future (2001-2099) for A2a scenario (a) and B2a scenario (b) as compared to the base line period (1976 to 200). (Bega season = October–February, Belg season = March–May, and Kiremit season = June–September).

(MAM) season while for B2a scenario it increases by a maximum of 0.72°C and decreases by 0.59°C within the same time horizon (2076 to 2099) and season (Belg) as that of A2a scenario. Regarding to the annual temperature, the minimum temperature indicates very minor changes due to climate changes for both A2a and B2a scenario as shown in the Figure 5a and b. Thus, it can be concluded that climate change causes high seasonal variation (increase and decrease) of maximum and minimum temperature in four different time horizons while annually the impact shows clear increasing trend.

Precipitation

As it can be seen from the Figure 6a and b, the overall results (2001 to 2099) for annual precipitation increases from 10.49 (2001 to 2025) to 13.7% (2076 to 2099) for A2a scenario and for B2a the increment ranges between 6.4 (2001 to 2025) and 13.72% (2076 to 2099). Seasonally, the precipitation increases in Belg (March to May) and Kiremit (June to September) in which the precipitation increases up to a maximum of 59.33% (2026 to 2050) for A2a scenario and 56.6% (2026 to 2050) for B2a scenario. Precipitation decreases in Bega (October to February) season for both scenarios by 43% (2001 to 2025) and 41.2% (2001 to 2025) for A2a and B2a scenarios respectively.

SWAT hydrological modelling

SWAT sensitivity analysis

In SWAT hydrological modeling, identifying the most sensitive parameter that highly influences the surface runoff and ground water flows, calibration and validation of SWAT model applicability and simulating the hydrological responses of Gumara catchment under present and future climatic variables were discussed.

Among twenty six parameters used for the sensitivity analysis, only 8 of them revealed meaningful effect on the monthly flow simulation of the Gumara River. Curve number (CNII), available water capacity (SOL_AWC), Channel effective hydraulic conductivity (CH_K2), and soil evaporation compensation factor (ESCO) were relatively high sensitive parameters that significantly affect surface runoff while the threshold water depth in shallow aquifer for flow (GWQMN), base flow Alpha factor (ALPHA_BF), Groundwater delay (GW_DELAY)

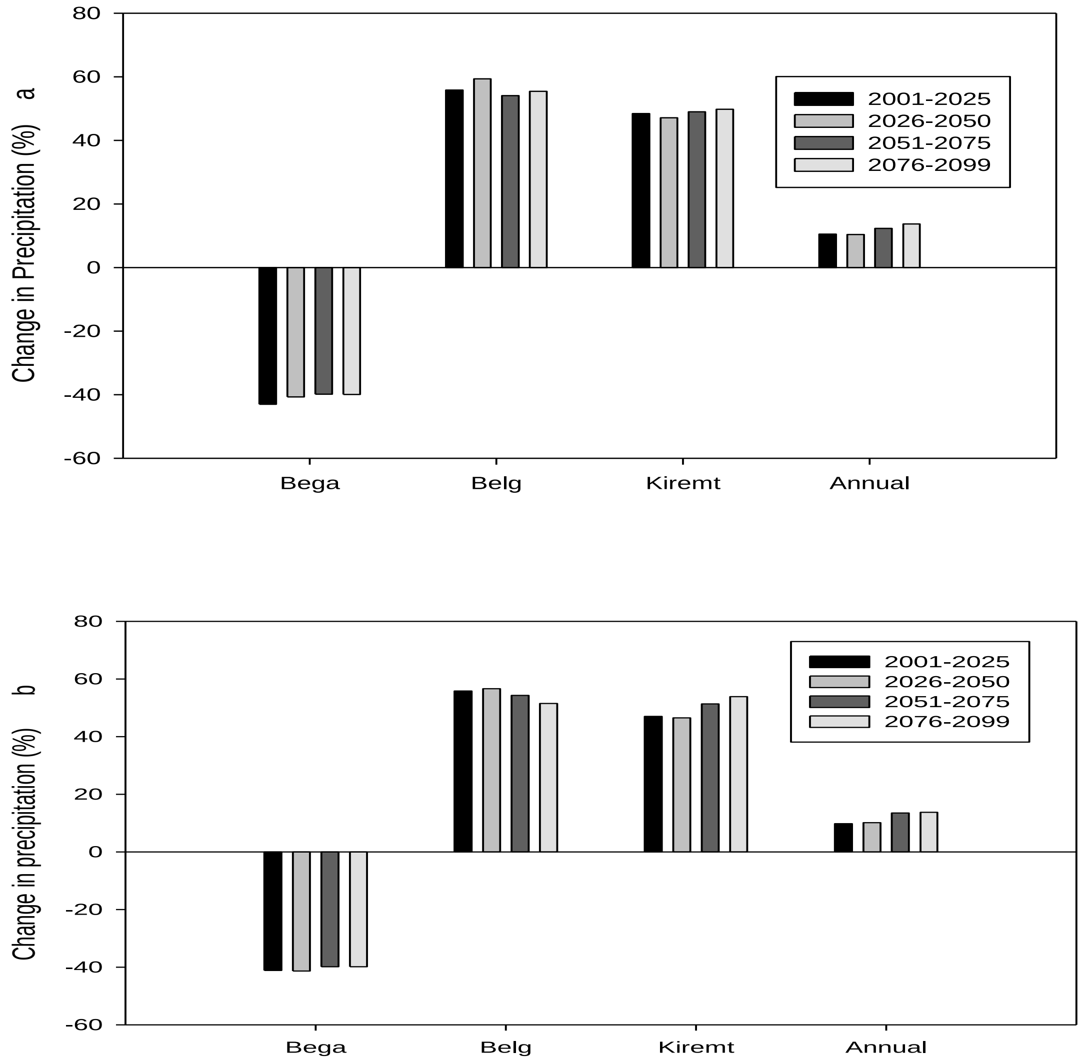

Figure 6. Percentage Change in seasonal and annual precipitations in the future (2001-2099) for A2a scenario (a) and B2ascenario (b) as compared to the base line period (1976-200). (Bega season = October–February, Belg season = March–May, and Kiremit season = June–September).

Table 3. Flow sensitive parameters and their category of sensitivity.

No	Code	lower and upper bound	Relative sensitivity	Category of sensitivity
1	CN2	0±25%	3.35	V. high
2	SOL_AWC	0±25%	0.94	High
3	GWQMN	0-5000	0.25	High
4	GW_DELAY	0-500	0.23	High
5	CH_K2	0-150	0.18	Medium
6	ALPHA_BF	0-1	0.17	Medium
7	ESCO	0-1	0.15	Medium
8	GW_REVAP	0.02-0.2	0.08	Medium

and Groundwater "revap" coefficients (GW_REVAP) were other parameters that mainly influence base flow. The selected sensitive parameters with their relative category of sensitivity are shown in Table 3.

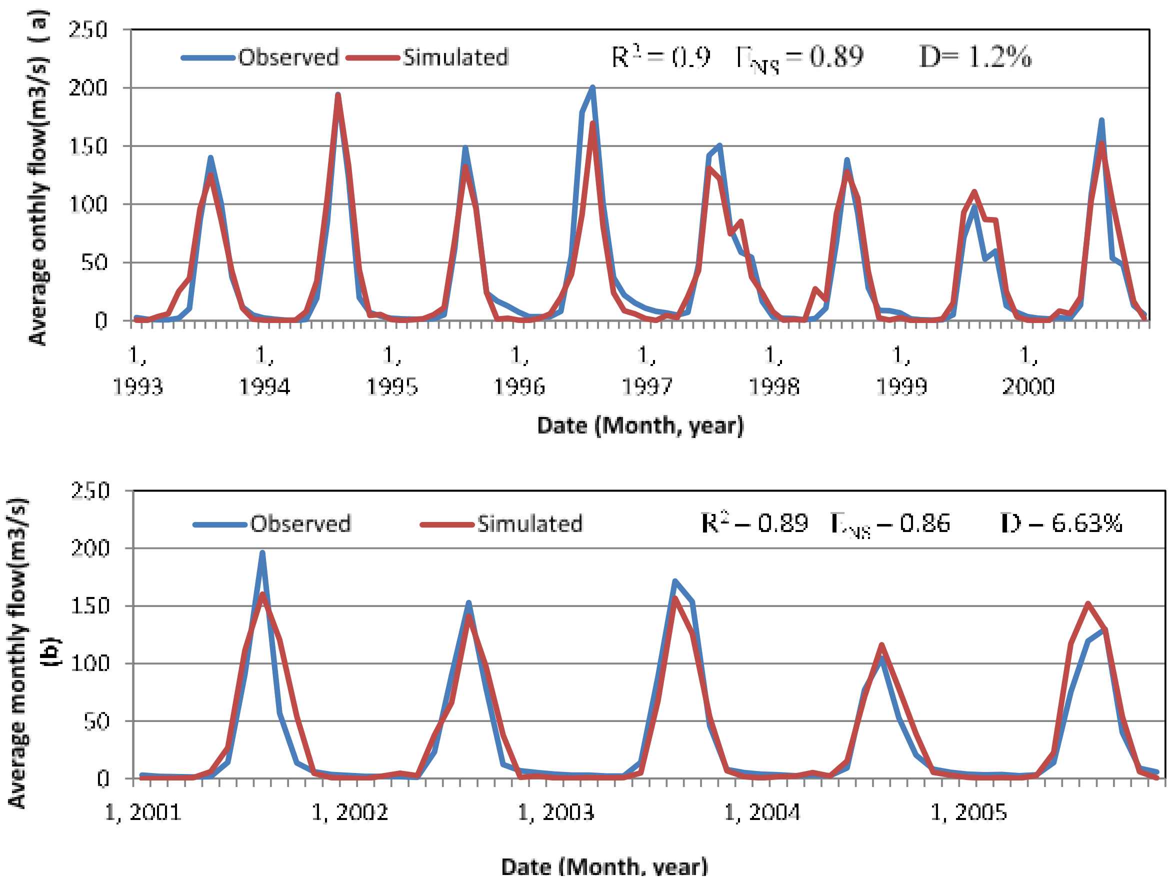

Figure 7. Calibration (a) and validation (b) results of average monthly simulated and observed flows at Gumara River gauge station.

SWAT calibration and validation outputs

The calibration and validation results (Figure 7a and b) showed that there is a good agreement between the simulated and measured monthly flows. Percent of errors of the observed and simulated monthly flows at Gumara gauge station during the calibration and validation are 1.2 and 6.63% respectively which are well within the acceptable range of ±15%.

Further a good agreement between observed and simulated monthly flows are shown by the coefficient of determinations (R^2=0.9) and the Nash-Suttcliffe simulation efficiency (E_{NS}=0.89) in the calibration period and R^2=0.89 and E_{NS}=0.86 during the validation period. Thus, all the model evaluation criteria fulfilled the requirements suggested by Santhi et al. (2001) for R^2 >0.6 and E_{NS}> 0.5. Hence, the set of optimized parameters used during calibration process can be taken as the representative set of parameter to explain the hydrologic characteristic of the Gumara watershed and further simulations using SWAT model can be carried out by using these parameters for any period of time. Thus, SWAT model was rerun to simulate the hydrological responses of Gumara catchment due to climate change using the predicted future precipitation and temperature as an input and keeping other climatic and land use changes constant.

From the calibration and validation results, it may be deduced that the model represents the hydrological characteristics of the watershed and can be used for further analysis.

Climate change impact on Gumara river flow

Stream flows largely depend on the amount of precipitation falling on the catchment, and the amount of evapotranspiration released from that catchment. The change in the amount of precipitation, minimum and maximum temperature due to climate change obviously changes Gumara River flow volumes. Since the main objective of this study is to get an indicative possible effect of climate change on the stream flow assuming changes only in the two main drivers (Temperature and precipitation), other climate variables such as wind speed, solar radiation, and relative humidity and non-climatic variables (that is, land use changes) were assumed constant throughout the future simulation periods which

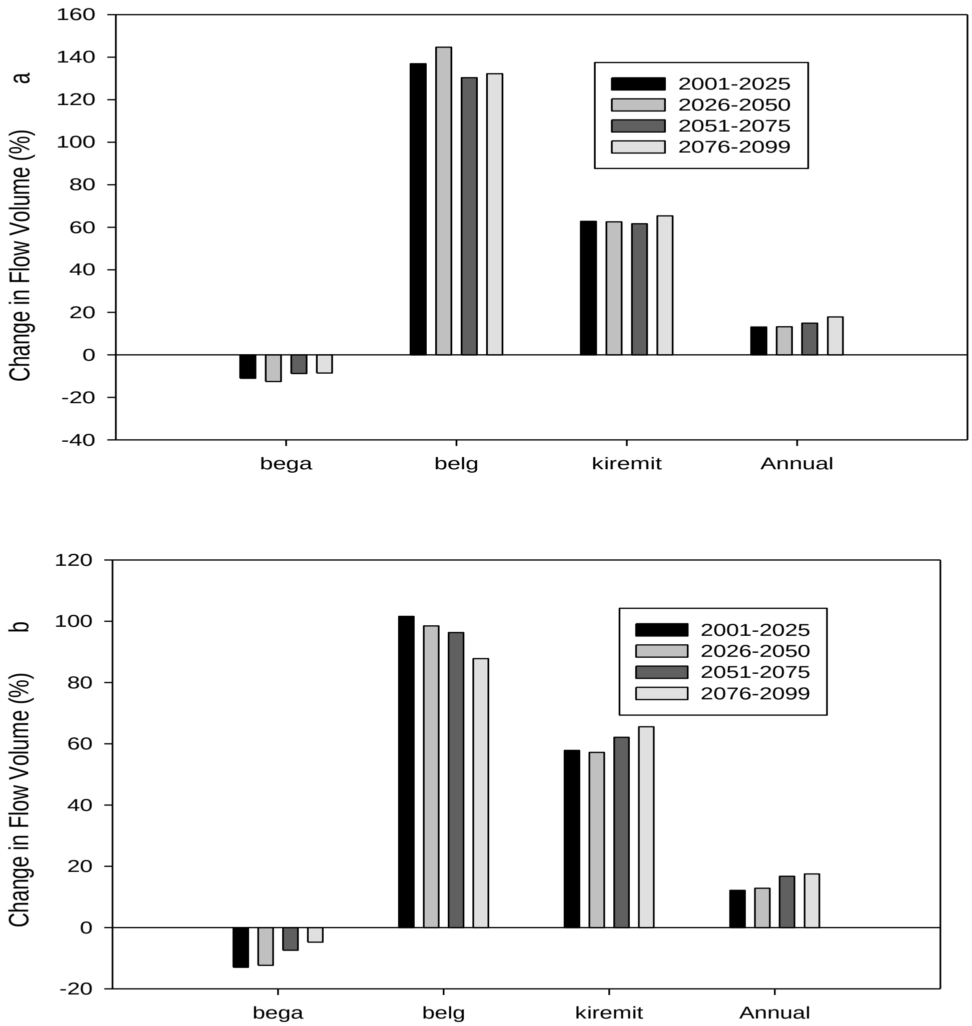

Figure 8. Percentage change in average seasonal and annual total flow volume for the period 2001 to 2099 as compared to the baseline period (1976 to 2000) at Gumara River gauge station for (a) A2a scenario and (b) B2a scenario. (Bega season = October to February, Belg season = March to May, and Kiremit season = June to September).

are not possible in actual case.

The impact of climate change on stream flow was predicted based on conditional temperature and rainfall changes on seasonal and annual basis. The average annual total flow volume for the future four time horizons showed an increasing trend (Figure 8) for both A2a and B2a scenarios as compared to the base period in which the flow volume increases from 13.04% (2001 to 2025) to 17.8% (2076 to 2099) for A2a scenario and for B2a scenario the increment ranges between 12.13% (2001 to 2025) and 17.5% (2076 to 2099). Increase in average total annual flow volume is observed for the periods which show a corresponding increase in mean annual precipitation (Figure 7), and the results of this study confirmed the previous researches (Beyene et al., 2010; Dile et al., 2013).

Seasonally, the highest increment is shown in Belg season (MAM) in which the flow volume increases from 130.33 (2051 to 2075) to 144.65% (2026 to 2050) for A2a scenario and from 87.76 (2076 to 2099) to 101.58% (2001 to 2025) for B2a scenario. Significant changes of average total flow volume were also found in Kiremit (JJAS) season in which the flow volume increases from 61.6 (2051 to 2075) to 65.33% (2076 to 2099) for A2a scenario and for B2a scenario the increment ranges between 57.2 (2026 to 2050) and 65.5% (2076 to 2099). In Bega season, the average total flow volume decreases between 8.8 (2051 to 2075) and 12.6% (2026 to 2050) for A2a scenario and for B2a scenario it decreases between 4.7 (2076 to 2099) and 13% (2001 to 2025). The decrease in flow volume in Bega season also corresponds to the decrease in precipitation and this may causes water shortage problems.

DISCUSSION

Understanding the problem is part of the solution and predicting the level of climate change impact on water resources is a prerequisite for planners, decision makers and concerned bodies to reduce prevent and/or to find the possible adaptation measures. Hence, the impact of climate change on Gumara River was carried out to address part of the global problem by showing the possible indicative predictions of climate changes.

The study predicted the conditional impact of rainfall and temperature changes on the hydrology of the Gumara catchment using the HadCM3 GCM A2a and B2a climatic scenarios for the 2001 to 2099 periods. We applied the SDSM statistical downscaling tool to evaluate the GCM outputs. The SWAT model was used to study the consequences of climate change on the hydrology of Gumara catchment. We believe that results presented in this research are representative for a majority of GCM output and therefore our results are plausible estimates of future effects of climate change.

The study confirmed that the Statistical downscaling Model (SDSM) is able to simulate climatic events. The calibration and validation results of SDSM showed that the model is able to simulate the climatic variables (precipitation and temperature) which follow the same trend with the observed one. Even though, the precipitation is a conditional process and high special variability, the overall result from SDSM is well correlated with the observed precipitations. Hence, SDSM can predict the future climatic events under changing conditions based on the assumption that the predictor-predictand relationships under the current condition remain valid for future climate conditions.

On seasonal basis, precipitation and temperature do not show systematic trends for both A2a and B2a scenarios that is, precipitation and temperature increases some season and decreases in some other season. On seasonal basis, the increment of maximum temperature reaches up to 1.74°C (2076 to 2099) in Kiremit (JJAS) season and the maximum reduction reaches 1.26°C in Belg (MAM) season for A2a scenario. For B2a scenario, the maximum mean seasonal increment of maximum temperature reaches up to 1.05°C (2076 to 2099) in Kiremit (JJAS) season and the maximum reduction reaches up to 0.62°C Kiremit (JJAS) season. This implies that seasonal precipitation and temperature will be highly fluctuated due to climate change for the future period and these variations in turn have great impacts on the variation of hydrological responses of Gumara catchment. On the annual basis, both temperature and precipitation shows systematic increasing trend for A2a and B2a scenarios for the future period. Our temperature projection results an increase in mean annual temperature up to 1.01°C (2076 to 2099) for A2a emission scenarios and 0.77°C (2076 to 2099) for B2a scenarios. The annual increment is not worth for both scenarios based on IPCC-TGICA (2007) in which the globally averaged surface air temperature is projected to warm 1.4°C to 5.8°C by 2100.

The SDSM precipitation weather generation satisfactorily replicates the observed precipitation (Table 2). This suggests that SDSM may perform well in simulating the future climatic condition of the study area. As in any type of modeling study the results have to be judged against uncertainties. Even if we cannot quantify these uncertainties in this study it is well known that uncertainty increases along the sequence temperature-precipitation-runoff. Consequently, results have to be viewed in this perspective.

On the other hand, similarity in results with other studies using other approaches corroborates results. In any case, percentage changes' of different hydro-meteorological quantities as in this study should not be seen as facts but instead as an indication of possible future outcomes with a high degree of uncertainty. In view of the above, the SDSM downscaling indicates that annual precipitation increases up to 13.7% (2076 to 2099) for A2a scenario and 13.72% (2076 to 2099) for A2a scenario. The results of this study was thus in line with the previous researches done on Tana basin, and upper Blue Nile basin (Kim et al., 2008; Taye, 2010). Moreover, researches done by UNFCCC (2007), Siri Eriksen et al. (2008) and Bates et al. (2008) showed that annual mean rainfall increases over parts of Eastern Africa due to climate change.

Seasonally, the precipitation increases (in Belg and Kiremit season) up to a maximum of 59.33% (2026 to 2050) for A2a scenario and 56.6% (2026 to 2050) for B2a scenario and decreases (Bega) by 43% (2001 to 2025) and 41.2% (2001 to 2025) for A2a and B2a scenarios respectively. Beyene et al. (2010), Rizwan et al. (2010) and Dile et al. (2013) on upper Blue Nile basin also showed increasing trends in Kiremit Season. The increment of precipitation in Belg and Kiremit season may have positive implications since these two seasons are the cropping season in Ethiopia.

The results of the hydrological model calibration and validation indicate that SWAT model is able to accurately explain the hydrological characteristic of Gumara watershed. The statistics of the model performance criteria (Nash–Sutcliffe model efficiency (ENS), coefficient of determination (R^2) and percentage deviation of simulated mean from measured one (D)) indicates that monthly simulated flow by SWAT corresponded very well with the measured values at Gumara River gauge station.

Following to the calibration and validation, the SWAT model was re-run using the downscaled precipitation and maximum and minimum temperature to predict the impact of climate changes on the hydrology of Gumara River. Results show that average seasonal and annual inflow volume changes mainly corresponding to the change in precipitation. Average Seasonal flow volume increases in Belg and Kiremit seasons and the increment is more significant in Belg season (144.65% for A2a scenario and 101.58% for B2a scenario).

Rizwan et al. (2010) also showed that the runoff increases in the future in the major rainy seasons (June-September) which causes the possibility of flood occurrences in the future due to the extreme runoff. This study also reveals the increment of runoff in Kiremit season in line with Rizwan et al. (2010). Annually, the average flow volume showed an increasing trend in which the flow volume increases from 13.04% (2001 to 2025) to 17.8% (2076 to 2099) for A2a scenario and for B2a scenario the increment ranges between 12.13% (2001 to 2025) and 17.5% (2076 to 2099). As Gumara River is one of the tributary River feeding in to Lake Tana, any change in River flow is likely to affect the Lake. The increased runoff generally improves water supply reliability and contributes significant inflows into the Lake Tana. On the other hand there is a flood prone area in some parts of Gumara catchment near the shore of the lake. Thus, the increased runoff volume in Kiremit season my devastate flood damages and due consideration should be taken to prevent future flood hazards.

In conclusion, the hydrology of Gumara River is highly vulnerable to climate change which causes high temporal variation of flow volumes. This may need serious concerns for food security and water resource sustainability. Therefore, prevention and adaptation strategies in and around the Gumara catchment have to be developed so as to maintain sustainability of available water resources and to prevent extreme events. Generally, Results presented in this study can provide valuable insight to decision makers on the degree of vulnerability of Lake Tana Basin to climate change, which is important to design appropriate adaptation and mitigation strategies.

Conflict of Interests

The authors have not declared any conflict of interests.

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Full Length Research Paper

Evidence based review of *Legionella* elimination in building water systems

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Legionnaires disease can be acquired through exposure to *Legionella pneumophila*, a gram-negative bacteria ubiquitous in both natural and engineered water systems. Over the years, a number of disinfection techniques notably, chlorination, ozonation, thermal, UV and copper-silver ionization have been employed across different kinds of engineered water systems with diverse measures of success. Available evidence portends, most of the aforementioned techniques often have to be combined to achieve long-term efficacy. Remarkably, albeit the extensive research and reportage on Legionnaires outbreak in the developed world, very few studies have been carried out with regards to Africa. We reviewed existing literature on the application of the aforementioned techniques in buildings. Our study concurs with earlier studies; most of the disinfection techniques will have to be combined to achieve the desired efficacy. We found very scanty studies on Legionella or reportage of its outbreak within Africa. Our study also found very little in terms of any of the techniques been applied with the specific aim of reducing Legionella proliferation in engineered water systems within Africa. This is alarming, especially, on a continent where several communities have little or no access to quality water and healthcare. In light of the above, stronger measures such as sensitization, properly managed water distribution systems, as well as policies aimed at enforcing national and international guidelines on Legionella control is recommended.

Key words: Legionnaires disease, water disinfection, engineered water system, Africa.

INTRODUCTION

Legionnaire's disease first commanded attention in 1976 during an American Legion convention in Philadelphia (Swanson and Hammer, 2000). Whilst initial documentation on Legionnaires was related to cooling towers, a study by Tobin et al. (1981) was one of the earliest to demonstrate *Legionella* could be found in water distribution systems of hotels and hospitals. Their study demonstrated infected water systems could be linked with cases of Legionnaires in the absence of air-conditioning equipment. Legionnaires is largely caused by Legionella *pneumophila* a pathogenic bacteria for free living, ubiquitous, freshwater, and soil amoebae of the

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genera Acanthamoeba and Naegleria (Rowbotham, 1980). The disease is characterized by pneumonia, often afflicting the elderly or immunosuppressed individuals (Parry et al., 1985; Kümpers et al., 2008; Hilbi et al., 2010). Although *Legionella* is a genetically diverse species, L. *pneumophila*, one of the many *Legionella* species, is common in natural and engineered water systems and its single serogroup, L. *pneumophila* Sg1 accounts for almost 84% of Legionnaire's cases reported world wide (Cold Spring Harbor Laboratory, 2008). Though several disinfection modalities have been tested and approved over the years, the dilemma in choosing an efficacious technology still lingers. The application and draw backs of most of the contemporary techniques employed continue to be evaluated whilst new techniques or devices aimed at *Legionella* control in water systems are still being experimented. Perhaps, this is because each of the techniques presents distinct characteristics (Marchesi et al., 2011). Over the last two decades, most of the notably documented techniques (e.g. superheating, copper-silver ionization, ozonation, Ultra violet light and hyper chlorination) have undergone evaluation and review in literature elsewhere (Kim et al., 2002a; Campos et al., 2003; Lin et al., 2002; Muraca et al., 1987; Muraca et al., 1990; Lin et al., 1998, 2011). Despite the above, these reviews along with documented efficacies often do not include Africa. While *Legionella* sampling in water systems is almost a routine in developed nations. Legionnaires disease is barely a subject in most African countries. Most patients are sub optimally treated for other diseases such as Tuberculosis in the face of likely symptoms. Owing to the fact that *Legionella* is ubiquitous in both natural and manmade water systems (CDC, 2016), the aforesaid is particularly disturbing considering the fact that piped-in water is non-existent in the poorest 40% of households in rural sub Saharan Africa (UNDESA, 2014). In this study, we review literature on some of the most commonly used techniques in *Legionella* control in engineered water systems. Keen attention is paid to water quality as well as the application of the respective techniques on the continent.

METHODS

The documented efficacy, advantage, disadvantage and effect on water quality of a number of disinfection modalities aimed at *Legionella* control and elimination was carried out. Thermal disinfection, hyper-chlorination, copper-silver ionization, ozonation and UV light were selected, taking into consideration similar reviews of the afore listed along with other techniques (Kim et al., 2002a; Campos et al., 2003; Lin et al., 1998). With the exception of copper silver ionization, the techniques were also selected based on existing evidence of their application across Africa for regular water treatment. Copper silver ionization was however added based evidence of its "positive" reviews in other literature. Finally, the review also sought to put together, documented efficacy in hospitals, hotels and water distribution networks; uncharacteristic of majority of such reviews.

CLASSIFICATION OF WATER DISINFECTION TECHNOLOGIES IN LEGIONELLA CONTROL

Water disinfection employed in *Legionella* control is varyingly classified. In certain literature, the techniques are classified as "localised methods" or point of use e.g. ozonation, UV lights and "systemic" e.g. thermal disinfection or copper silver ionization (Peiró Callizo et al., 2005). Other literature also groups the techniques as systemic or emergency disinfection (Lin et al., 2011). Emergency techniques such as thermal disinfection often employed during outbreaks have been reported to lack residual effects over longer periods (Stout et al., 1986; Chen et al. 2005; Mouchtouri et al., 2007), while disinfection techniques such as copper-silver ionization which have been linked with long term *Legionella* control are still under evaluation albeit being implemented (Cachafeiro et al., 2007).

THERMAL DISINFECTION ("HEAT AND FLUSH")

Method

Water temperature greater than 60°C inhibits the survival 19 and growth of L. *pneumophila in vitro* (Muraca et al., 1987, 1990; Campos et al., 2003). Although one of the earliest in *Legionella* control, available literature suggests it is inefficacious unless repeatedly applied alongside faucets chlorine disinfection (Stout et al., 1986; Mouchtouri et al., 2007). Nonetheless, the temperature range for proliferation (20°C to 43°C) as well as inactivation (>44°C, < 20°C) are well documented (Konishi et al., 2006; Schulze-Robbecke and Buchholtz, 1992). Though varying forms of implementing this technique exists, the basic principle involves elevating the temperature of water in a storage tank above 70°C while ensuring temperatures at distal fixtures are not below 60°C. Distal fixtures may then be run at respective time intervals for days and monitored in accordance with required standards or regulations.

Characterization of efficacy, advantages and disadvantages

In a review, Campos et al. (2003), described thermal disinfection as a temporal control strategy as bacteria colonization is often evident months after implementation. Perhaps, due to 'repository biofilm' which provide protective mechanism for survival and re-colonization, complete elimination of *Legionella* in water systems remains farfetched (Mouchtouri et al., 2007). The above is evident in a study by Steinert et al. (1998), who observed re-colonization of two *Legionella* strains, three months after implementing the technique (70°C) in a hospital water system (Figure 1). A study by Chen et al. (2005), also observed regrowth's, two months after implementing the technique at a medical centre (Figure 1). Other studies have also reported insignificant reduction in *Legionella* contamination counts within the first months of its implementation (Marchesi et al., 2011). In terms of its edge over other disinfection techniques, thermal disinfection does not require any special equipment's aside the use of devices that register water temperature. It can be implemented expeditiously in cases of outbreaks or emergencies. On the other hand, the possibility of scalding and the amount of work involved in monitoring distal sites could be time consuming. Challenges with its application in larger buildings e.g. hotels or hospitals where stable temperature may be difficult to attain along entire water networks is also noteworthy (Chen et al., 2005; Mouchtouri et al., 2007). In view of the afore-stated, routine implementation could be challenging especially as such facilities (Hotels or hospitals) will have to be unoccupied at best. Finally, dead legs, operation at deliberate low temperatures per concerns of scalding, as well as its implementation in old water

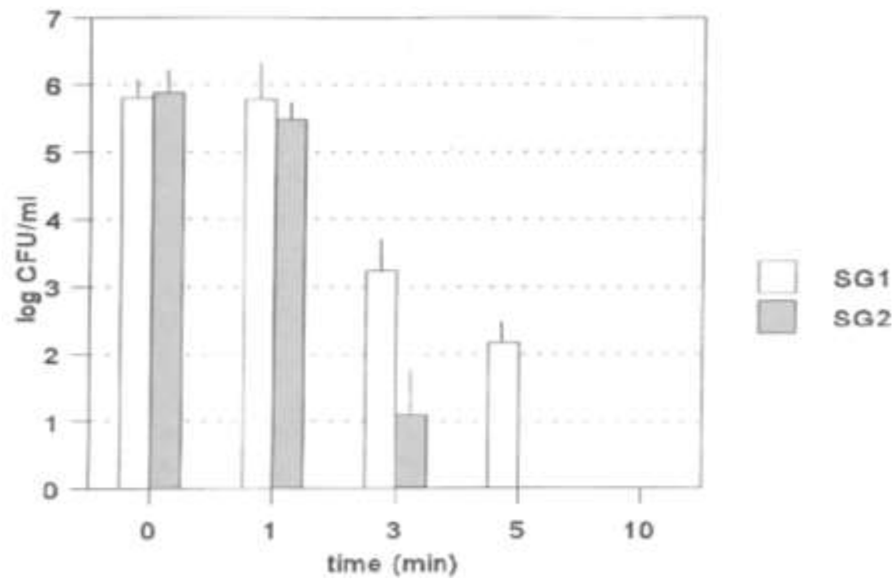

Figure 1. Comparison of the heat resistance of *L. pneumophila* serogroup 1 (SG1) and serogroup 2 (SG2). The heat resistance was determined by plotting the number of survivors (CFU/ml) versus period of exposure at 60°C. Data are expressed as the means of 5 independent experiments. Source: Steinert et al. (1998).

distribution networks are also noteworthy inhibitions (Groothuis et al., 1985; Plouffe et al., 1983).

Effect of thermal disinfection on water quality and its application in Africa

The overall effect of thermal disinfection on water quality remains conspicuously better than other water disinfection technologies especially due to lack of biocidal effect of chemicals as may be the case in other disinfection modalities. Minus "circulation" through the water distribution network along with "special devices" that monitor water temperature at distal sites, the technique is almost synonymous to boiling which remains perhaps, one of the default household water treatment methods in the developing world (Rosa and Clasen, 2010). Evidence of easy contamination after cooling coupled with economic and environmental unsustainability in its application (Luby et al., 2000; Gilman and Skillicorn 1985; Parikka, 2004) perchance, remains the defining reason why the technique is not used as a routine water disinfection modality. Interestingly, boiling remains relatively rare in Africa (4.5%) even though other African countries such as Uganda (39.8%) and Zambia (15.2%) report significantly high rates of its application (Rosa and Clasen, 2010). Nonetheless, whereas boiling will serve the same purpose of *Legionella* inactivation (> 70°C), evidence of literature on boiling or heat treatment specifically aimed at *Legionella* control is almost nonexistent. Boiling is however largely documented as a household water treatment method.

HYPER CHLORINATION

Method

Hyper chlorination involves the addition of chlorine to water with existing chlorine residue. So far, two ways of implementing the technique has been documented: (1) Shock hyper chlorination, which involves the pulse injection of chlorine into a given water system (range of 20 to 50 mg/l), and (2) continuous chlorination which involves continuous injection of chlorine in a form of gas, liquid or solid. The treated water is later drained and fresh water introduced to reduce chlorine concentration to about 0.5 to 1 mg/l. Typically, the installation involves, mounting chlorine injectors in highly pressured water supply lines with venturi orifice which create a vacuum; consequently, drawing chlorine gas into the water stream. Overall, adequate contact time and mixing is required to achieve desired efficacy.

Characterization of efficacy, advantages and disadvantages

Although the technique represents the decisive treatment for bacteria control and elimination in most water systems most especially in old water distribution networks (Schoenen, 2002; Orsi et al., 2014), *Legionella* is reported to be more tolerant to chlorine than other bacteria including *Escherichia coli* (World Health Organization (WHO), 2007). Evidence of the presence of biofilm is reported to be a key element in its ability to offer such resistance. As described by Cooper and Hanlon (2010), continuous growth and survival of L. *pneumophila* biofilms (1-2 month old at 50 mg/L over an hour) were observed despite high levels of chlorine. An earlier study by Kuchta et al. (1983) also showed different *Legionella* strains were more resistant to chlorine compared to other coliform bacteria; even more resistant at low chlorine dosages. In terms of its long term efficacy, an environmental surveillance study by García et al. (2008), showed *L. pneumophila* sero-group 1 survived despite successive episodes of hyperchlorination for 10, 5 and 17 years in a hotel, fishing boat and hospital water system respectively. By far, available studies continue to suggest, hyper chlorination appears to be only effective in its initial stages with bacteria levels often exceeding pre-treatment levels after a short while (Marchesi et al., 2011) (Figure 2). There is also evidence of facilities (e.g. hospitals) switching to other disinfection techniques having previously implemented hyper chlorination (Lin et al., 2011).

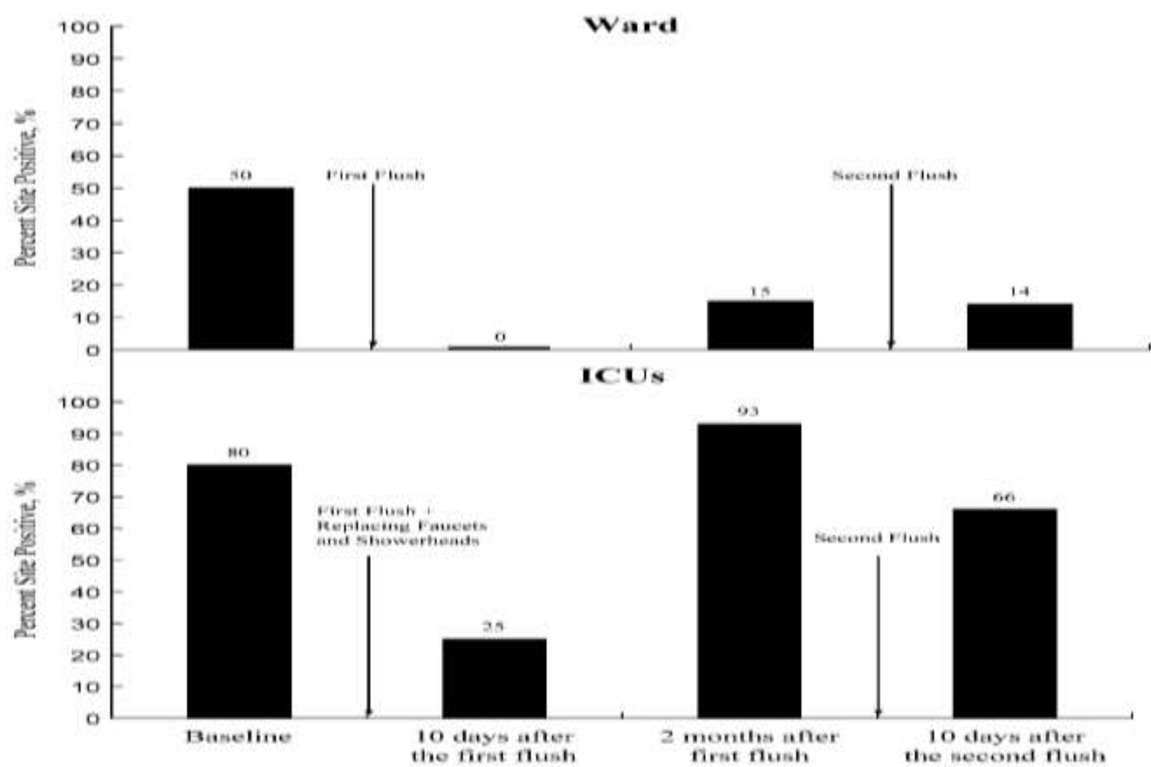

Figure 2. Short duration of superheat and flush failed to eliminate the site positivity for Legionella in patient ward and intensive care units (ICUs). Source: Chen et al. (2005).

Thus, hyper chlorination is inadequate for long term disinfection and only suitable for emergencies or during commissioning (DOH, 2009). Coupled with the above, the after effects of its application e.g. corrosion of pipping material over longer periods and the associated health effects of chlorine by-products such as trihalomethanes linked to cancer is also noteworthy (Gopal et al., 2007; USEPA, 2001; Miller, 2008; DOH, 2009; Mcdonnell et al., 1999). Finally, it has been suggested varying residual concentration due to changes in water flow rates may result in inadequate residual quantity at distal fixture, this, may in the long run have no significant effect on bacteria present (DOH, 2009).

Effect of hyper chlorination on water quality and its application in Africa

Although the use of chlorine eliminates water odour (Wajon et al., 1988), water quality is reduced (organoleptic and chemical) often, as a result of chlorine levels (>0.5 < 1.0 mg/L) (Orsi et al., 2014). In terms of health, an increased risk of bladder cancer also appears to be associated with the consumption of chlorinated water (Cantor, 1997) along with other illnesses such as asthma and dermatitis which have also been reported (Gorchev and Ozolins, 2011; Fawell, 2003). Within Africa, available literature shows hyper chlorination is used extensively. Albeit reports of its effect on human health in countries such as Algeria (Benhamimed and Moulessehoul, 2010), hyper chlorination has been documented as an emergency technique during a Legionnaires outbreak in South Africa (NICD, 2016). Its application in conflict areas or disasters zones e.g. Kenya during Cholera outbreaks, alongside the promotion of hygiene and safe food preparation has also been reported (UNICEF, 2011). More so there is documented evidence on its use in the control of Hepatitis E outbreak in northern Uganda. These, reports show, higher concentration of residual chlorine is often required to facilitate control of the virus (IFRC, 2008). Overall, the use of chlorine within drinking water networks either as centralised or point of use is quite extensive in many African countries e.g. Angola, Cameroon, Ethiopia, Guinea, Kenya, Madagascar, Malawi, Mozambique, Nigeria, Rwanda, Tanzania, Uganda, and Zambia (Peletz and Mahin, 2009; Walfer, 2013).

COPPER-SILVER IONIZATION

Method

Copper-silver ionization involves passing water through a device which applies low potential electricity to electrodes of silver and copper, consequently, dissolving and distributing smaller ions (Cachafeiro et al., 2007). The Copper ions (Cu^{2+}) present, form electrostatic bonds with the negatively charged cell walls of microorganisms (*Legionella* inclusive) resulting in the disruption of cell wall permeability (Muraca et al., 1990; Lenntech, 2011). On the other hand, the silver ions bond with the DNA and RNA of the microorganism, leading to immobilization and cell death (Lenntech, 2011). Overall, the concentration of ions and the nature of the water system must be carefully evaluated, in order to achieve eradication of *Legionella.*

Characterization of efficacy, advantages and disadvantages

Despite the conventional argument that most disinfection techniques cannot be used in isolation, there is evidence to

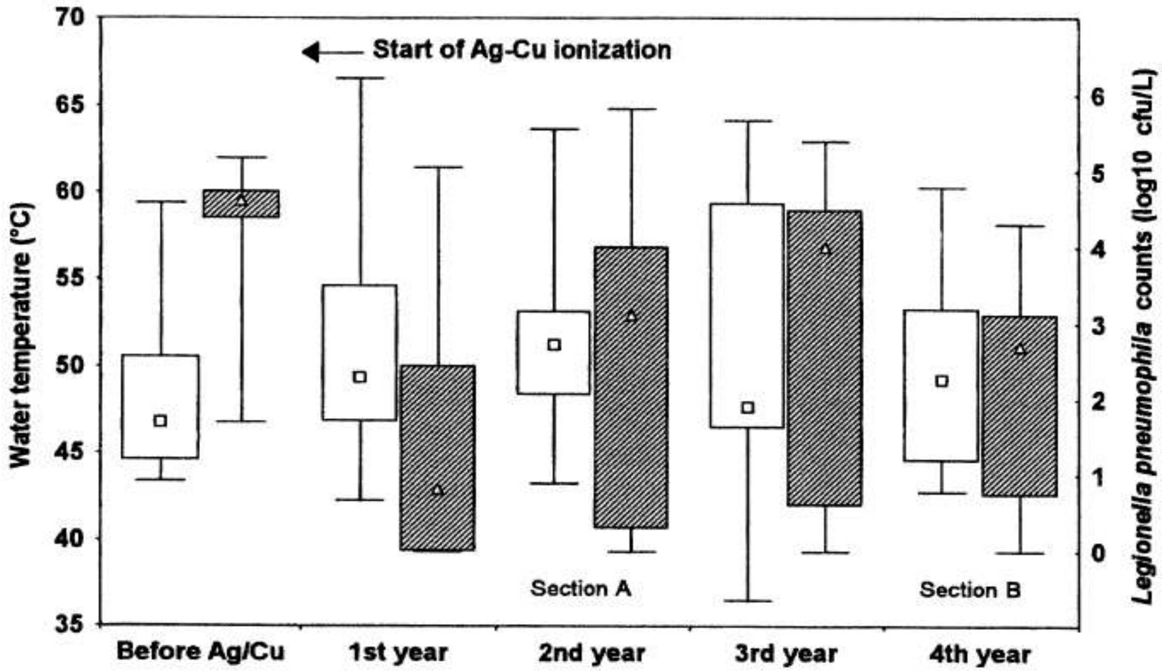

Figure 3. *Legionella pneurnophila* counts (cfu/L; shaded bars) and water temperature (°C; white bars) in hot water system of a university hospital, with use of silver-copper ionization in the year before ionization, 3 years with first ionization unit (Section A), and 1 year with a new ionization unit (Section B; fourth year). Box plot: Median, 25 to 75th percentile, minimum to maximum. Source: Rohr et al. (1999).

suggest, copper-silver ionization continues to gain popularity across the globe as an effective and safe technique so long as ions are monitored according to requisite standards (Cachafeiro et al., 2007). In terms of its effect, its application leads to lysis and cell death by "distortion of cellular permeability coupled with protein denaturation" (USEPA, 2001). Its ability to kill as opposed to suppression or control of bacteria is also well documented (Lin and Vidic, 1996; Lin et al., 1998; DOH 2009). With respect to other microorganism aside *Legionella*, States et al. (1998) argue, copper silver-ionization is ineffective against amoeba and other non-Legionellaceae bacteria. Nonetheless, there is evidence the technique is efficacious against other waterborne pathogens such as *Pseudomonas aeruginosa*, *Stenotrophomonas maltophilia* and *Acinetobacter baumannii* (Huang et al., 2008). Its application in both hot and cold water point of entry is also reported (Chen et al., 2008).

A survey by Stout and Yu (2003) across 16 US hospitals over a 5 to 11 year period, observed copper-silver ionization was most effective compared to other previously implemented disinfection techniques. They reported 0% positivity for *Legionella* for 50 and 43% of the hospitals as of 1995 and 2000 respectively. This was against 7 out of 15 of the hospitals reporting 30% *Legionella* positivity at distal fixtures prior to application. Only a single incidence of Legionnaires was reported after the technique had been implemented. A study by Rohr et al. (1999), also showed copper silver ionization achieved a reduction *in Legionella* counts from 40,000 to 7 cfu/L during the first year of disinfection (average silver ion concentration <10 ug/L). Nevertheless, an increment of 10,000 cfu/L was observed in the third year over a four-year period (Figure 3). Thus, the study concluded, the effect of the technique was only suitable for short-term applications and influenced by factors such as water temperature and content of silver ions in water (>45°C, up to 66.6°C).

Following the concentration of nontuberculous mycobacteria and legionellae for three and four years respectively on the influence of the technique, Kusnetsov et al. (2001), reported electronically released copper and silver ions were inefficacious at taps and showers of a hospital water system despite an increase in ion concentration in the circulating water. Mòdol et al. (2007) in an evaluation of the impact of the technique after the implementation of other techniques, reported a significant decrease in *Legionella* counts as well as reduction in nosocomial legionellosis (2.45 to 0.18 cases per 1000 patient discharges)

Overall, although advantages such as ease of installation and maintenance have been reported, difficulty in monitoring residual levels, formation of insoluble hydroxides and the need for periodic cleaning of electrodes are also noteworthy (Lin et al., 2011; Campos et al., 2003). A review by Kim et al. (2002a), on studies conducted by other authors suggests the use of metal ions, "*either copper alone or both copper or silver*" is a good option for *Legionella* control especially in hot water recirculation systems. Nonetheless, its long term effect is yet to be listed as a major advantage. There are also studies on its application in swimming pools although peer reviewed literature on its efficacy is rarely been reported (Abad et al., 1994; Beer et al., 1999).

Effect of Copper-Silver Ionization on water quality and its application in Africa

According to Mcdonnell et al. (1999), the oral consumption of ions through the use of copper-silver ionization is often limited as ions are only added to recirculating lines in hot water systems. Largely, copper-silver ionization poses very minimal potential safety hazards compared to other chemical disinfection techniques even though its continuous use is however barely encouraged (Zheng et al., 2012).

Table 1. Water and swab samples obtained before control measures, during ozonation, and during ozonation and increased temperature (65°C).

Periods	Control measures	Water samples			Swabs	
		No. of positives/no. performed (%)	p	Cfu/ml (mean of positives) (SD)	No. of positives/no. performed (%)	P
1993-1995	None	66/100 (66)		10.9G17	Not done	
1996-1998	Ozonation	67/120 (56)	0.12	5.2G97	56/106 (53)	
1999-2001	Ozonation and increased temperature (55°C)	23/79 (29)	0.0004	7.6G16	54/169 (32)	0.006

Source: Blanc et al. (2005).

In a study on the technique, Lin et al. (2002), found variations in water quality as a cause of its inefficacy as on-site pH measurement were high (8.9). There are also reports on the effect of water type (hard or soft) on the efficacy of the technique (TARN-PURE Ltd, 2016). Within Africa, there seem to very little or non-existent literature on the application of the technique in *Legionella* control. There are however some studies related to copper and silver metals. In Swaziland, Varkey (2010) reported on the antibacterial effect of copper and silver metals on Coliform and E. *Coli* through immersion of the metals in water. Paper filters containing AgNP and CuNP were tested on water sourced from contaminated streams in Limpopo South Africa resulting in marked reduction in coliform bacteria and *E. coli* counts and in the incorporation of a copper mesh in the design of clay pot water filters (CPWFs), E. *coli* and coliforms concentrations in contaminated water were reported to have reduced markedly (Varkey and Dlamini, 2012; Dankovich and Gray, 2011).

OZONATION

Method

Ozone is an unstable potent biocide and oxidizing agent which must be produced on site due to its short half-life especially as rising temperature can results in increase in decomposition (NRC, 1980). Ozone can be produced in a number of ways notably phosphorus contact, silent discharge, photochemical reactions, and electrochemical reactions (Wei et al., 2016). Generated electrically by exciting oxygen O_2 to a tri-atomic state O_3 , ozone can be injected to an allowable quantity but should be maintained at a residual dosage.

Characterization of efficacy, advantages and disadvantages

Comparably, ozone is more effective in L. *pneumophila* control compared to other oxidizing biocides (Dominique et al., 1988). In a review, Kim et al. (2002b) reported there is an appreciable use of ozone across Europe although its better complimented with other disinfectants such as chlorine. In light of it being unstable, ozone does not stay in water sufficiently long to provide the residual effects often required in the control of pathogenic bacteria (Kim et al., 2002b; WHO, 2007; Blanc et al., 2005). Ozone is reported to somewhat more effective at a lower temperature, with a potential of faster destruction of microorganisms at higher pH (Botzenhart and Tarcson, 1993)

In terms of efficacy, Edelstein et al. (1982) documented, ozone reduced L. *pneumophilla* counts in one wing of an unoccupied hospital with average ozone concentration of 0.79 mg/L.

Blanc et al. (2005) however reported no significant reduction in *Legionella* counts after the application of just ozonation. Appreciable reduction in *Legionella* counts were however observed after the complimentary implementation of thermal eradication (Table 1).

Overall, ozone generation consumes a significant amount of energy and thus require a lot of monitoring in order to ensure power is optimized while achieving disinfection targets (Casey et al., 1998). Additionally, its requirement of onsite generation and the use of special equipment as opposed to other disinfection modalities make it less favourable. Based on its quick decomposition characteristics and its lack of residual effect, a growing body of reviews and independent studies show ozonation is best implemented as a secondary disinfection technique (Campos et al., 2003; Kim et al., 2002a; Blanc et al., 2005). Reports of of its instantaneous effect in bacterial inactivation, rapid decomposition and on site generation are however listed as major advantages (Casey et al., 1998; Campos et al., 2003).

Effect of ozonation on water quality and its application in Africa

A varying body of literature shows, ozonation significantly improves water quality either in building water systems or even when used in aqua culture (Davidson et al., 2011; Von Gunten, 2003). A study by Von Gunten, (2003) reported ozone as an excellent disinfectant in the inactivation of protozoa compared to other very conventional disinfectants. In terms of water quality, ozonation has been documented to result in a significant increase in ultraviolet transmittance as well as a reduction in carbonaceous BOD and colour (Davidson et al., 2011). By combining ozonation with UV treatment, available literature has shown the potential for minimizing bromate as well as the oxidation or micro pollutants in water (Meunier et al., 2006). Practically, studies have also shown the application of ozonation for disinfection has a positive impact on distribution water system, reducing both levels of disinfection by products and complaints about the taste and odour of water (Dyksen et al., 2016). Essentially, it is evident problems in water quality that are often addressed with peroxide, chlorine etc. can also be addressed through ozonation (Eagleton, 1999). Within Africa, there is extensive evidence on the application of ozonation although much of its use is not directly aimed at the elimination of L. *pneumophillia*. The post-ozone plant at Wiggins waterworks which was commissioned in 1984 in South Africa is one such example. The purpose of the plant has been to properly disinfect water by eliminating viruses in raw water pumped from the polluted lower Umgeni river (Rencken, 1994). There is also evidence on the application of ozonation in industrial waste water and drinking water treatment plants in parts of South Africa (Van der Merwe et al., 2012). Its use at the Midvaal water company Durban Water Recycle

Plant and Magalies Water plant are also documented (Rajagopaul et al., 2008; Morrison et al., 2012).

UV IRRADIATION

Method

UV disinfection can be applied in two ways: (1) Positioning UV lights at specific points within a given water distribution system that service a designated area or (2) installation of a UV-sterilizers for the disinfection of incoming water. Monochromatic low pressure UV lamps and polychromatic medium pressure lamps are some of the lamps used (Oguma et al., 2004).

Characterization of efficacy, advantages and disadvantages

In terms of efficacy, available literatures shows UV radiation kills bacteria by hampering DNA replication through the production of "thymine dimers" (Gavdy and Gavdy, 1980 as cited in Hambidge, 2001). Typically, there are different types of UV lamb systems although low pressure UV bulb systems are almost an industry standard supplying monochromatic irradiation specific to 254 nm wavelength (Summerfelt, 2003). Its efficacy against other microorganisms is documented elsewhere (Harris et al., 1987; Hijnen et al., 2006; Chevrefils et al., 2006). On the other hand, the use of UV alone in a persistently colonised hospital water distribution system ("point of use application") showed it was ineffective in the elimination of *Legionella* (Liu et al., 1995). The concurrent application of other disinfection techniques e.g. Superheat/Flush and shock chlorination however achieved some reduction in *Legionella* counts. In a study by Franzin et al. (2002) a reduction in *Legionella* counts (L. *pneumophila* sero-group 3) was achieved even at distal sites using UV light. The authors therefore concluded UV disinfection could be suitable in small areas of water system. In Hall et al. (2003), UV was efficacious in preventing *Legionella* contamination over a 13 year period. Overall, despite reports of the extensive application of UV in both cold and hot water systems (Liu et al., 1995; Kim et al., 2002a), its limitations include maintenance against the formation of scales, likelihood of malfunctions, lack of residual protection beyond points of application and turbidity (Muraca et al., 1990; USEPA, 2001; Campos et al., 2003). The use of filters in minimizing the accumulation of scale on UV quatz sleeves has also been reported (Liu et al., 1995). In terms of other advantages, UV light is easy to install (Campos et al., 2003). Conspicuously, continuous monitoring as may be the case in other disinfection modalities is also limited. Finally, although the energy used in typical UV disinfection system in an average size home is comparable to the energy used by a 40 watts bulb (UV Dynamics, 2016), the energy cost associated with technique cannot be ignored.

Effect of UV irradiation on water quality and its application in Africa

Overall, the application of Ultraviolet light (UV-Lamp) is an established and increasingly popular alternative to chemicals for the disinfection of water distribution systems. Interestingly, the quality of water is one of the many defining factors in its application (Wright and Cairns, 1998). Amid it being a cost effective disinfection technology, there is evidence, UV provides no residual effect in water towards the protection against post treatment contamination (Clancy et al., 2000; Said and Otaki, 2013). A study by Choi and Choi (2010) has shown the technology has an effect on dissolved organic matter structure (DOM) in distribution systems including an increase in biodegradability (Frimmel, 1998; Drikas et al., 2004). By far, the aforementioned remains the most documented effect on water quality across an existing body of research (Kruithof et al., 1992; Oppenheimer et al., 1997). Within Africa, a study on a device (UV light 254 nm) that utilizes the technique to disinfect community drinking water demonstrated efficacy for close to 4.5 months; delivering water that meets WHO and USEPA bacteria standards (USEPA, 2001; Gadgil et al., 1998). At the Durban Metro Water and hospice for infants, the application of a UV unit also achieved a reduction in E. *coli* and total coliforms concentration per local standards (Gadgil et al., 1998). Largely, there is no literature on the application of this technology specifically aimed at *Legionella* control. There is however extensive publication on its application as a regular water disinfection technology coupled with the proliferation of numerous devices or units that utilize the technology for disinfection (Brahmi and Hassen, 2014; Gadgil et al., 1997). Perhaps, Solar Water Disinfection (SODIS) which is appears to be highly patronised due to the conspicuously low cost implication associated with it compared to the conventional use of UV lamps, positions the use of UV- light as somewhat unpopular. Reports on the efficacy of SODIS and application in developing nations is been reported (Mosler et al., 2013; Murinda and Kraemer 2008; Altherr et al., 2008; Conroy et al., 2001). Nevertheless, its limitations such as the need for sufficient solar radiation, relatively clear water and difficulty in treating large volumes cannot be overlooked (Mintz et al., 2001).

DISCUSSION

This work provides further knowledge on an already explored area of comparing different water disinfection techniques in *Legionella* control and elimination. Additionally, the study also attempts to identify cases of Legionnaires reportage in Africa as well as the application of some selected disinfection techniques in *Legionella* control within the continent. The overall aim of the fore going, is to provide an update on some of the most commonly used water disinfection techniques employed in *Legionella* control so as to provide a pool of evidence based options (locally and internationally) in the event of Legionnaires outbreak within Africa.

Globally, reports on the outbreak of Legionnaires occur almost every year; often reported by the developed countries. Countries such as the United States through the Centre for Diseases Control (CDC) are known to document almost 5,000 cases of Legionnaires' annually (Dooling et al., 2015). This is no different in Europe. Well-regulated surveillance programmes across almost 35 countries within Europe, exist with the mandate to collect and provide information with regards to the disease (Heuner and Swanson, 2008). The European Surveillance Scheme for Travel Associated Legionnaires Disease now known as EWGLINET, is known to be instrumental in recommending standards for Legionnaires surveillance (Ricketts and Joseph, 2005). The case is however very different in the African context. With the exception of a handful African countries e.g. South Africa, there is very little in terms of institutions or organizations aimed solely at monitoring Legionnaires on the national scale or on the continent at large. The lack of statutory notification of Legionnaires, coupled with clearly defined health based standards is evident in the lack of academic literature or studies related to Legionnaires on the continent, as may be the case in Europe. For instance, there are very few studies or reports on particular water disinfection techniques aimed at *Legionella* control or evidence of them being applied during an outbreak as shown in this review. Perhaps, political importance, clinical impact or rareness of disease (Heuner and Swanson, 2008) that are motivating factors in paying attention to most infectious diseases is minimal.

Unfortunately, the argument cannot be made that reportage or studies related to *Legionella* are very little because proliferation, infection or outbreaks rarely occur. L. *pneumophila* is known to grow and survive over a wide range of temperature (20, 40 and 50°C) (Rogers et al., 1994; Konishi et al., 2006) and these temperatures are typical in a greater part of sub Saharan Africa. Moreover, there is evidence to suggest temperature increase over land regions across the continent is consistent with anthropogenic climate change (Aalst et al., 2014), thus, the implication of the foregoing are favourable temperature for bacteria proliferation in already precarious water distribution networks across the continent. More so, at the root of the many challenges with water supply are the poor maintenance and servicing culture of already deteriorated pipe networks (Marin, 2009). Many of the water distribution networks are faced with massive leakages, irregular supply and low water pressure; these factors create avenue for easy water contamination (Marin, 2009). Implicitly, much of the water prior to being consumed at distal sites are already contaminated with pathogenic bacteria; a challenge that must be avoided from the onset as a step in achieving *Legionella* control (Borella et al., 2005; Rangel et al., 1999; WHO, 2007).

On the other hand, evidence of a single most consistent and permanent method at *Legionella* control is barely been established globally. Our review noted most of the disinfection techniques often had to be combined to achieve long term efficacy; consistent with literature elsewhere. For instance, while techniques such as thermal disinfection record some measure of efficacy, the lack of residual effect days after application, often require the application of other techniques e.g. chlorination. Thus, the application of such methods have demonstrated efficacy only in the short term. Additionally, it would also seem somewhat challenging to flush entire water systems of heavily occupied hotels or hospitals especially as occupancy and monitoring at distal sites are significant in achieving success. In terms of Chlorination, evidence of re-colonization as shown in this review, suggests it can arguably be placed under the category of short term or emergency techniques notwithstanding its residual effect. Moreover, the role of biofilm and *Legionella* resistance to Chlorine as reported in other literature (Kuchta et al., 1983; Cooper and Hanlon, 2010) imply, larger doses of chlorine are often required to achieve complete elimination. In view of the fact that chlorination is already used extensively as a common water disinfection technique within Africa (Whitacre, 2010), it seems at best, one of the most accessible disinfection techniques to be employed in the event of an outbreak. Chlorine dosage will however have to be based on local regulations or known international standards.

Copper silver ionization appears the most efficacious compared to the other techniques in this review. In addition to its ease of installation, evidence of its application even in hot and cold water systems with keen consideration to ion quantities, provides the basis for arguing, the technique can be employed during outbreaks and over longer periods. Additionally, its ability to kill as opposed to suppression, proves copper-silver ionization will be the most suitable disinfection modality in heavily colonised water distribution networks. The afore highlights, coupled with findings in other literature (Marchesi et al., 2011; Lin et al., 1998) therefore positions copper silver ionization, conceivably as one of the best alternatives for *Legionella* control.

With Ozonation, albeit, its extensive use within Europe and Africa as shown in this report, the need for onsite generation and special equipment could be challenging in most domestic installation or small public buildings in rural areas; heavily colonised by bacteria. Additionally, its lack of residual effect, energy consumption and need for monitoring, implies the technique will be difficult to apply in colonised water systems in places with less manpower or electricity. Nevertheless, its rapid destruction of microorganism at higher pH (Botzenhart and Tarcson, 1993) along with its ability to compliment other disinfection techniques, positions the technique as a viable option in *Legionella* control within Africa.

Finally, on the grounds of challenges such as maintenance against the formation of scales, lack of residual effect, use of filters for scale prevention and the need to combine with other disinfection techniques as already evidenced in this report, UV cannot be considered a “singular disinfection method“. Albeit its ease of installation, the lack of evidence of its efficacy in large-scale water systems, suggests UV should be considered in less colonised water systems or systems with little water volume, where greater water quantity can be exposed at point of contact. On the hand, the use of Solar Water Disinfection (SODIS) in Africa as suggested in the earlier part of this study will serve the greater advantage of bacteria control in rural areas especially in the absence of the commonly “advanced technologies” in water disinfection. A foreseeable challenge to this measure will be its inability to be implemented in large scale water systems where treating large volumes of water will pose a challenge (Mintz et al., 2001).

Overall, while all the aforementioned techniques have their respective disadvantages, their proven reliability across different types of buildings and water systems, suggest they can all be described as efficacious in one way or the other. Their implementation will therefore vary on a number of factors such as cost, ease of installation, maintenance, age and design of plumbing system, availability of electricity (for certain techniques), as well as the measure of colonization of the water system under consideration. An overall consideration should however be the prevention of contamination from the onset as reported elsewhere as well as effective monitoring of water system towards the identification of colonization at the early stages. The need for sensitizing the general population about Legionnaires, symptoms as well as factors that can lead to contamination in water distribution networks is also important within Africa.

Conflict of Interests

The authors have not declared any conflict of interests.

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