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Full Length Research Paper

Potential contaminant runoff from California's dairy concentrated animal feeding operations (CAFOs): A geospatial analysis

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Concentrated animal feeding operations (CAFOs) contain large quantities of dairy cows and therefore have the potential to contribute significant amounts of harmful waste products to the environment. Although previous studies have used geospatial tools to assess potential contaminant runoff, the results from these studies are dependent on the unique geographical characteristics of specific regions. This study incorporated geographical characteristics unique to California to: 1) characterize the distribution of dairy CAFOs in California; and 2) determine and compare the potential for dairy CAFOs in high vs. low runoff potential regions in subject counties to contaminate surface water. The CAFOs were grouped by their location in either high or low runoff potential regions characterized by Curve Number (CN) grids. The potential for the CAFOs in either group to contaminate surface water was determined by calculating the proportion of CAFOs with runoff that intersected with surface water. Among the CAFOs in high runoff potential regions, 180 out of 193 facilities had the potential to contaminate surface water. This proportion was found to be significantly different from the proportion of CAFOs in low runoff potential regions (p=0.023), indicating validity of the CN grids used to approximate runoff potential.

Key words: Concentrated animal feeding operation (CAFO), dairy, water pollution, geographic information system (GIS), curve number (CN) grids

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INTRODUCTION

Concentrated animal feeding operations (CAFOs) contain large quantities of livestock and therefore have the potential to contribute significant amounts of waste products to the environment (Environmental Protection Agency, 2010). California has the highest number of dairy CAFOs out of all 50 states (Sherman, 2008). Moreover, dairy CAFOs in California pose a threat because they are clustered (Sherman, 2008). This raises a public health concern to the communities surrounding the clusters, as numerous studies indicate that contaminants present in the excrement of dairy cows housed in CAFOs are harmful to humans. *Escherichia coli*, estradiol, and

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nitrogen compounds in particular have been associated with gastrointestinal illness, breast cancer, and hyperthyroidism, respectively (Cabelli et al., 1982; van Maanen et al., 1994; Bendrik and Dabrosin, 2009).

Agricultural use of dairy cow excrement as fertilizer may contaminate runoff from rain events. This runoff can then contaminate surface waters including lakes, rivers, streams, estuaries, reservoirs, and swamps. Manure is often applied to crop or pasture land as the primary disposal method for CAFO farmers. Farmers report that moving manure from the facilities to an adequate landfill is a financial burden (Aillery et al., 2005). The use of dairy cow excrement as an agricultural fertilizer increases the likelihood of surface water contamination, as farmers do not typically assess risk factors such as slope and proximity to surface water when applying manure (Kolpin et al., 2002). Individuals may then be exposed to the contaminants through accidental ingestion in recreational and occupational settings (Aillery et al., 2005; Mitloehner and Calvo, 2008). Children and elderly living in close proximity to the CAFOs are at higher risk of exposure (Burkholder et al., 2007).

The health consequences of exposure can be severe, so it is important to understand the mechanisms of surface water contamination. Studies have shown that slope and proximity influence the degree of surface water contamination (Dabrowski et al., 2002; De Winnaar et al., 2007). This is not surprising, as runoff flows from high to low elevation, and a shorter distance between a CAFO and the receiving surface water will likely decrease the amount of movement-impairing factors such as vegetation and residential housing that the runoff may come in contact with (De Winnaar et al., 2007).

Soil content may also affect the degree of surface water contamination. Common contaminants present in dairy cow excrement, such as *E. coli*, estradiol, and nitrogen compounds, have all been shown to be affected by soil content in terms of both quantity and toxicity. For example, estradiol degrades faster in soils with higher organic carbon content and loses its ability to bind to the soil. This decreased soil absorption increases the amount of free estradiol that can contaminate nearby surface water. A similar relationship is applicable to *E. coli* and nitrogen compounds (Noborio et al., 2003; Karthikeyan et al., 2005; Khanal et al., 2006; Semenov et al., 2009; Hamid and Eskicioglu, 2012).

Mitigation through regulatory action

Despite increasing evidence of surface water contamination by CAFOs, risk management strategies have been imposed with minimal success. The final CAFO rule was enacted in 2003 by the United States Environmental Protection Agency (EPA) to require more CAFOs to secure National Pollutant Discharge Elimination System (NPDES) permits unless they could demonstrate they had no potential to discharge as a "point source" of pollution (Centner, 2007). However, in the Water keeper Alliance, Inc. v. Environmental Protection Agency (2005) case, the Court of Appeals (D.C. Circuit) found that the Clean Water Act (CWA) grants the EPA jurisdiction to regulate and control actual discharges, but not facilities that have the potential to discharge (Centner and Newton, 2011). In response, the EPA rewrote its provision to address the proposals to discharge determined by the design, construction, and operation of a CAFO, but this was objected to again in National Pork Producers Council v. EPA (2011) on the basis that the EPA exceeded the authority given to them by the CWA (Centner and Newton, 2011).

Many studies have used Geographic Information System (GIS) tools to determine if runoff has the potential to contaminate water bodies (Tong and Chen, 2002; De Winnaar et al., 2007). A common approach includes inputting digital elevation, land cover, and soil data to generate Curve Number (CN) grids that depict runoff potential (De Winnaar et al., 2007; Shukur, 2017). However, the results from studies that used this method are derived from unique geographical characteristics of specific regions and therefore cannot be generalized to California. Furthermore, to our knowledge, no study has used CN grids to measure the potential for dairy CAFOs to contaminate surface water bodies.

This study used GIS tools and California county-level geography data to determine if elevation, proximity, land cover, and soil content surrounding dairy CAFOs in California present a risk to the state's surface water bodies. Due to lack of available soil data for the entire state, counties with the highest density of dairy CAFOs and sufficient soil data were identified and their respective CN grids were created using the Hydrologic Modeling System (HEC-HMS) 4.2.1 extension designed by the United States Army Corps of Engineers (USACE). The CAFOs were grouped according to their location in either high or low runoff potential regions using the HEC-HMS extension in ArcMap 10.5.1 (Esri, Redlands). The potential for the CAFOs in either group to contaminate surface water was assessed by calculating the proportion of CAFOs with runoff that intersected with surface water. The two proportions were tested for statistically significant difference as a test of the validity of the HEC-HMS extension using Fisher's exact chi-square test. The aim of this study was to assess the severity of the threat that runoff from dairy CAFOs in California presents to the state's surface water bodies, and to promote the implementation of more stringent regulations to protect individuals who may come in contact with contaminated surface water.

METHODS

Geocoding

Dairy CAFO addresses (N=1,334) were acquired from the California

Department of Public Health (CDPH). The address list was converted to coordinate points using the Geocode tool in ArcGIS Pro 10.2 (Esri, Redlands) which utilizes the Esri World Geocoding Service (WGS). One facility in France with a permit held by a company in the United States was removed from the study. Out of the 73 locations with low match statistics score (≤ 77), 27 were randomly picked and checked for accuracy in Google Earth Pro (Google, Mountain View). Two of the checked locations and three other visibly inaccurate locations were determined to be erroneous and the appropriate coordinates were manually obtained using Google Earth Pro. The remaining facilities were projected in WGS_1984_Web_Mercator_Auxillary_Sphere in ArcMap 10.5.1 on top of a California county boundaries layer obtained from the MAF/TIGER database of the United States Census Bureau and were visually verified to be located in California.

Dairy CAFO hotspots

The distribution of dairy CAFOs shown in the previous report from the California Department of Food and Agriculture (CDFA) pointed to the existence of hotspots (areas that have significantly high dairy CAFO densities) (California Department of Food and Agriculture, 2016). The Kernel Density tool was used in ArcMap 10.5.1 to identify counties in California that may be characterized as dairy CAFO hotspots. In kernel density, each point site is given a surface value that is highest at the location of the point and diminishes with increasing distance from the point. The density at each output raster (grid) cell is calculated by adding the values of all the surfaces where they overlay. Visually, the resulting map depicts hotspots of dairy CAFOs in California. Dairy CAFOs in the counties part of a hotspot were grouped according to their respective counties using the Clip tool in ArcGIS 10.5.1.

Classification of CAFOs by runoff potential region

To classify the different runoff potential regions in each county, SCS CN grids were generated using the HEC-HMS 4.2.1 extension designed by the USACE. The HEC-HMS extension considers the relationship between slope, land cover, and hydrologic soil group to create CN grids that depict the degree of surface runoff in a given area (Schulze et al., 1992; Gangodagamage 2001). Curve numbers vary from 30 to 100, where greater curve numbers represent a greater potential for surface runoff (Schulze et al., 1992; Stuebe and Johnston, 2007).

The underlying Digital Elevation Model (DEM) data for the CN grids were obtained through the National Map Viewer made available by the United States Geological Survey (USGS). All the DEM data used in the study had a resolution of 10 m (last updated in 2016).

County-level soil data were obtained from the Web Soil Survey of the United States Department of Agriculture (USDA). The Soil Data Viewer extension built by the USDA was used in ArcMap 10.5.1 to extract hydrologic soil group data from the original dataset. Each hydrologic soil group dataset consists of regions classified into groups A, B, C, or D, where each letter denotes the hydrologic soil group they belong to. Each hydrologic group is associated with different soil content and degree of runoff. Groups A, B, C, and D have low, moderately low, moderately high, and high runoff potential, respectively (Mockus, 2007).

The National Land Cover Database (NLCD) 2011 with a resolution of 30 m was obtained from the Multi-Resolution Land Characteristics (MRLC) Consortium. The national-level data were reduced to county-level data using the Clip Raster tool in ArcMap 10.5.1. The original data consisting of regions classified into 15 NLCD classifications were simplified into four reclassified regions: 1=water, 2=residential, 3=forest, or 4=agricultural (Table 1) (Merwade, 2012). The reclassified raster data were then converted to polygons using the Raster to Polygon tool to conform to the data requirements of ArcGIS 10.5.1 Spatial Analyst tool.

A lookup table that assigned each hydrologic group to different percentages of the four land cover classifications was used to link the soil data with the land cover data (United States Department of Agriculture, 1986). The DEM, soil content, and land cover data along with the lookup table were inputted into the HEC-HMS extension to generate the final CN grids for the subject counties. Merced County, one of the four counties chosen for analysis from Kernel Density, was eliminated from the study due to lack of soil data.

In order to determine which of the CAFOs were located in regions with high or low runoff potential, the CN grids were reclassified to low, moderate, and high runoff potential regions based on their curve numbers. The cutoff curve numbers were determined by using natural breaks classification in ArcGIS 10.2.1. The natural breaks classes are based on natural groupings inherent in the data distribution and maximize the differences between classes. Because there is no established cutoff value for different degrees of runoff, the use of natural breaks allowed for the best estimation of the cutoff curve numbers. All three CN grids (one per county) produced breaks to create three ranges: 30-72, 72-83, and 83-100. There were small variations in the decimal values of the ranges, so the cutoff values were manually set to 72 and 83 in order to eliminate small differences between the three counties.

The reclassified CN grids were converted to polygons in order to spatially join them with the CAFOs. The spatial join counted the number of CAFOs that were located in low, moderate, or high runoff potential regions for each county. The CAFOs were classified by runoff potential region and the proportion of CAFOs located in either high or low runoff potential regions was recorded.

Proportion of CAFOs with the potential to contaminate

Dairy CAFOs in high or low runoff potential regions were used as the starting points in the Flow Accumulation tool in ArcGIS 10.2.1. The Flow Accumulation tool calculates the accumulated weight of all cells flowing into each downslope cell in the output. The exact direction of flow was determined using the DEM data to create Flow Direction layers (Figure 1). The resulting areas of concentrated flow represented runoff from the individual CAFOs.

All runoffs were overlaid with a California surface water layer obtained from the National Hydrography Dataset Plus Version 2 (NHDPlusV2) dataset maintained by the EPA in partnership with the USGS. The original layer, which covered the entirety of California in a resolution of 30 m, was converted and clipped to separate county boundaries. For each of the subject counties, potential runoff from dairy CAFOs in either high or low runoff potential regions was assessed by calculating the proportion of CAFOs with runoff that intersected with surface water. A cumulative proportion was then recorded for both groups of CAFOs from the proportions calculated for each of the subject counties. Because the unit of analysis was not on the county-level, it was appropriate to combine the proportions calculated from each county. In this study, county boundaries were used as arbitrary boundaries identified by the Kernel Density tool and did not affect the research question.

Test for statistical significance

A table consisting of two variables “Runoff potential region - high/low” and “Intersection - yes/no” (N=243) was created in Microsoft Excel (Microsoft, Redmond WA) and read into Stata 15 (StataCorp, College Station) to test for a statistically significant difference in the proportion of CAFOs, in either high or low runoff potential regions that had the potential to contaminate surface

Table 1. Original and reclassified numbers and labels of the National Land Cover Database (NLCD).

Original NLCD classification		Reclassification	
Number	**Label**	**Number**	**Label**
11	Open Water	1	Water
90	Woody wetlands		
95	Emergent herbaceous wetlands		
21	Developed, open space	2	Residential
22	Developed, low intensity		
23	Developed, medium intensity		
24	Developed, high intensity		
41	Deciduous forest	3	Forest
42	Evergreen forest		
43	Mixed forest		
31	Barren land	4	Agricultural
52	Shrub/scrub		
71	Grassland/herbaceous		
81	Pasture/hay		
82	Cultivated crops		

water. Expected values for each cell were calculated to test for eligibility for Pearson's chi-square test. One of the cells did not meet the criteria (N>5) so Fisher's exact chi-square test was used instead. A probability value (p) of 0.05 was used to determine statistical significance.

The test was conducted to check for the validity of the HEC-HMS extension used to classify the CAFOs by the type of runoff potential region they were in. The absence of a statistically significant difference would indicate that the high and low runoff potential regions generated by the HEC-HMS extension were inaccurate and did not differ in runoff potential.

RESULTS

Dairy CAFO hotspots

Two prominent hotspots were identified from the Kernel Density analysis. One hotspot stretched over Stanislaus and Merced Counties with a range of 25 to 29 dairy CAFOs per 100 square miles. The other hotspot stretched over Tulare and Kings Counties with a range of 22 to 25 dairy CAFOs per 100 square miles (Figure 2). There were seven other hotspots over Sonoma, Marin, Humboldt, Sacramento, Glenn, Kern, San Joaquin, Riverside, Los Angeles, Orange, and San Bernardino Counties. These hotspots had a significantly lower range (three to nine) of dairy CAFOs per 100 square miles and were omitted from the study.

Classification of CAFOs by runoff potential region

Out of the three counties with the highest density of dairy CAFOs, Tulare County had the highest number (N=140) and proportion (0.55) of dairy CAFOs in high runoff potential regions (Table 2). All CAFOs were located in the western half of Tulare County where low runoff potential regions did not exist (Figure 3). This was different in the other two counties, where the majority of the CAFOs were found to be located in low or moderate runoff potential regions. In Kings County, 18, 72, and nine CAFOs were located in low, moderate, and high runoff potential regions, respectively. These counts led to proportions of 0.18, 0.72, and 0.10 (Figure 4) (Table 2). Stanislaus County had a similar distribution with lower proportions of CAFOs in low and moderate runoff potential regions (Figure 5) (Table 2).

Proportion of CAFOs with the potential to contaminate

The dairy CAFOs in either high or low runoff potential regions in all three counties were exported separately and assessed for potential runoff. There were no CAFOs in low runoff potential regions in Tulare County. Out of the 140 CAFOs in high runoff potential regions, 131 had the potential to contaminate surface water (Figure 6). There was a small number of CAFOs (N=7) with runoff that flowed beyond the county boundary and the surface water beyond the boundary had to be considered to test for intersection (Figure 7). All of these CAFOs had runoff that intersected with surface water and were included as part of the 131 potentially contaminating facilities (Table 3).

All of the runoff originated from CAFOs in high runoff potential regions in Kings County combined (Figure 8). Eight of the nine CAFOs (marked yellow in Figure 8) had the potential to contaminate surface water (Table 3).

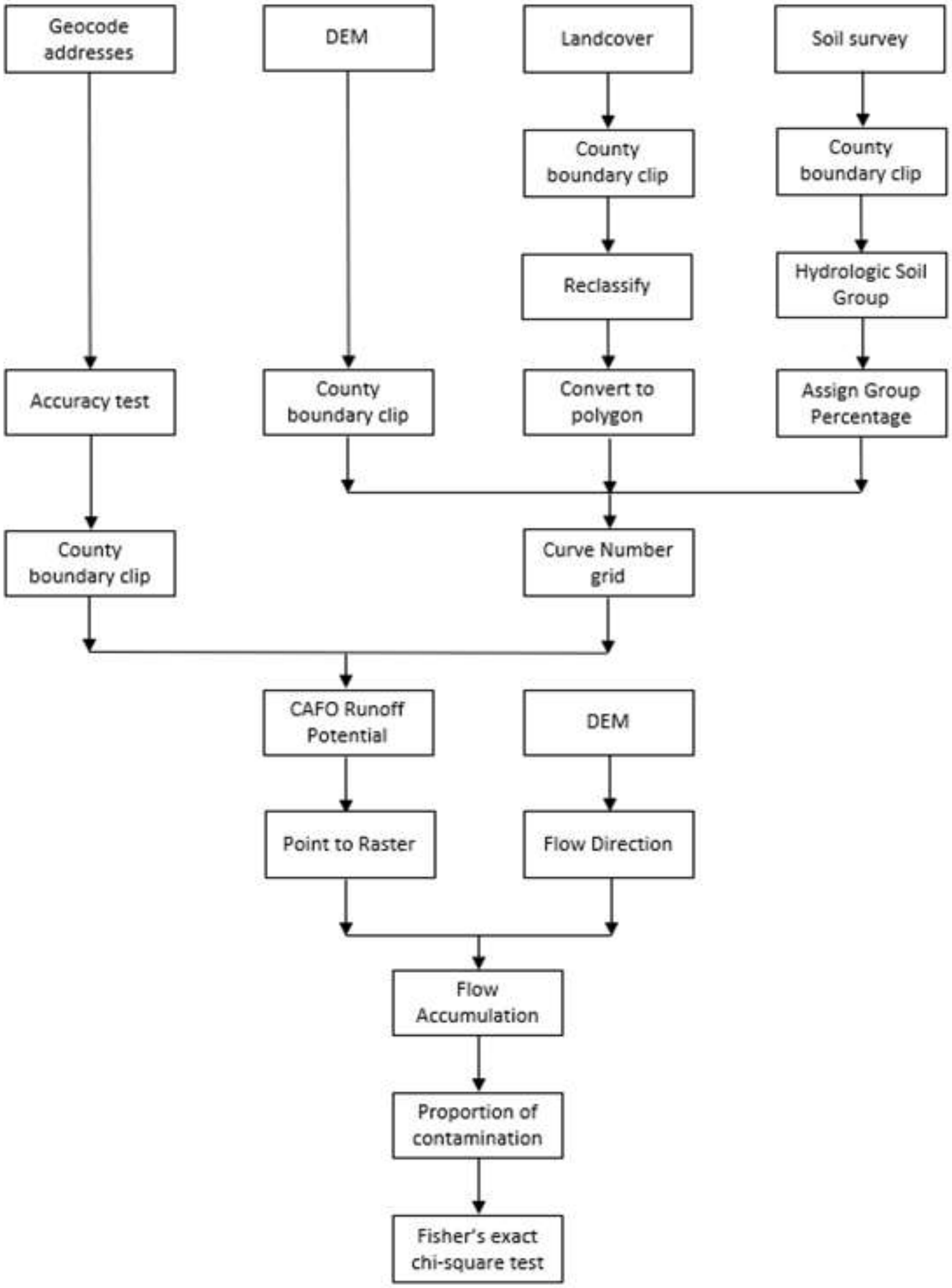

Figure 1. Flowchart of GIS and statistical analyses.

Runoff originating from CAFO in low runoff potential regions in Kings County did not always combine with one another (Figure 9). Out of the 19 CAFOs, 14 had the potential to contaminate surface water (Table 3).

In Stanislaus County, the majority of the CAFOs located in high or low runoff potential regions were in the central region of the county where the surface water was relatively sparse compared to the upper and lower halves of the county. Among the CAFOs located in high runoff potential regions, 41 out of 44 had the potential to contaminate surface water (Table 3). One CAFO had runoff that did not fully emerge until approximately half a mile away from the facility (marked yellow in Figure 10). Among the CAFOs located in low runoff potential regions, 27 out of 32 had the potential to contaminate surface water (Table 3). Three facilities had runoff that did not

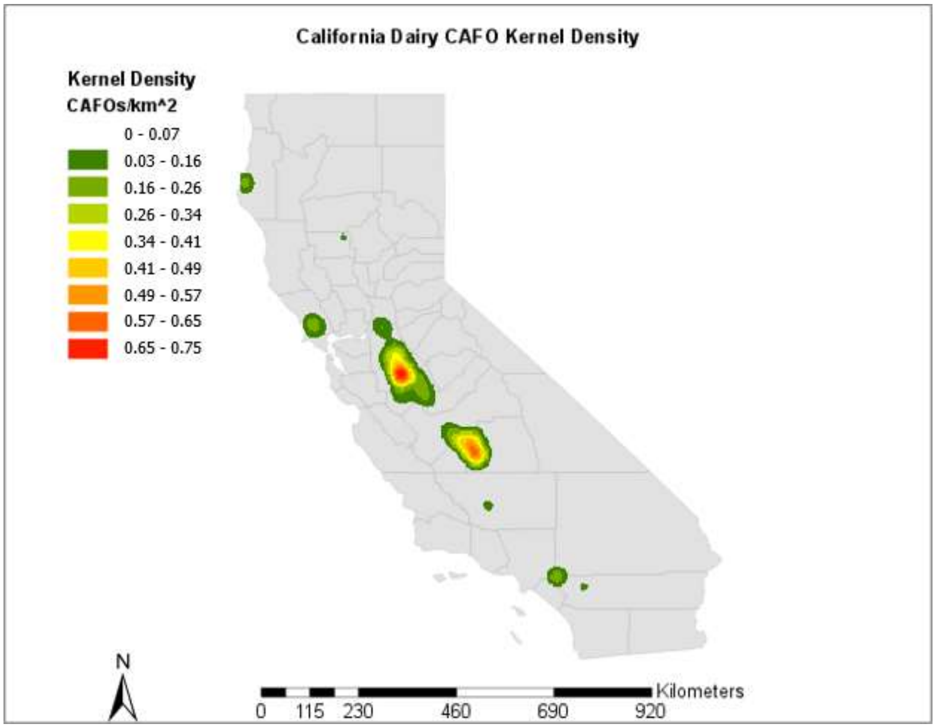

Figure 2. Dairy CAFO hotspots identified by kernel density.

Table 2. Number of CAFOs in each runoff potential region.

Variable	Tulare	Kings	Stanislaus	Total
	Count (p)			
Low Runoff Potential	0 (.00)	18 (.18)	32 (.16)	50 (.09)
Moderate Runoff Potential	114 (.45)	72 (.72)	122 (.62)	308 (.56)
High Runoff Potential	140 (.55)	9 (.10)	44 (.22)	193 (.35)
Total	254 (1.00)	99 (1.00)	198 (1.00)	551 (1.00)

intersect with surface water (marked yellow in Figure 11).

Test for statistical significance

Fisher's exact chi-square test was used to test for statistically significant difference in the proportion of potentially contaminating CAFOs located in either high or low runoff potential regions. In total, 180 out of 193 (93%) CAFOs in high runoff potential regions had the potential to contaminate surface water, whereas 41 out of 50 (82%) CAFOs in low runoff potential regions had the potential to contaminate surface water (Table 3). The difference in the two proportions was statistically significant with a p-value of 0.023. (Table 4)

DISCUSSION

The high proportion of potentially contaminating CAFOs in the high runoff potential regions was expected, but the proportion for CAFOs in the low runoff potential regions was surprisingly high and concerning. This high proportion may have resulted because surface water bodies in the subject counties were abundant and densely packed, causing many CAFOs with short distances to a surface water body to have the potential to contaminate surface water despite being in a low runoff potential region. The statistically significant difference in the proportion of potentially contaminating CAFOs located in either high or low runoff potential regions was indicative of the validity of the HEC-HMS.

Hotspot counties were identified first for two reasons: 1) soil data required to make the CN grids were not available statewide; and 2) The computational power and data required to process hydrologic models on a statewide level are not readily available. Although the CDFA posts annual data on dairy farm counts per county, these counts include smaller facilities that do not meet

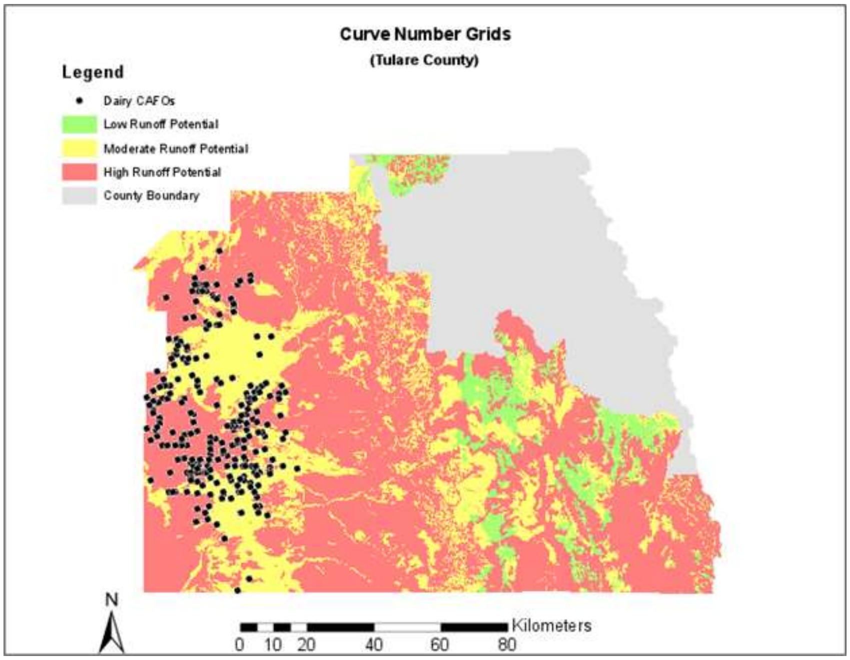

Figure 3. Dairy CAFOs in different runoff potential regions, Tulare County.

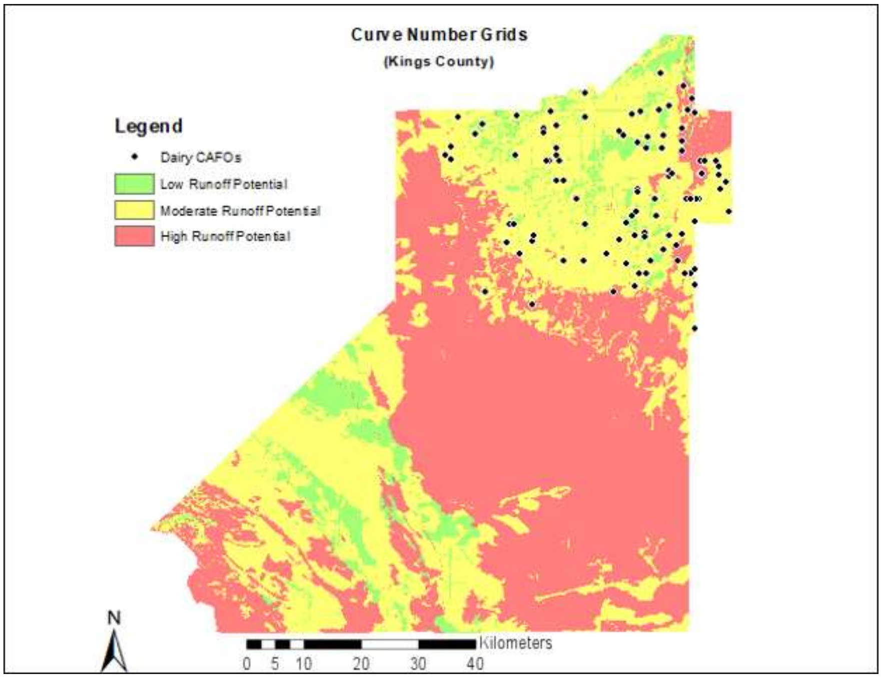

Figure 4. Dairy CAFOs in different runoff potential regions, Kings County.

the definition of a CAFO and are not reliable indicators of CAFO hotspots. Identification of hotspots using dairy CAFO coordinate points allowed for a more accurate identification of hotspot counties. This knowledge also allowed for the use of smaller county-level data to run in-depth analyses that were not computationally possible with larger state-level data.

Previous studies have used similar methods to

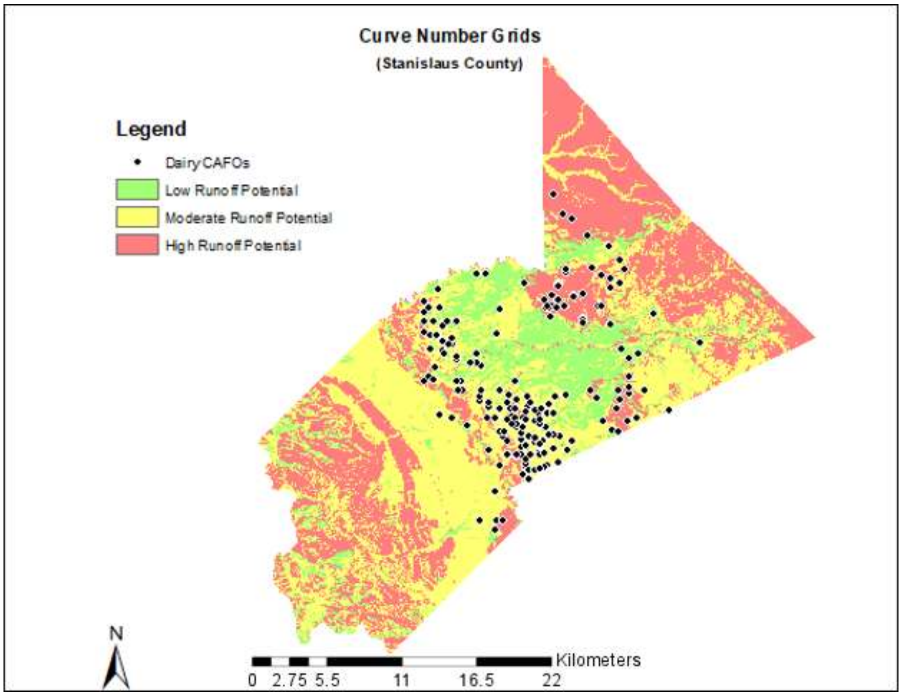

Figure 5. Dairy CAFOs in different runoff potential regions, Stanislaus County.

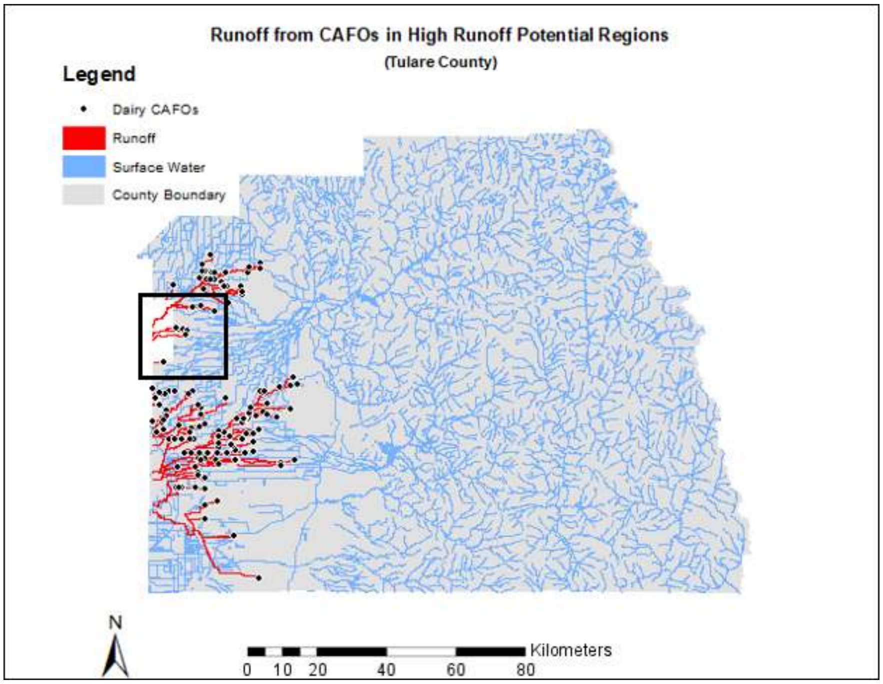

Figure 6. Runoff from CAFOs in high runoff potential regions, Tulare County.

generate CN grids as indicators of runoff potential. De Winnaar et al. (2007) used CN grids along with distance to homes and crops to locate optimal runoff harvesting sites in the Thukela River Basin, South Africa, that would supplement water availability (California Department of Food and Agriculture, 2016). Although the methodology

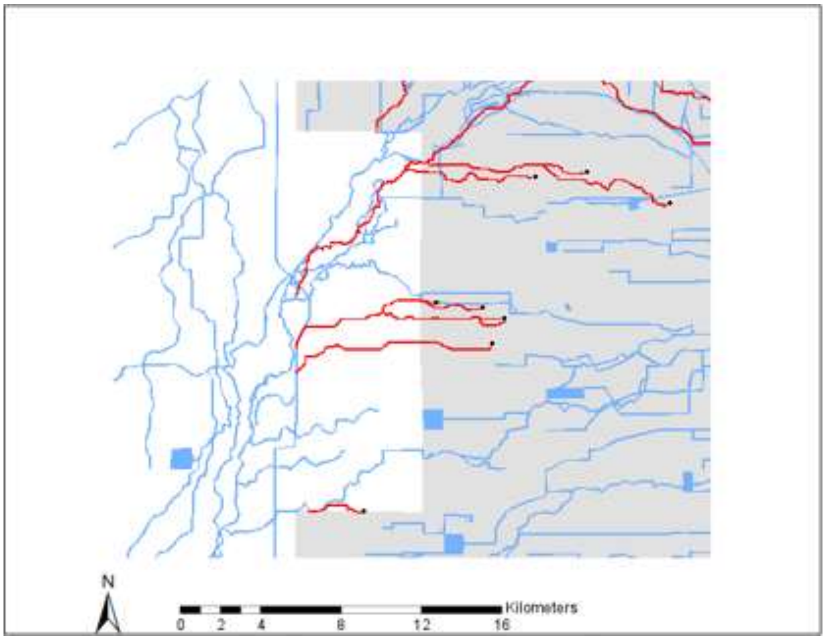

Figure 7. Runoff and surface water beyond Tulare County boundary.

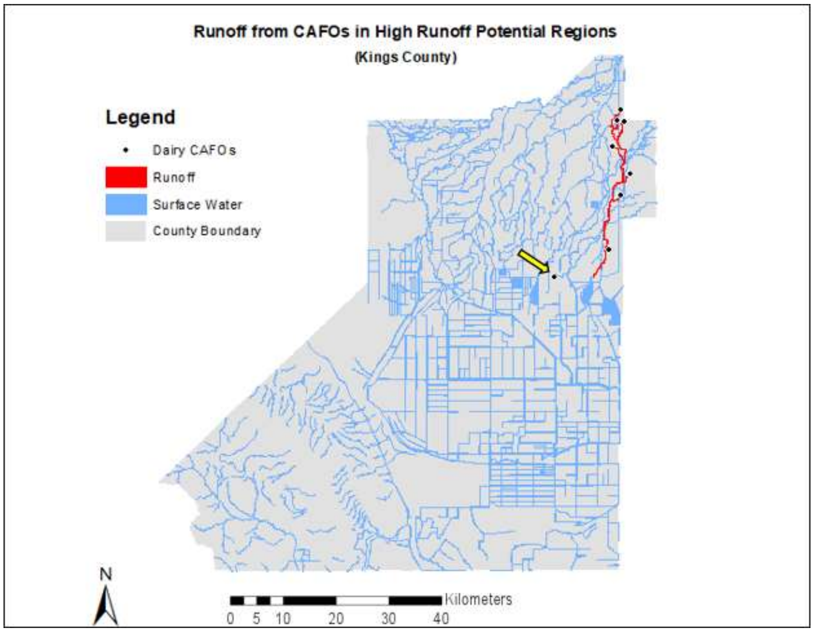

Figure 8. Runoff from CAFOs in high runoff potential regions, Kings County.

used to create the CN grids is similar, the aforementioned article directly used the CN grids to obtain the outcome. This study used the CN grids to group the CAFOs according to the type of runoff potential regions where they were located. The groups of CAFOs were then used to assess the outcome. Having an outcome (CN grids) that did not require prior knowledge of the location of the CAFOs was crucial in this study to understand what kind of runoff potential regions the CAFOs were located. Moreover, the outcome of interest in De Winnaar et al. (2007) involved specific sites to which the runoff ended up. This was in contrast to this study where the outcome was a proportion.

A similar study was undertaken by Lee et al. (2015) to

Table 3. Proportion of potentially contaminating CAFOs in high or low runoff potential regions by county.

Variable	Tulare	Kings	Stanislaus	Total (p)
Potentially Contaminating CAFOs in High Runoff Potential Regions	131/140	8/9	41/44	180/193 (.93)
Potentially Contaminating CAFOs in Low Runoff Potential Regions	N/A	14/18	27/32	41/50 (.82)

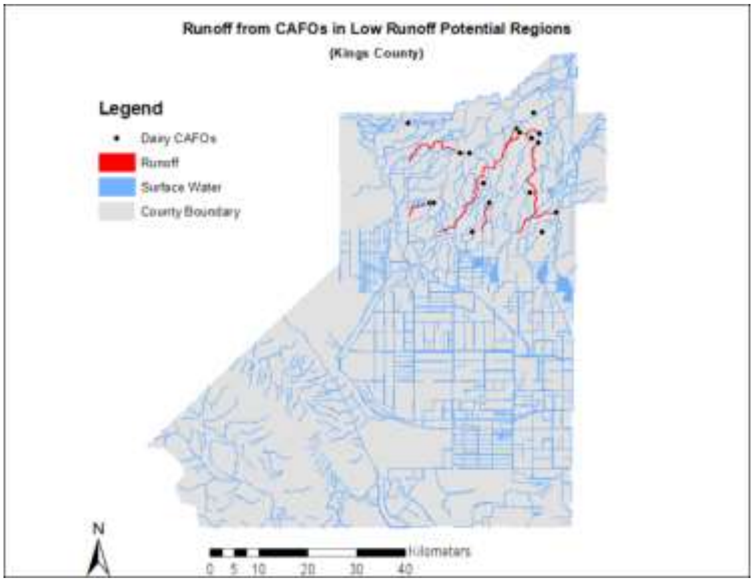

Figure 9. Runoff from CAFOs in low runoff potential regions, Kings County.

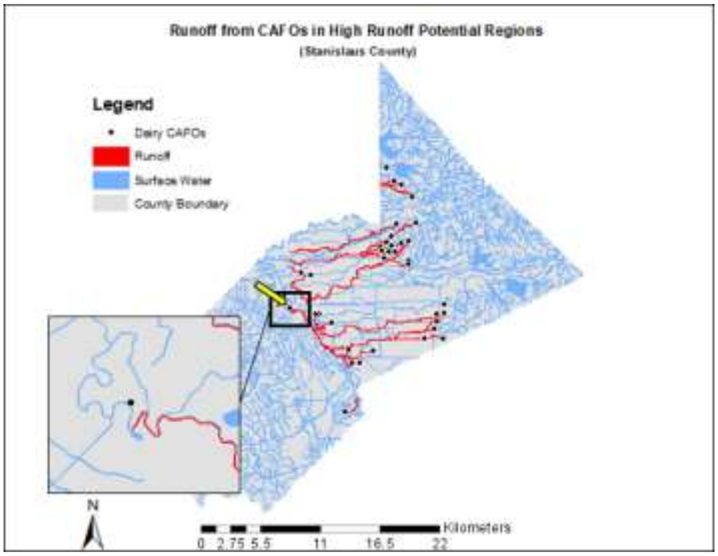

Figure 10. Runoff from CAFOs in high runoff potential regions, Stanislaus County.

predict estrogen runoff from swine Animal Feeding Operations (AFOs). Although AFOs have lower animal numbers than CAFOs, the concept of incorporating CN grids to study animal excrement-containing runoff supports the use of CN grids in this study. However, the CN grids in Lee et al. (2015) were a subpart of a

Table 4. Fisher's exact chi-square test: Runoff from CAFOs in either high or low runoff potential regions by intersection with surface water.

p = 0.023	**Intersect**	**Non-intersect**	**Total**
CAFOs in High Runoff Potential Regions	180	13	193
CAFOs in Low Runoff Potential Regions	41	9	50
Total	221	22	243

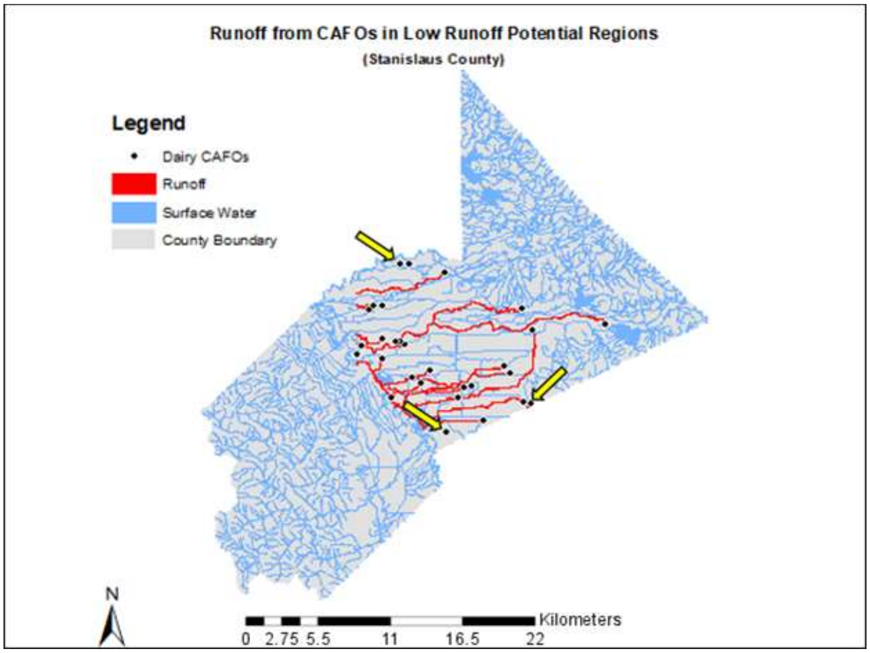

Figure 11. Runoff from CAFOs in low runoff potential regions, Stanislaus County.

Bayesian Network model that was dependent on the physical properties of their chemical of interest – estrogen (Lee et al., 2015). The degree of runoff observed with this approach can only be associated with estrogen and none of the other contaminants present in swine or dairy cow excrement. This study differed in that the identified runoff was unaffected by the specific physical properties of a single contaminant.

Unique to this study was the incorporation of a validity test. Due to the unique study area and design, there were no compatible comparisons in the current literature in which the validity of the outcomes could be assessed. The observed statistically significant difference in the proportion of potentially contaminating CAFOs increased the likelihood that the high and low runoff potential regions generated by the HEC-HMS extension were accurate and significantly differed in runoff potential.

A limitation of this analysis is that any potential runoff contaminating surface waters derived in this study were set to originate from the CAFO facilities and not the agricultural farms. Although the exact locations of the agricultural farms owned by CAFO owners are unknown, it is possible that some of the farms where manure is applied are distant from the CAFOs. Therefore, the results from this study cannot be linked to the concerns raised by agricultural reuse of dairy cow excrement as fertilizer unless the majority of manure-applied agricultural farms can be verified to be in close proximity to the dairy CAFOs. On the other hand, manure overflow from the CAFOs would minimize this concern. An additional study would be required to determine if an increase in runoff volume affects the proportion of dairy CAFOs with the potential to contaminate surface water, and if those CAFOs contribute higher concentrations of contaminants.

Conclusions

The CN grid results indicated that numerous high runoff potential regions exist in Tulare, Kings, and Stanislaus Counties. Out of the 551 dairy CAFOs in the three counties, 193 facilities were in high runoff potential regions and 50 facilities were in low runoff potential regions (Table 2). Identification of runoff from the CAFOs in either high or low runoff potential regions showed that 180 out of 193 (93%) CAFOs in high runoff potential regions had the potential to contaminate surface water, whereas 41 out of 50 (82%) CAFOs in low runoff potential regions had the potential to contaminate surface water (Table 3). Current legislation forbids the EPA from regulating CAFOs solely on the potential to contaminate surface water (Centner and Newton, 2011). Given the current evidence on the harmful health effects of prevalent contaminants in dairy cow excrement, it is crucial to monitor CAFOs and adjacent surface water bodies to ensure the safety of inhabitants living in close proximity to the facilities who rely on those water bodies as drinking water sources or recreational activity sites. This study presented evidence of the potential for dairy CAFO contaminant runoff in California and may serve as a foundation for future studies that would focus on monitoring the dairy CAFOs with the potential to contaminate surface water. Definitive evidence for contamination could facilitate regulatory action from the state government and encourage other states to consider monitoring of CAFOs relative to their potential to contaminate surface water bodies.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

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Effect of first watering month on water requirement of sugarcane using CROPWAT Model in Finchaa Valley, Ethiopia

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This study investigates the optimum water requirements of Sugarcane planted in different months under rainfall and irrigation management, using CROPWAT model at Finchaa Valley in view of the importance of efficient water use as a key to grow crops and satisfy water demand. Analysis of soil physical properties was performed following the standard field and laboratories procedures and methods. The result of investigation indicated that total and monthly crop (irrigation) water requirement of sugarcane varied with the first watering month, ranging from 1554.6 mm (764.5 mm) to 1677.8 mm (1090.9 mm) with the average value of 1614.45 mm (903.8 mm). per growing season The highest and lowest amount of both rainfall and irrigation water demands were obtained for the first watering month (from irrigation or rainfall) of May and August respectively. The finding of the study also implies that, irrespective of the planting and harvesting months' irrigation water provision is not required in June, July and August months for sugarcane cultivated in Finchaa Valley under current climatic condition. Thus, applying fixed depth of irrigation water at a fixed frequency to different soil types throughout the growing season probably lower water use efficiency and reduce crop yield. It is recommended to use CROPWAT model for proper and effective irrigation scheduling for efficient use of available water and improved yields of sugarcane.

Key words*:* Sugarcane, first watering month, water requirement, CROPWAT model.

INTRODUCTION

Water is the primary input for plant growth and food production. There is a competition among water users as many different uses of water resources are interdependent. For instance, agricultural water use can be affected by other uses and it also affects other uses through competition and pollution, respectively (Cap-Net UNDP, 2018). Accurately, estimating the volume of water required at different growth stages for cultivated crops is very essential for efficient use of available finite water resources. Furthermore, the knowledge of water requirement of crops allows to get maximum yields through controlling over or under irrigation problems such as water logging or insufficient water at root zone, salinization of soil and water stress to plant which can reduce yields of crops (Michael, 1999; Savva and Freken, 2002; Katerji and Rana, 2008). Crop water requirements

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(CWR) include the total volume of water used in evapotranspiration. Doorenbos and Pruit (1992) defined crop water requirements as 'the depth of water needed to meet the water loss through evapotranspiration of a crop, being disease-free, growing in large fields under non restricting soil conditions, including soil water and fertility, and achieving full production potential under the given growing environment'. Irrigation Water Requirements (IWR) refer to the water that must be supplied through the irrigation system to ensure that the crop receives its full crop water requirements.

A number of empirical, radiation based, energy budget, water balance, mass transfer and measurement based methods were developed around the world to determine crop water requirement ranging from the simplest and oldest Blaney Criddle method to the most recent and accurate FAO Penman-Montheith method and spatial analyzer GIS based method (Doorenbos and Pruit, 1992; Blaney-Criddle, 1950; Makkink, 1957; Priestly and Taylor, 1972; Allen et al., 1998; Thornthwaite, 1948; Hargreaves and Samani, 1985). Some of the most commonly used methods were Blaney-Criddle model (Burman and Pochop, 1994), Makkink model (Maged, 2017), Priestly-Taylor model (McNaughton and Jarvis, 1983; Cristea et al., 2012; Maged, 2017), Penman-Monteith-FAO-56 model (Abirdew et al., 2018; Shakeel et al., 2017), Thornthwaite model (Ahmadi and Fooladmand, 2008), and Hargreaves-Samani model (Feng et al., 2017).

According to Allen et al. (1998), the FAO Penman-Monteith method is now recommended as the sole standard method for the definition and calculation of the reference crop evapotranspiration. It has been found to be a method with a strong likelihood of correctly predicting ETo in a wide range of locations and climates. The method provides values that are more accurate and consistent with actual crop water use worldwide. In addition, the method has provisions for calculating ETo in cases where some of the climatic data are missing (Allen et al., 1998).

CROPWAT software, developed by FAO, is a computer program, which was based on the sole recommended FAO Penman-Monteith (FAO-PM) model for estimating crop and irrigation water requirement. In Finchaa Valley most of the land was covered by sugarcane plant due to the presence of a sugar factory in the valley. Therefore, the aim of this study is to determine rainfall water and irrigation water requirement of sugarcane planted in different months at Finchaa Valley, Western part of Ethiopia.

MATERIALS AND METHODS

Description of study area

The Finchaa Valley is located in the Horro Guduru Wollega Zone of Oromia administrative regional state, at a distance of 350 km West-North Latitude and 70 km East-North Latitude of the Addis Ababa and Shambu, which is the capital city of Ethiopia and Horro Guduru Wollega zone, respectively. The study area positioned at coordinates of 9°30' to 10°00' North and 37°15' to 37°30' East (Figure 1). It is a sub-basin of Blue Nile (Abbay) basin.

Major part of the land has slopes between 2 and 5%, there is no land with slopes less than 2%. Due to the topographic features of the project area, distribution of rain is very smooth and regular, easy to manage and adjust water distribution to crop requirement during cropping cycle. The average annual rainfall within the valley is about 1300 mm. The rains are more intense during the four rainy months of such that more than 80% of the rain falls during June to September period (Figure 2a).

As illustrated in Figure 2b, mean maximum air temperatures range from 26 to 34°C, the lowest prevailing between July and October. Average minimum air temperatures begin to decline around September and reach their lowest levels in December and January (about 11.5°C). The annual average relative humidity is around 84%. Monthly maximum average humidity varies from June to September (94-96%) to February to March (62-65%). The minimum relative humidity was observed from December to April.

Description of CROPWAT model

CROPWAT is a decision support system developed by the Land and Water Development Division of FAO for planning and management of irrigation. CROPWAT is meant as a practical tool to carry out standard calculations for reference evapotranspiration, crop water requirements and crop irrigation requirements, and more specifically the design and management of irrigation schemes. It allows the development of recommendations for improved irrigation practices, the planning of irrigation schedules under varying water supply conditions, and the assessment of production under rain fed conditions or deficit irrigation (Smith, 1992).

CROPWAT calculates daily reference evapotranspiration (ETo) from weather data according to the equation of FAO-PM (Allen et al., 1998) as presented in Equation 1.

$$ET_O = \frac{0.408\times\Delta(R_n - G) + \gamma\times\frac{900}{T+273}\times u_2\times(e_s - e_a)}{\Delta + \gamma(1+0.34\times u_2)} \quad (1)$$

where ET_O: Reference evapotranspiration [mm day^{-1}], R_n: Net radiation at the crop surface [MJ m^{-2} day^{-1}], G: Soil heat flux density [MJ m^{-2} day^{-1}], T Mean daily air temperature at 2 m height [°C], u_2: Wind speed at 2 m height [m s^{-1}], e_s: Saturation vapor pressure [kPa], e_a: Actual vapor pressure [kPa], e_s - e_a: Saturation vapor pressure deficit [kPa], Δ: Slope vapor pressure curve [kPa °C^{-1}], and γ: Psychometric constant [kPa °C^{-1}].

Again, CROPWAT estimated crop evapotranspiration (ETc) or crop water requirement using crop coefficient according to Equation 2.

$$ET_C = ET_O \times K_C \quad (2)$$

where ETc: Crop water Requirement (mm/day), ET_O: Reference evapotranspiration [mm day^{-1}], and Kc: Crop coefficient.

Further, CROPWAT model calculates irrigation water requirement (IWR) using Equation 3.

$$IWR = ET_C - Pe \quad (3)$$

where IWR: Irrigation water requirement (mm/day), ETc: Crop water Requirement (mm/day), and Pe: Effective Rainfall (mm).

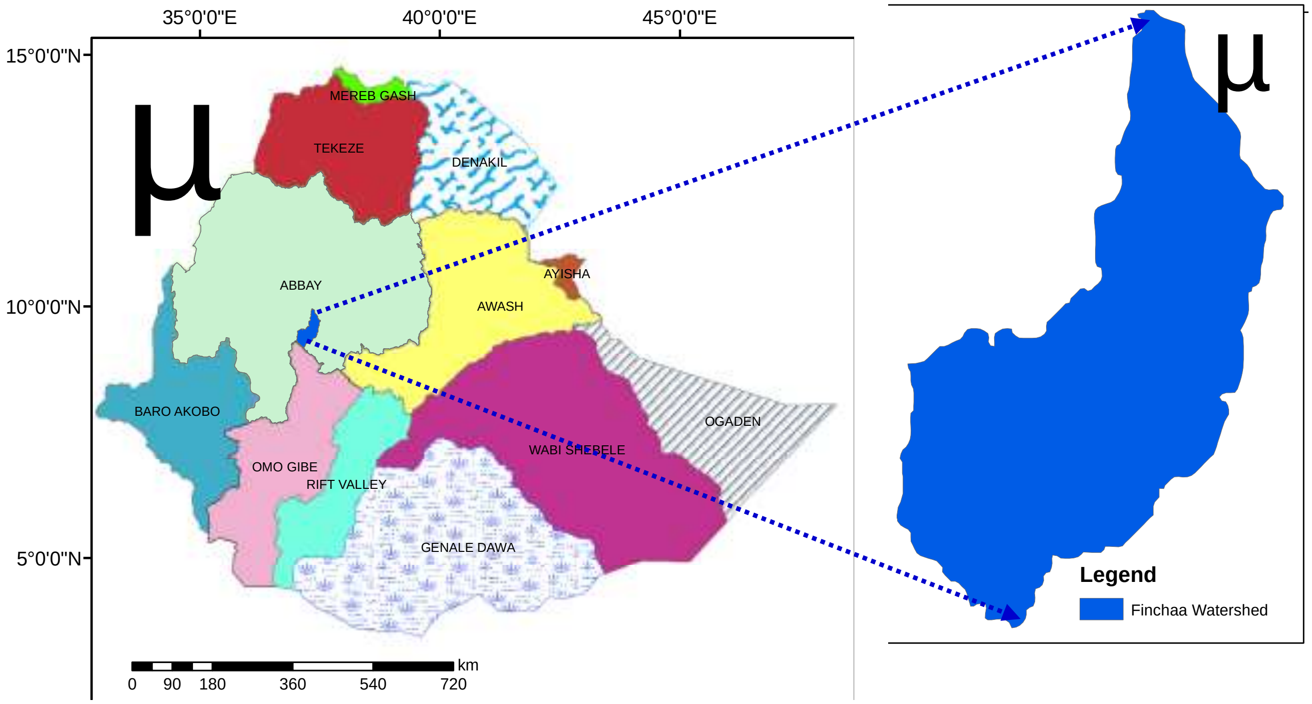

Figure 1. Location of Finchaa Valley Watershed.

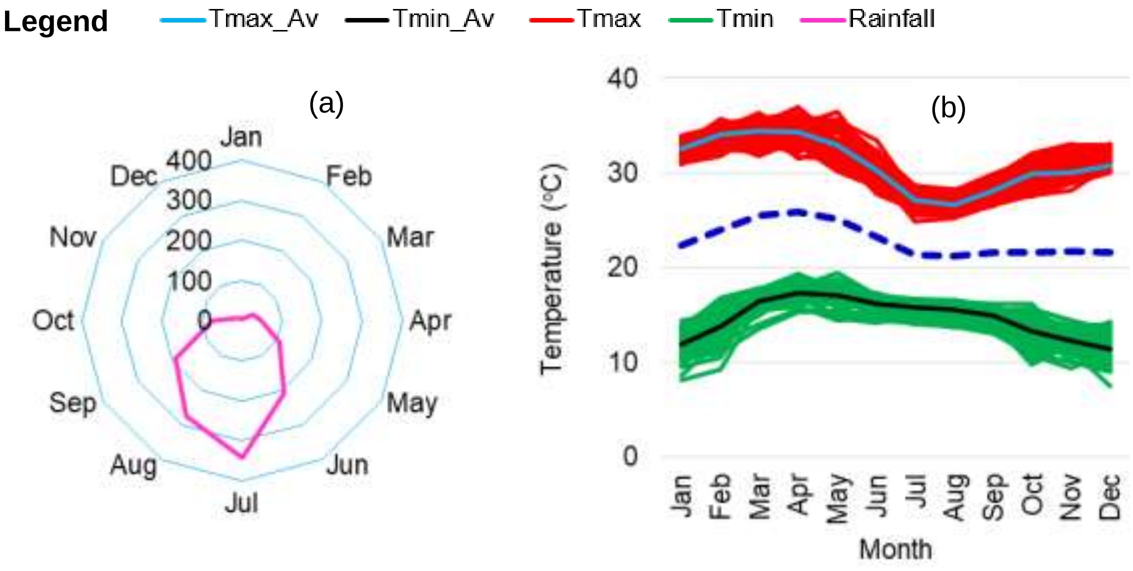

Figure 2. Long term monthly (a) rainfall (in mm) and (b) temperature (in °C) of Finchaa Valley.

Input data and analysis

Basically, CROPWAT model requires four categories of input data. These are Climate data, Rainfall data, Crop data and Soil data. The first two data sets were collected for meteorological station located in the valley from Ethiopian National Meteorological Agency for 25 years. Whereas, the third data set was taken from CROPWAT FAO database. The fourth data set was collected by the researcher and analyzed using the standard procedures.

Climate data set

Climate data set was collected from the meteorological station of

Finchaa Valley. This data set includes maximum and minimum temperature, humidity, wind speed and sunshine hours. These climatic data types are essential because CROPWAT depends on the to calculate Radiation and Reference evapotranspiration (ETo).

Rainfall data and analysis

Rain data were also collected from the meteorological station and analyzed for their quality. Station average and normal ratio methods were used to fill the missing rainfall data based on Richard (1998) criteria. Similarly, double mass curve method was used to check the consistency and homogeneity of rainfall data and for adjustment of the inconsistent rainfall data. Then, it was inserted into CROPWAT software to obtain effective rainfall. Effective rainfall was computed using USDA soil conservation service method (USDA, 1997) and it is described in the Equations 4 and 5.

$$P_e = \frac{(P \times (125 - 0.2 \times 3 \times P))}{125} \qquad \text{for P} \le \frac{250}{3} mm \tag{4}$$

$$P_e = \frac{125}{3} + 0.1 \times P \qquad \text{for P} > \frac{250}{3} mm \tag{5}$$

where P: Total Rainfall (mm) and Pe: Effective Rainfall (mm).

Crop data

The software needs some information about sugarcane crop. This information was obtained from CROPWAT FAO crop database for sugarcane crop, including crop name, planting date, harvesting date, crop coefficient (Kc), rooting depth, length of plant, growth stages, critical depletion and yield response factor.

Soil data and analysis

The software needs some general soil data like total available soil moisture, maximum rain infiltration rate, maximum rooting depth, initial soil moisture depletion and initial available soil moisture. This information was obtained through field and laboratorial procedures and recommendation manuals of Kamara and Haque (1991) and Sahlemedhin and Taye (2000). The analysis procedure detail of each soil physical properties was explained subsequently.

Soil samples were taken to analyze the soil texture, bulk density, field capacity (FC) and wilting point (PWP). The sampling points for the analysis of each parameter were spread over two sections/villages of Finchaa sugar estate farm, namely, village C and village Hora and three fields, P513, EPS-705 and G204. The soil of field number G204 and P513 was classified as Luvisols (L) and that of field number EPS-705 was classified as Vertisols (V) as obtained from soil map of the area (FSF, 2016).

Soil texture

To determine soil texture, six samples of disturbed soil were collected from the selected locations in the field and determined in the laboratory using mechanical analysis and textural triangle.

Bulk density

Bulk density and porosity of the study area was determined using twenty two undisturbed soil samples collected from six pits at different intervals starting from surface to a depth of 150 cm based on sugarcane root abundance with core samplers volume of 100 cm^3 each. The samples were placed in an oven and dried at 105°C for 24 h. After drying, the soil and container were again weighed. The dry weight of the soil was divided by the sample volume to determine the dry bulk density.

Moisture content

Moisture contents at field capacity and wilting point were determined using twenty two disturbed soil samples collected from six sampling points at different intervals. Soil samples were soaked in water for one day and a pressure of 1/3 (for field capacity) and 15 bars (for permanent wilting point) were exerted in the laboratory using pressure plate apparatus until no further change in soil moisture content was observed for the determination of field capacity and permanent wilting point, respectively at the national soil laboratory center.

Water holding capacity

To determine the total available water (TAW, mm) in each soil layer, Equation 6 was used. TAW is the amount of water that a crop can extract from its root zone, and its magnitude depends on the type of soil and the rooting depth (Walker and Skogerboe, 1987; Allen et al., 1998).

$$TAW = 10\sum_{i=1}^{n}((FC - PWP) \times \rho bi \times RZi) \tag{6}$$

where TAW: Total available water (mm), RZi: Depth of soil horizon i (cm), FCi: Gravimetric water content of soil horizon i at field capacity, PWPi: Gravimetric water content of soil horizon i at wilting point, and ρ_bi: Bulk density of soil horizon i (g/cm^3).

Water requirement analysis

The crop water requirements (CWR) and irrigation water requirement (IWR) of the sugarcane planted in different months of the year or for different first watering months practiced at different fields in Finchaa Valley (Finchaa Sugar Estate irrigation system) were estimated by CROPWAT software for Windows Version 8.0.

The outputs were arranged and analyzed in seasonal, growth stage and monthly time scale as per their respective first watering month. The computation was done under two considerations. Firstly, sugarcane is a perennial crop having the growth length of 365 and more days (Ouda et al., 2016; MoANR, 2011). This indicates that fields first irrigated or watered in January will be harvested in December. Secondly, at Finchaa Valley, sugarcane is cultivated for the production of sugar and ethanol from the byproducts. This means, there is harvesting and planting (first watering) activities in all months to provide sugarcane for the factory for continuous sugar production.

Provided that, in each months of every year some portion of cultivated farms will be harvested and then after it can be either newly planted with seed pieces or stalk cuttings or the shoots grow from the buds on the underground part of the stubble left in the field and this crop is termed as ratoon crop. Therefore, the analysis of crop and irrigation water requirements were performed for sugarcane farms covered with ratoon canes in the twelve months of

Table 1. Bulk density and porosity of soil.

Soil type	Depth, cm	Bulk density, g/cm^3	Porosity, %
Luvisols	0-20	1.38	47.93
	20-50	1.417	46.95
	50-95	1.43	53.86
	95-150	1.615	39.07
Vertisols	0-25	1.154	56.46
	25-85	1.47	44.47
	>85	1.52	42.58

Source: Field and Lab analysis.

Table 2. Physical characteristics of the soils.

Soil property		L	V
Mechanical composition	Sand (%)	44.31	28.18
	Silt (%)	17.59	19.46
	Clay (%)	38.10	52.36
FC (%)		22.53	38.68
PWP (%)		14.24	21.22
Bulk density (g/cm^3)		1.46	1.38
TAW (mm/m)		144.14	244.0

Source: Field and Lab analysis.

the year, hereafter called first watering month.

Descriptive statistics such as mean, standard deviation, minimum, maximum and variance were calculated for soil, crop, rainfall and meteorological data with MS-Excel 2016. It was also used to draw different graphs and charts.

RESULTS

Soil properties of the study area

Bulk density and porosity

The bulk densities and porosity of the soils wereanalyzed for two major soil types (Luvisols and Vertisols). Due to the difference in abundance of sugarcane root in soils, analysis wasdone in four layers (0 - 20 cm, 20 - 50 cm, 50 - 95 cm and 90 - 150 cm) and three layers (0 - 25 cm, 25 - 85 cm and >85 cm) for Luvisols and Vertisols soil depth, respectively. The obtained bulk density of the upper layer of Luvisols is higher than the lower layer. This may be due to lower sprinkler operating pressure that causes the sealing of the surface soil because of the larger drop size produced (Table 1).

Water holding capacity

Another soil physical property important for CROPWAT model is the ability of soil to retain water which is so called, water holding capacity. The result of soil sample analysis indicated that the total available water content of the Luvisols and Vertisols was 144.14 and 244 mm per meter of soil depth respectively (Table 2). This shows that Vertisols store more water than Luvisols in Finchaa Valley. Thus, Luvisols has to be irrigated more frequently than Vertisols. Applying equal volume of water at similar rate leads to loss of water or deficiency of water.

Crop water requirement and irrigation water requirement

Seasonal crop water requirement and irrigation water requirement

The obtained result revealed that the average seasonal water requirement of sugarcane planted in any months of the year in Finchaa Valley was 1614.45 mm. The maximum and minimum seasonal crop water requirements was 1677.8 and 1554.6 mm per season for sugarcane first watered in the month of August (harvested in July) and March (harvested in February), respectively (Figure 3).

Further analysis showed that the total seasonal water requirements of ratoon sugarcane plants harvested in the months of November, December, January, February, March and April were less than the average of all first watering months' total water requirements 1614.45

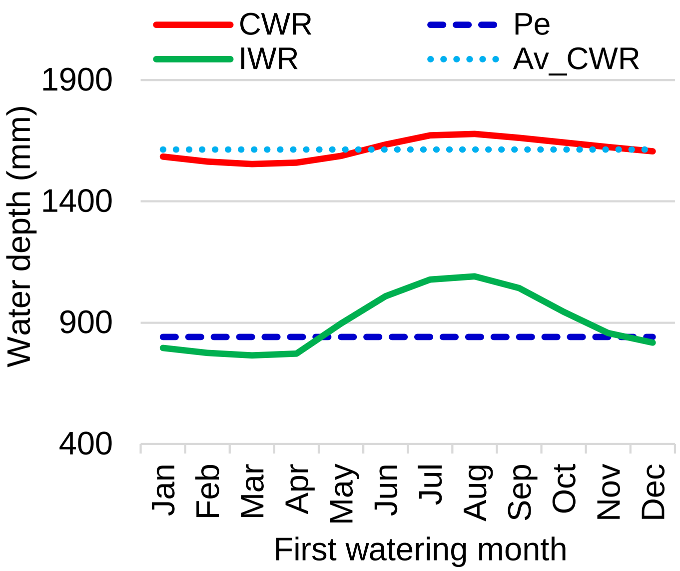

Figure 3. Seasonal (Total) CWR and IWR of sugarcane having different first watering month.

mm/season. Sugarcane harvested in the remaining months requires more water than the average demand in Finchaa Valley.

Interestingly, the result of the study highlighted that, the seasonal irrigation water requirements pattern followed the crop water requirement pattern as indicated in Figure 3. Seasonal total net irrigation water requirement of sugarcane in Finchaa Valley ranges from 764.5 to 1090.9 mm per season with average value of 903.8 mm/season (Table 3).

Growth stage crop water requirement and irrigation water requirement

As can be seen from the Table 4, the crop water requirement (ETc) of sugarcane reached peak value at mid growth stage for all crops harvested in any month. Moreover, crop water requirement during initial and mid-season stage does not show significant change. However, it shows significant increase and decrease over time during crop development stage and late season stage, respectively.

The result of the study further showed that, sugarcane that can be harvested in the months of November, December, January, February and March require less irrigation water than others. The reason is the overlap of peak effective rainfall and peak water demand of the crop. On the other hand, for the remaining months, particularly for the first watering month of August, September and October, due to the mismatch between water demand of sugarcane and availability of rainfall relatively, more irrigation is demanded.

Monthly crop water requirement and irrigation water requirement

The monthly water requirements and irrigation water requirements of sugarcane planted in different months of the year is presented in Figure 4. Figure 4 illustrates that monthly crop water demand and irrigation water requirement is varied with first watering month. The maximum monthly crop water requirement can be obtained in the month of March (197.3 mm/month) for sugarcane that can be harvested in the month of July every year under current climatic conditions of Finchaa Valley.

The result obtained also indicates that for all harvesting months or first watering months' irrigation, water supply is not required in the months of June, July and August. The reason is that in these months' crop, water demand is satisfied from rainfall only. However, the volume of water required for irrigation months is highly variable based on season of the year and water required by sugarcane as per growth stage.

The finding of the current study also shows that, average daily water requirement of sugarcane crop cultivated in Finchaa Valley ranges from 1.35 to 6.42 mm/day. Figure 5 demonstrates the variation daily water requirements of sugarcane crop having a different first watering month or harvesting month. Maximum and minimum average daily water requirement can be reached in April and August months, respectively, both for sugarcane first watered in the month of August.

DISCUSSION

Analysis of the physical properties of soil samples indicated that there are two dominant soil types in Finchaa Valley, namely, Luvisols (Sandy-loam to Sandy-clay loam) and Vertisols (Clay). These soil types differ in their textural class and water holding capacity, which affects the irrigation depth, frequency and rate of water application. It possibly leads to poor irrigation water management. Lack of proper irrigation water management may enhance loss of fertilizers by leaching and parallel salinity and waterlogging of the soil. Pal and Yihenew (2018) concluded that, due to waterlogging of soil, there is a possible risk of considerable yield reduction which may affect the project's economic viability.

The finding of the study shows that the sugarcane crop (ratoon) with 365 days growing period would require an average of 1614.45 mm of water per season. Of this, 44% can be obtained from effective portions of annual rainfall (841.2 mm) in Finchaa Valley. The remaining 56% (903.8 mm) would be supplemented from irrigation water sources. The obtained sugarcane water requirement was in the range of previous study which stated that depending on climate, water requirements (ETc) of

Table 3. Crop Water requirement and Irrigation requirement for sugarcane planted in different months.

First watering month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop water requirement, mm/season	1585.4	1564.9	1554.6	1559.4	1587.1	1635.0	1672.2	1677.8	1662.5	1643.2	1624.9	1606.4
Irrigation requirement, mm/season	795.8	775.7	764.5	773.0	897.1	1009.6	1077.7	1090.9	1042.1	944.3	857.6	817.3

Source: CROPWAT model output.

Table 4. Crop Water Requirement (mm), Effective Rainfall (mm) and Irrigation Water Requirement (mm) of sugarcane per growth stages for different first watering month.

Month	Crop Water Requirement				Effective Rainfall				Irrigation Requirement			
	Init	Dev	Mid	Lat	Init	Dev	Mid	Lat	Init	Dev	Mid	Lat
Jan	30.2	236.8	821.5	369.0	2.1	37.8	679.0	122.2	28.1	198.9	220.6	246.6
Feb	48.2	228.3	782.9	377.0	6.4	75.7	722.3	36.7	41.7	152.5	139.1	340.1
Mar	37.4	200.2	806.0	379.7	18.2	111.5	693.4	18.0	19.2	88.7	190.3	361.6
Apr	57.6	167.9	782.5	416.9	45.5	178.4	575.5	41.7	12.0	2.0	283.7	375.1
May	37.9	162.0	802.7	446.7	54	279.8	424.0	83.3	0.0	0.0	426.3	363.3
Jun	48.6	128.0	848.3	467.0	138.9	262.5	270.9	168.8	0.0	0.0	588.9	298.2
Jul	27.7	149.9	881.7	465.7	105.9	299.7	150.1	285.4	0.0	0.0	731.3	221.9
Aug	25.6	157.8	927.5	423.6	103.5	231.9	99.7	406.0	0.0	24.1	827.5	117.4
Sep	43.1	145.0	960.4	377.6	132.3	75.7	147.7	485.4	0.0	80.2	812.6	35.8
Oct	30.3	156.0	984.3	342.5	50.6	31.6	265.6	493.3	0.0	124.4	718.7	0.0
Nov	43.7	143.1	961.5	348.9	11.1	8.8	417.1	404.1	32.4	134.3	569.0	24.7
Dec	29.0	215.2	874.5	360.2	4.9	11.5	566.1	258.6	24.0	203.8	370.0	120.4

Source: CROPWAT model output.

sugarcane are 1500 to 2500 mm evenly distributed over the growing season (FAO Water, 2018; MoANR, 2011). The findings of the current study, however, differ from those of Win et al. (2014) and Bhingardeve et al. (2017) who stated that, on annual basis the average water requirements of sugarcane as 1369.84 and 1135.5 mm using lysimeter and pan evaporation methods, respectively. This is may be due the difference in methods used and location of the study area.

The result of the analysis shows that, on annual basis, the total water requirements of sugarcane harvested in different months of the same year is not equal. For instance, the difference between seasonal water requirement of sugarcane harvested in July and February months was 123.2 mm. This difference indicates that sugarcane first watered in the month of August and harvested in July can demand 123.2 mm (1232 m^3) of water more than sugarcane first watered in March and harvested in February month per a single hectare of cultivated land. This may allow to bring more areas under irrigation and leads to increased sugarcane yields (MoANR, 2011). Furthermore, the finding of this study shows that, irrigation water requirement of sugarcane also varies from month to month and with growth stages for different first watering months (Win et al., 2014). This may highly affect the irrigation schedule (depth of application, irrigation period and irrigation interval) and efficiency of water use. In other words, applying uniform depth of water

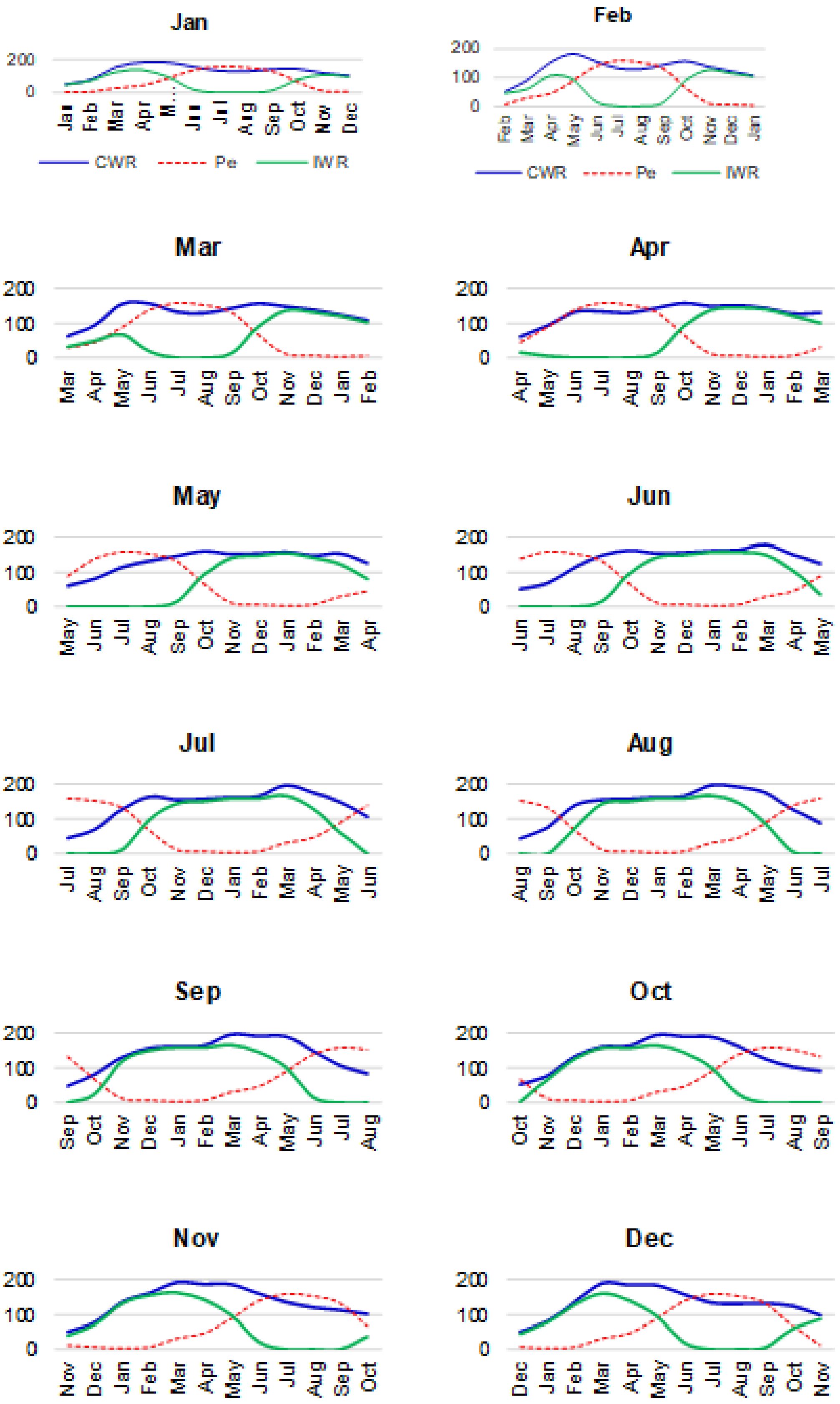

Figure 4. Monthly Crop Water Requirement (mm), Irrigation Water requirement (mm) and Effective Rainfall (mm) for each first water months.

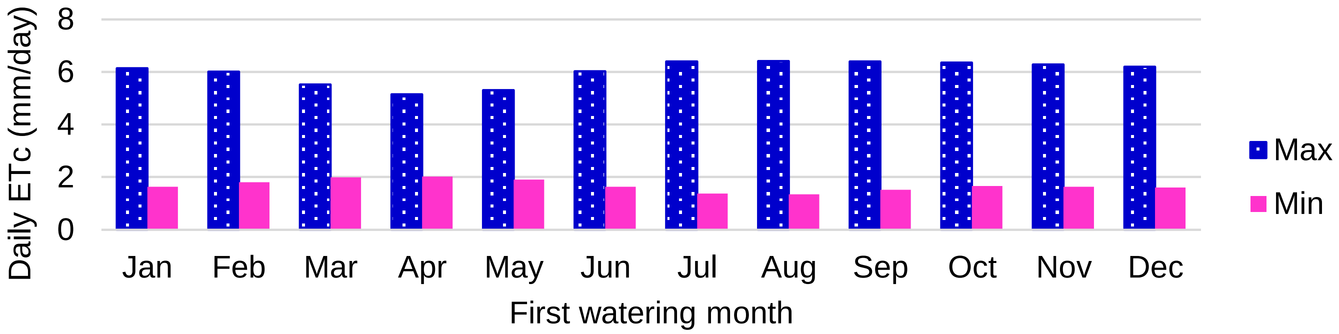

Figure 5. Maximum and minimum daily Crop Water Requirement for each first water months.

with fixed interval at all growth stages of sugarcane crop harvested in different months of the year may lead to a shortage of water and loss or excess application of irrigation water. Particularly, this type of irrigation schedule causes moisture stress to the crop during the early stage and post-harvest, when rapid and light irrigation of soil profile is necessary since the root is shallow, due to larger irrigation interval. Therefore, the quantity of water applied and the interval of irrigation must be adjusted to the actual water requirement of the crop, the water-holding capacity of the soil and rooting depth (MoANR, 2011).

In addition, applying fixed depth of irrigation water at constant frequency to the soils (Luvisols and Vertisols) having quite different textural classes and water retaining and absorbing capacities may result in excess of water application in turn leading to wastage or low efficiency and some side effects like rising of water table level and accumulation of unwanted water on the soil surface which may reduce crop yield and cause outbreak of malaria disease in vicinity area unless adequate drainage system is provided.

In general, the most significant implication of the current study is that proper irrigation scheduling as per soil water holding capacity, crop water demand based on growth stages (especially, during critical stages of water requirement of sugarcane crop, that is, vegetative period of sugarcane is the most critical stage, particularly during period of tillering and stem elongation as it is yield formation stage) for efficient use of available water and improved yield.

Conclusion

This study has shown that seasonal and monthly crop water requirement and irrigation water requirement of sugarcane vary with growth stages, harvesting and first watering month. Applying fixed amount of irrigation water at a fixed frequency throughout the growing season to soils having different water holding capacities possibly lower water use efficiency and decline yield and make irrigation scheduling more complex in terms of practicability and probably incur additional cost. However, it is suggested that to use CROPWAT model for proper and effective scheduling of sugarcane irrigation practices. The current study has only been examined for ratoon (regrow) sugarcane using the present weather data of Finchaa Valley. Therefore, it is further suggested that a future study investigating impacts of climate change on sugarcane water and irrigation requirements would be very interesting.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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Tannery wastewater treatment using two-stage anaerobic sequence batch reactor (ASBR) at mesophilic and thermophilic phase

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Industrialization has resulted in the formation of huge amount of waste products, which are released into the environment in the form of wastewater leading to environmental pollution and deterioration. Tannery effluent is among one of the dangerous pollutants of the industry. Most of the leather industries in Ethiopia discharge their effluent partially or without any treatment to the nearby water bodies. This creates a serious effect on aquatic biota and surrounding environment due to its high organic loading and chromium content. To minimize the effect of tannery wastewater, it should be treated before the effluent is discharged to the environment. Therefore, the main objective of the study was to use a two-stage laboratory scale Anaerobic Sequence Batch Digester (Reactor) in order to investigate the treatment potential of composite tannery wastewater at mesophilic and thermophilic phases. Two-Stage Anaerobic Sequence Batch Digester was used because it has a conducive environment for micro-organisms at a different temperature. Four sets of conditions were investigated; 1) mesophilic to mesophilic; 2) thermophilic to thermophilic; 3) mesophilic to thermophilic; 4) thermophilic to mesophilic, respectively. The Hydraulic Retention Time (HRT) of the hydrolysis/acidification was between 2 and 3 days and greater than 7 days in acetogenesis /methanogenesis. The Organic Loading Rate (OLR) was wide-ranging between 9.58 to 10.28 kg COD/m^3-day throughout the study. The removal efficiency of COD, TN, NO^3-N, S^{-2} and SO$_4$$^{-2}$ of all digesters were in the range of 57-70, 38-51, 44-61, 90-96 and 57-71%, respectively. While the concentration of NH^{4+}-N showed an increment from the influent by 22-31% in all digester. Generally, treatment of composite tannery wastewater by two-stage ASBR shows significant removal of pollutants at thermophilic - thermophilic phase especially S-2.

Key words: Anaerobic sequential batch reactor, composite tannery wastewater, removal efficiency, organic loading rate.

INTRODUCTION

Water is a source of life and regarded as the most essential of natural resources. Furthermore, existing

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freshwater resources are gradually becoming polluted and unavailable due to human or industrial activities. The increasing contamination of water systems with thousands of industrial and chemical compounds has become one of the most important environmental problem (Kumar and, Lee, 2012).

Industrialization is causing more demand than ever for the dwindling supply of water, which makes water crisis on a global scale. Wastewater is generated and dispersed in large amounts such that one out of six people (1.1 billion) has no access to safe drinking water and two out of six people (2.6 billion) lack adequate sanitation (WHO and UNICEF, 2004). This a contributor to a wide range of health problems and disorders in humans.

During the last century, a huge amount of industrial wastewater was discharged into rivers, lakes and coastal areas. With a rapidly expanding human population and a growing trend of industrial development added with limited technological advancement, problems related to the management of industrial waste have become a major problem in Ethiopia (Seyoum et al., 2004). The leather industry sector is one of the fast-growing economic sectors in Ethiopia. Currently there are 19 functioning leather tanneries with 20 new leather industry facilities in the planning stages (Abadi, 2000). According to EPA (2003) in Ethiopia, there are more than 20 tanneries. Accumulation of large volumes of dried-sludge in treatment compound has become common (Seyoum et al., 2004). This has immediate public health implications, which are manifested as frequent outbreak of major epidemic diseases and contributes to climate change as it releases greenhouse gases; methane and carbon dioxide (Dida, 2010).

The industrial strategic development plan of Ethiopia gives great emphasis to improve export-led products to join the international market in large-scale such as leather products. However, in Ethiopia, most of the leather industries discharge their effluent without any treatment to nearby rivers (EPA, 2003; Seyoum et al., 2004). This creates a serious effect on aquatic biota and the surrounding environment. For developing countries such as Ethiopia, the cost is a major issue. One of the many economically, as well as environmentally friendly strategies suggested, is to design a protocol that can treat hazardous tannery wastewater with biological system. The purpose of this study was to investigate the potential of a two-stage laboratory scale Anaerobic Sequence Batch Reactor (ASBR) for the treatment of composite tannery wastewater at a different temperature.

MATERIALS AND METHODS

Description of the study area

Modjo is a town in the central rift valley of Ethiopia, named after Modjo River. It is Located in East Shewa Zone of the Oromia Regional State (Figure 1). It has a latitude and longitude of 8°39′N 39°5′E with an elevation between 1788 and 1825 m above sea level with tropical rainfall climate (Richard, 1968).

In this study, materials such as amber glass bottle, influent feeding tanker, rubber hose, gas kit maker, hose, incubator, furnace, peristaltic pumps, measuring cylinder, analytical balance, air compressor, beaker, 100 ml syringe, scissors, desiccators, iron wire, iron rings and standings, clamps, hot plate, crucibles, plastic bags, stopper, burettes, pipettes, controlling valves and water bath were used. Analytical equipment such as a spectrophotometer, AAS, DO meter, pH meters and thermometer were used. All apparatus was properly washed first with soap solution and then with 1 normal nitric acid, finally washed with distilled water, and allowed to dry on hot air oven.

Different chemicals were used in the study. The chemicals used were polyvinyl alcohol, sulfuric acid, sulfide reagent 1, sulfide reagent 2, potassium hydroxide, sodium hydroxide, nitraver 5 nitrate, hydrochloric acid, nitrogen persulfide, hydrogen peroxide, potassium sulfate, total nitrogen reagent A, B and C, boric acid, Nessler reagent and copper sulfate.

Sample collection and preparation

Tannery wastewater samples were collected from Modjo Tannery, central Ethiopia using different size plastic bags every seven days for three months (12 days). The samples were collected from three different effluent lines which included the sulfur line; chrome line and general wastewater line and a composite sample was prepared by combining the three stream samples proportional to their respective volumes. Every 7-days, 20 L composite sample was collected and transported to the research lab at the Centre for Environmental Sciences, Addis Ababa University and stored at 4^0C in the refrigerator until added to the digester for treatment.

Experimental set up of the two-stage anaerobic sequential batch reactor (ASBR)

Two parallel anaerobic digestions, consisting of four ASBRs in series, were tested. The two reactors in the first system were operated at the same temperature of 35°C (mesophilic), respectively; the two reactors in the second system were at the same temperature of 55°C (thermophilic) respectively, the two reactors in the third system were at two different temperatures of 35 and 55°C (mesophilic to thermophilic), respectively and the two reactors in the fourth system were at two different temperatures at 55 and 35°C (thermophilic to mesophilic), respectively. Each reactor had a total liquid volume of 2.8 L. Totally, eight reactors were prepared to observe the treatment potential of composite tannery wastewater. The objective of the first stage reactor was to have a good solid settlement of composite tannery wastewater, reduce the effect of shock loadings and improve the stability of the two-phase system in an effort to improve the performance of the second stage reactors. The first stage reactor was fed the composite tannery wastewater from Mojo Tanner and the second stage reactor was fed composite tannery wastewater from the first stage reactor.

In the first stage, the first hose was stretched up to the bottom of the solution enabling decanting of all the solution to the second stage while the second hose was placed above the solution. In a similar manner, the second phase reactors had also two hoses at the top. The first hose was immersed to half-height of the reactor and used for filling of the solution from the first stage and decanting the solution while the second hose was above the solution with a plastic bag at the top to collect unwanted gas from the digester and control the temperature (Figure 2). In the experiment, each treatment was run in triplicates. The system was adapted from

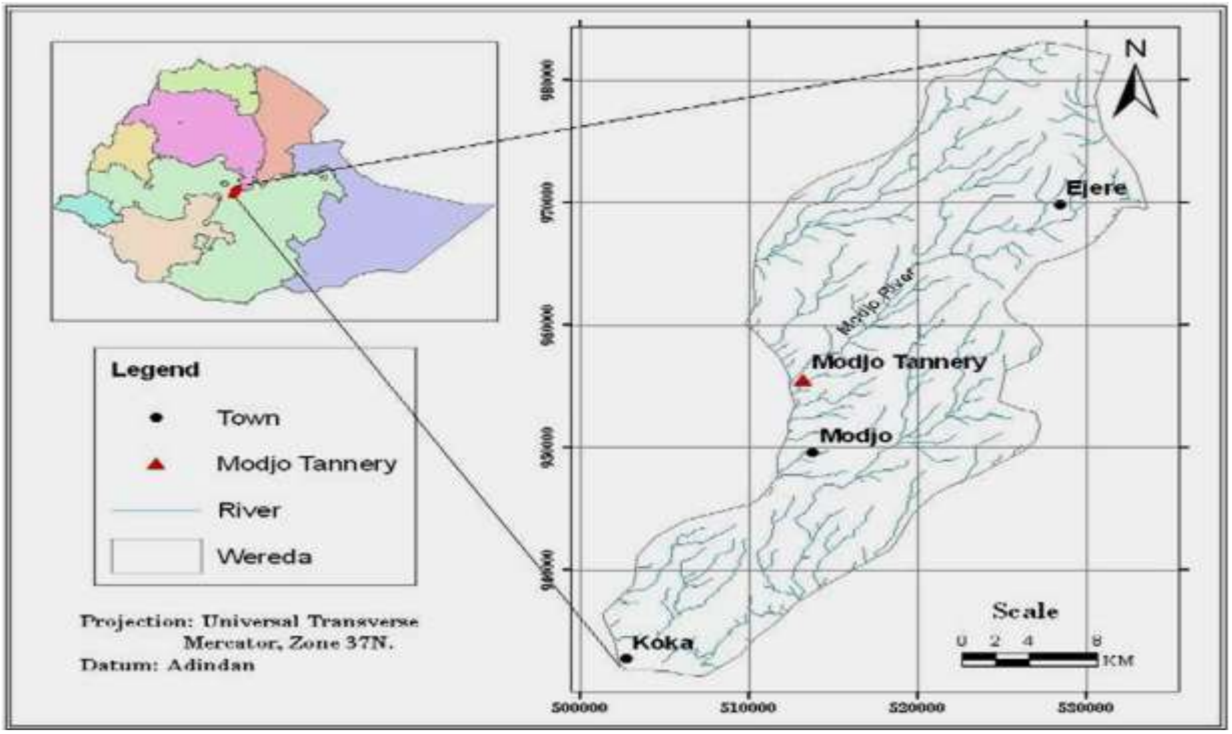

Figure 1. Map of the study area.

Figure 2. The two-stage ASBR set up.

Dugba and Zhang (1999). Table 1

Operation of the ASBR

The study was conducted for 90 days (3 months) in two different operational phases. The first phase at the startup period of the ASBR was operated for 30 days. This time was assigned for the accumulation of biomass. During this period, the digester was operated in 24 h cycle mode, whereas 20 h was given for the reaction phase (T_R) and 3 h given for settling (T_S). To have a good biomass, the supernatant was manually decanted from the uppermost of the reactor for 30 minwith the help of pump drivers (PD 5206) at a speed of 606 rpm. Batch feeding was performed mechanically through the top of the reactor at the beginning of the next cycle for 30 min at the same speed as the substrate was

Table 1. The general description of phase1 operational cycle.

Phase	Cycle period
Fill and mixing	30 min
React	20 h
Settle	3 h
Decant	30 min
Total cycle time	24 h

Table 2. General description of phase 2 operational cycle.

Phase	Cycle period
Fill and mixing	30 Min
React	46 h
Settle	1 h
Decant	30 Min
Total cycle time	48 h

Table 3. Characterization of composite wastewater in terms pollutant levels.

Parameters	Composite tannery wastewater
pH	9.49± 1.15
COD	11,980± 1033.71 mg/l
TN	1150± 131.26 mg/l
NO^{-}_{3}-N	320± 22.13 mg/l
NH4+-N	256 ± 72.13 mg/l
S-2	232± 28.44 mg/l
SO4-2	600± 74.55 mg/l
TN%	1.53

decanted.

During the second phase (Table 2), the ASBR was operated for 60 days (2 months) with a different cycle time from the first phase. The reactors were operated at 48 h cycle mode, where 46 h was given for the reaction period (T_R), 1 h for settling (T_S) and the remaining 1 h was for fill and decants, operated in the same way as in the first phase.

The total cycle time (t_c) is the sum of all the four phases as presented in Equation 1

$$T_C = T_F + T_R + T_S + T_D \qquad (1)$$

Where, T_C = total cycle time; TF = total fill time; T_R = total react time; T_S = total settled time and T_D = total decant time.

Chemical analysis

Chemical Oxygen Demand (COD), total nitrogen (TN) nitrate-nitrogen (NO_3^--N), ammonium-nitrogen (NH_4^+-N), sulphides (S^{-2}), and sulphate (SO_4^{-2}) were determined colorimetrically using spectrophotometer (DR/2010 HACH, Loveland, USA) according to HACH instructions. Percent of removal efficiency (% RE) for each parameter was determined by the following Equation;

$$\% \text{ RE} = \frac{\text{Ci} - \text{Cf}}{\text{Ci}} \text{ X } 100 \qquad (2)$$

Where, Ci = Initial parameter concentration; Cf = Final parameter concentration.

RESULTS AND DISCUSSION

Characterization of Modjo Tannery composite wastewater in terms of pollutant levels

The average value of chemical oxygen demand (COD), total nitrogen (TN), nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4^+-N), sulfide (S^{-2}) and sulphate (SO_4^{-2}) of the feedstock are presented in Table 3. The average COD and NO^-_3-N, content of the composite tannery wastewater was 11,980 and 320 respectively which is similar to those of Seyoum (2004) and Taddese (2010) and the average NH_4^+-N and S^{-2} was 256 and 232 mg/l respectively and similar with those of Hanna (2010) and Andualem (2008). The average value TN% in this study were 1.53.

The temperatures in this study were controlled at mesophilic condition (35 ± 2°C) and at thermophilic condition (55 ± 2°C). The pH of each digester was maintained between 6.02 to 7.66. As described in Table 3, the average pH of composite wastewater was 9.49. In the first week of the startup period, the pH of the substrate in the reactor was between 9.49 to 8.13; in the next weeks the pH decreased. This may be due to the formation of acids by acidogenic bacteria during the incubation period. Generally, the average value of the pH in the first stage reactor in this study was 6.02± 0.51 almost similar to the value 5.7 to 5.8 reported by Kasapgil et al. (1995). Acidity plays a crucial role in the breakdown of organic matter because pH affects the solubility of compounds which indirectly affect the accessibility by bacteria (Vieno et al., 2006). Extremely high or low pH levels are able to kill bacteria; deposition of organic matter occurs due to lack of degradation (Haandel and Lettinga, 1994). The pH of the second stage reactor in this study ranged from 6.30 to 7.66 and with an average pH of 7.26 ± 0.3 over the duration of the study. According to Gerardi (2002), suitable pH range for organic matter degradation is a range of 7 to 8.

Characteristics of the effluent

Evaluating the removal efficiency of pollutants

The performance of the whole system was evaluated to assess the removal efficiency of the characterized pollutant. The analysis test result of two-stage ASBR

Table 4. Removal efficiency of the Two Stage ASBR system.

Parameter	Effluent from D_1	Effluent from D_2	Effluent from D_3	Effluent from D_4	%Removal efficiency of D_1	%Removal efficiency of D_2	%Removal efficiency of D_3	%Removal efficiency of D_4
COD	5100	3550	3850	4650	57.42	70.36	67.86	61.18
TN	710	562	587	621	38.26	51.13	48.95	46
NO^-_3-N	177	124	143	165	44.68	61.25	55.31	48.43
NH_4^+-N	376	332	348	369	-	-	-	-
S_2^-	21	9	16	18	90.94	96.12	93.10	92.24
SO_4^{-2}	254	172	181	203	57.66	71.33	69.83	66.16

Concentration is in mg/L.

system is shown in Table 4.

The result in this study shows the average COD after anaerobic digestion of composite tannery wastewater was 5100, 3550, 3850, and 4650 mg/l, respectively from D_1 to D_4. Considerable removal efficiencies for COD were achieved (57.42, 70.36, 67.86 and 61.18%, respectively recorded from D_1 to D_4).

The main reason for good removal of COD could be related to maintenance of optimum environmental conditions like temperature and pH required for anaerobic acetogenic and methanogenic bacteria. According to Metcalf and Eddy (1991), environmental factors that affect biological organic matter removal are pH and inhibitory substances. pH level less than 6.8 affects biological organic matter removal while pH around neutral makes enables optimum performance to occur. Another factor could be related to the uptake of a substantial amount of organic matter by methanogenic and sulfate reducing bacteria. Moreover, in the mesophilic range, the bacterial activity and growth decrease by one half for each 10°C drop below 35°C (Hulshoff, 1995). Thus, for a given degree of digestion to be attained, the lower the temperature, the longer is the digestion time (Messay.and Mekibib (2017). Bacterial growth is sensitive to temperature because the high temperature can increase the fluidity of the phospholipid bilayer which leads to cell lysis. However, bacteria are known to have higher enzymatic activity at the higher temperature because of increased thermal energy (Meabe et al., 2013). The growth rates of thermophilic methanogens are 2-3 times higher than those of the mesophilic ones (Van Lier et al., 1993; Mladenovska and Ahring, 2000).

The TN before AD was 1150 mg/l and 710, 562, 587 and 621 mg/l after anaerobic digestion of composite tannery wastewater from D_1 to D_4. The removal efficiency of the digesters from D_1 to D_4 was 38.26, 51.13, 48.95 and 46%, correspondingly. The reduction of nitrogen in the effluent might have occurred due to the assimilation (followed by cell wastage) or the oxidation of ammonium into nitrite and nitrate by nitrifying bacteria (Metcalf and Eddy, 2003). The other factors might be associated with inhibition of nitrification by excessive COD loading. This can be attributed to the depletion of dissolved oxygen caused by heterotrophic organisms which utilized the organic matter present in the wastewater. Although COD levels up to 60-80 mg/L can be tolerated by nitrifying bacteria, it has been shown that COD levels above 60 mg/L can lead to as little as 50% nitrification (Wild et al., 1971). The optimum pH and temperature condition for the nitrification process were in the range of 6.5 to 8.6 and 20-30°C respectively (Grunditz and Dalhammar, 2001). The pH and the temperature of the reactor were 8.17 ± 0.18 pH units and 23°C, respectively. These were in the normal range of nitrification processes.

The average NO_3^--N after anaerobic digestion of composite tannery wastewater was 177,124,143 and 165 $mg.L^{-1}$ and the removal efficiency was 44.68, 61.25, 55.31 and 48.43%, respectively from D_1 to D_4. Nitrate was converted to gaseous nitrogen by denitrifying bacteria with optimum temperature and other driven parameters. The abundance of highly efficient denitrifying bacteria in system could be directly related to the removal efficiency of the system. In wastewater, denitrification is most effective at pH values between 7.0 and 8.5 and the optimum is around 7.0 (Metcalf and Eddy, 1991). Denitrification favors a temperature range of 35 –50°C. It also occurs with the temperature range of 5–100°C) at a slower rate. The biological activity will decrease by a factor of about 3 with an associated temperature drop of 15ºC (Levenspiel, 1972). Therefore, the environmental condition at thermophilic phase favors the removal of NO_3^--N. D_2 (thermophilic-thermophilic) removes high amount of NO_3^--N and D_1 (mesophilic – mesophilic) removes the lowest amount of NO_3^--N.

The removal efficiency of S_2^- was 90.94, 96.12, 93.10, and 92.24% recorded from D_1 to D_4. Further in this study, the removal efficiency for SO_4^{-2} was 57.66, 71.33, 69.83 and 66.16%, respectively from D_1 to D_4. Sulfate reduction in anaerobic system could be related to the use of acetate and hydrogen by sulfate reducers which reduces sulfate to hydrogen sulfide. Like methanogens, some sulfate reducers can oxidize H_2 and acetate and thus may compete with methanogens for these substrates (Rinzema and Lettinga, 1988). Thermodynamic and

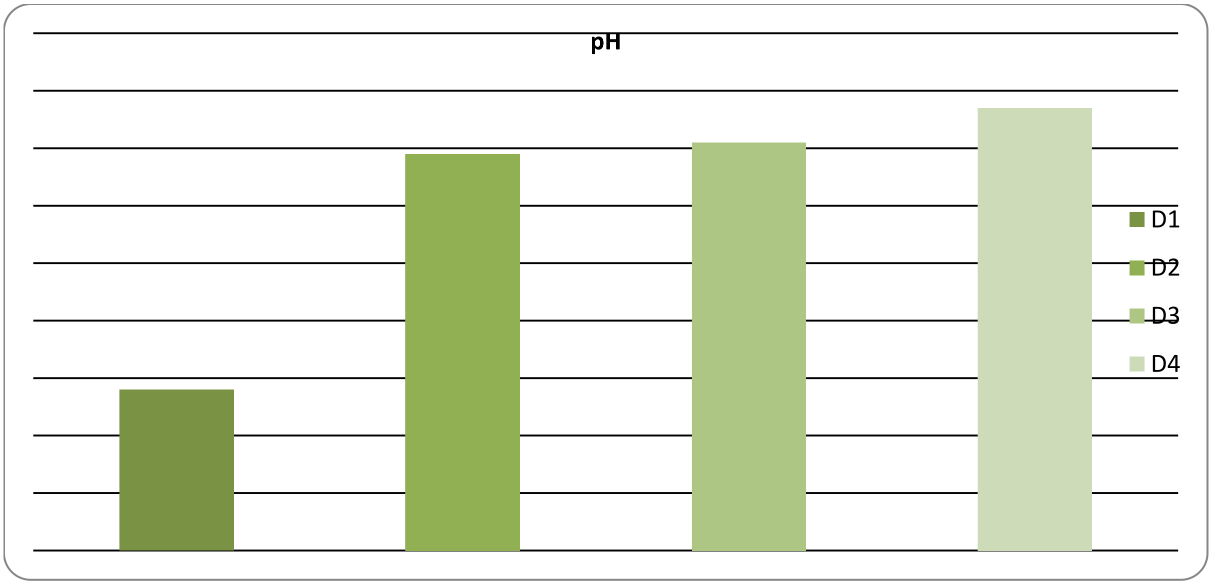

Figure 3. Average ph of the effluent.

Monod-kinetic data shown that sulfate reducer generally have higher growth rates and higher affinity for substrates than acetogenic and methanogenic bacteria. Therefore, sulfate reducing bacteria out-competes acetogenic and methanogenic bacteria (Oude Elferink et al., 1994).

Another reason for sulfide removal in anaerobic reactor could be its use as sulfur source by anaerobic bacteria. Methanogenic bacteria use ammonia and sulfide as nitrogen and sulfur sources respectively. Although un-ionized sulfide is toxic to methanogens at level exceeding 150–200 mg/L (Rinzema and Lettinga, 1988; Speece, 1983), the concentration of sulfide in anaerobic SBR effluent was 232 mg/L which was far lower than the limit. Therefore, it favored methanogens to use sulfide as sulfur source to synthesis of new biomass.

The concentration of NH_4^+-N increased in all digesters; it was observed that the feed NH_4^+-N was slightly lower than the effluent NH_4^+-N which indicates that there is no reduction of NH_4^+-N during AD. Kheradmand et al. (2010) found the similar observation of increase of NH_4^+-N concentration in effluent than feed by 8.7 to 31.6%. In addition, Bohdziewicz et al. (2008) observed increase in NH_4^+-N concentration treating leachate. Similarly, this experiment calculates the increase of concentration by 23%. The increase of NH_4^+-N concentrate ion is mainly due to ammonia production by degradation of protein and amino acid of leachate.

pH of the effluent

The average pH value of the effluent for each digester in this study is summarized in Figure 3.

Determination of pH plays an important role in the wastewater treatment process. The average pH value of the effluent varied from 7.18 to 7.67. The minimum and maximum pH accepted values for slurry was 6.0 and 8.5, respectively (Fokhrul, 2009). In addition, William (1998) reported that the values lie in the range of the pH of the compost 6 to 7.

Conclusions

The current study demonstrated that two stage anaerobic sequential batch reactor has a great potential for treating composite tannery wastewater under thermophilic-thermophilic condition and used as wastewater management option. Moreover, this system of managing wastewater significantly contributes towards resource-recovery and pollution management around tannery industry.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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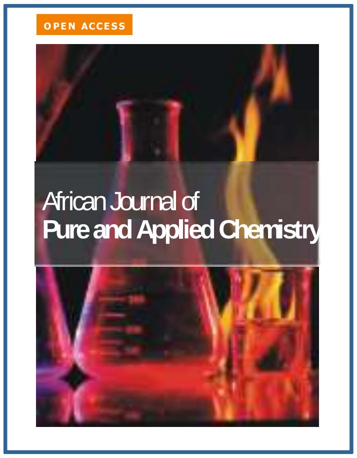

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