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Effect of land use/cover change on the regimes of surface runoff for Lake Basaka catchment

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Lake Basaka is expanding at a very fast rate. An appropriate method of estimating the surface runoff from such dynamic catchment is extremely important to delineate sensitive areas to be protected and to develop suitable management measures. In this study, the surface (direct) runoff was estimated using SCS-CN model, assisted by remote sensing and GIS. The result indicated that Lake Basaka catchment showed significant variability (temporal and spatial) in runoff responses depending on the rainfall amount and distribution pattern and land use/cover change. The significant increase of surface runoff (runoff coefficient) was observed to occur after 1973, which is in line with the significant increment of lake level after that period. The reduction in vegetation cover also resulted in increase of runoff coefficient of the Lake catchment from 0.07 in 1960s to about 0.23 in 2000s.

Introduction

Lake Basaka, unlike most of the other closed basin type Main Ethiopian Rift (MER) valley Lakes, is expanding at a very fast rate (Tessema, 1998; Abebe, 2000; Alemayehu et al., 2006; Ayenew, 2007; Belay, 2009; Goerner et al., 2009; Dinka et al., 2009; Dinka, 2010, 2012). The total surface area of the lake was about 3 km^2 in 1957 and is estimated to be 45 km^2 in the year 2010 (Dinka, 2012).

Runoff, as one of the most important hydrologic variables, has many applications: planning, designing, operation and environmental impact analysis of water resources project (Noyak & Jaiswal, 2003; Dutta et al., 2006). It may be caused by the cumulative effects of different factors such as change in LUC, high intensity rainstorms during the main rainy season, topography and pedogenic characteristics. Estimation of surface runoff is essential for (Shi et al., 2009): (1) the assessment of water yield potential; (2) planning of soil and water conservation measures and; (3) reducing the sedimentation and flooding hazard at downstream. Hence, an accurate prediction or measurement of runoff (quantity and rate) is required. Reliable prediction of runoff is, however, very difficult and time consuming for ungauged catchments (Noyak & Jaiswal, 2003) like that of Lake Basaka.

A significant amount of water and sediment are flowing annually into Lake Basaka due to erosion (Dinka et al., 2014), thereby increasing the capacity of the Lake at a rapid rate. An appropriate method of estimating the surface runoff from the catchment is, therefore, extremely important to delineate sensitive areas (based on their runoff responses) to be protected and to develop suitable measures that will reduce runoff and the associated soil loss. The current study, therefore, was initiated with the main objective to estimate the runoff regime (spatial and temporal) of Basaka Lake catchment using the Soil Conservation Service-Curve Number (SCS-CN) model, assisted by Remote Sensing in GIS (grid-based) environment.

Methodology

Study area: overview

Lake Basaka is located in the Middle Awash Basin, Fantalle Woreda of Oromiya Region at about 200 km southeast of the capital city, Addis Ababa (Fig. 1). Matahara Sugar Estate (MSE) is bounding the Lake in the southeast side. The lake catchment has variable altitude ranging from 950 m at Basaka Lake to over

1700 m at Fentalle Crater (Volcanic Mountain). Lake Basaka is situated in the upper Main Ethiopian Rift (MER), central rift valley region. Therefore, it is vulnerable to the occurrences of different tectonic and volcanic activities (Dinka, 2010, 2012). The formation of common rock types in the area is the products of the recent volcano complexes, along with fissural basalt, rhyolite and alluvial and lacustrine sediments (Mohr, 1971; Dinka, 2012).

The area is characterized by bimodal and erratic rainfall distribution pattern with the major rainy season occurring from July to September. Minor, occasional rains are also occurring between March and May. Analysis of the long year's average (LYA) weather data (1966-2009) of the area indicates that mean annual rainfall and temperature are about 543.7mm and 26.5 °C, respectively. The LYA pan evaporation of the area is 6.92 mm/day and the reference ET is about 4.65 mm/day. The climate of the area, in general, is classified to be semi-arid (Dinka, 2010).

SCS input data bases

In the current study, the surface runoff was estimated using SCS-CN model in GIS (grid-based) environment, assisted by RS. CN-index represents the runoff potential of the land cover-soil complex. It is the function of soil type, soil development, LUC and soil moisture condition of the watershed (Sharma & Singh, 1992). It was estimated based on the Hydrologic Soil Group (HSG) and LUC condition of the study area. The LUC classes were obtained from the works of Dinka (2010, 2012a). The image acquisition and image processing procedures adopted were described in detail in the works of Dinka (2010, 2012).

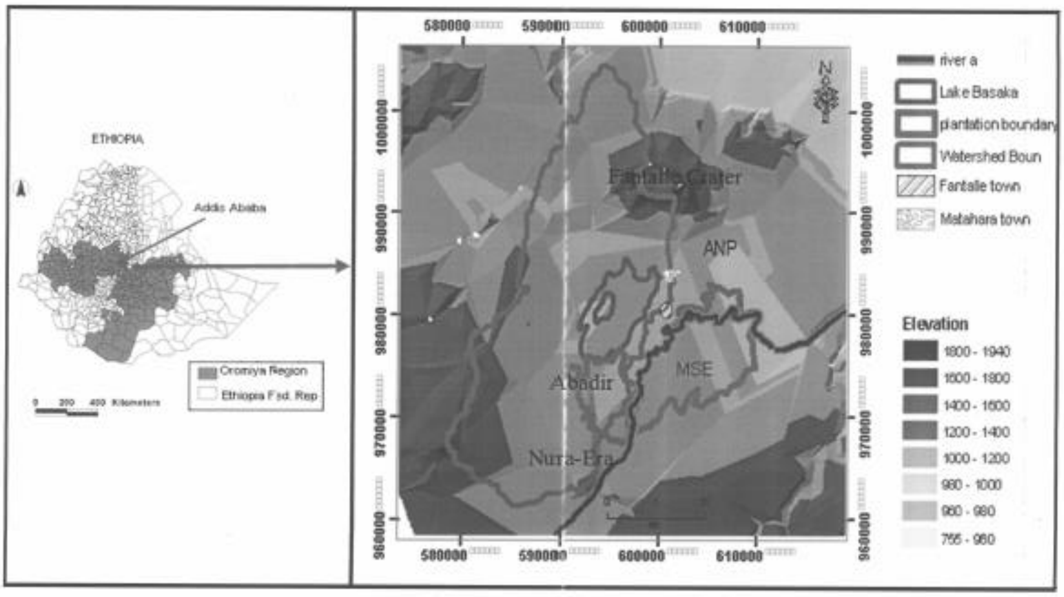

Figure 1. The study area: location (left) and topographic view (TIN) extracted from DEM (right). MSE- Matahara Sugar Estate, ANP- Awash National Park

The soil map of the watershed was modified from the works of WWDCE (1999) in conjunction with FAO/UNESCO (1974) Digital Soil Map (http://www.isric.org). These soils were texturally characterized from field measurement data to produce the final soil map based on HSG. The establishment of the HSG was based on the analysis of some parameters: texture, infiltration and retention capacity of each pedological entity. The AMC condition was established for each month (with expected runoff) of the periods considered. The theoretical CN values for AMC-II condition was obtained from SCS handbook table (USDA-SCS, 1972). In order to account the effect of soil moisture conditions on runoff, the CN (AMC-II) was adjusted to the other AMC (I & III) levels based on the total 5-day antecedent rainfall preceding each rainfall value in the area (Gupta & Panigray, 2008). This is due to the fact that soil moisture is the most important factor defining the initial abstraction (I_a) (Huang et al., 2007). Refer Gupta & Panigray (2008) for the 5-day antecedent rainfall values for the three AMC conditions. The LUC and HSG maps were combined in the

GIS environment by overlay operations (spatial join) in order to obtain the combined map of LUC type and HSG.

The following conversion formulas were used to convert the CN from AMC-II (average) to the AMC-I (dry) and AMC-III (wet) conditions.The curve number is adjusted for the AMC–I and -III conditions using eq. 1, which can also be taken from USDA (1972) table. Then the weighted CN for the entire lake catchments was computed as:

$$CN\left(AMC-I\right) = \frac{4.2CN_{II}}{10-0.058CN_{II}} \quad for\ AMC-I\ (dry\ condition)$$
$$CN\left(AMC-III\right) = \frac{23CN_{II}}{10+0.13CN_{II}} \quad for\ AMC-III\ (wet\ condition) \qquad (1)$$

$$Weighted\ CN = \frac{\sum A_i * CN_i}{\sum A_i} \qquad (2)$$

S is shape (retention) parameter, which is the function of soil, vegetation, land use and soil moisture prior to a rainfall event (Huang et al., 2006) and is expressed in terms of a dimensionless CN:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad (3)$$

where, CN is an integer value varying between 0-100 (Dutta et al., 2006). It is determined from information on HSG and LUC condition. P, S and Q are in mm. Then, the surface runoff depth was calculated using:

$$Q = \frac{\left(P - I_a\right)^2}{\left(P - I_a + S\right)} = \frac{\left(P - \lambda S\right)^2}{P + (1-\lambda)S} \qquad (4)$$

The I_a includes the interception, surface depression storage, and infiltration into the soil. λ is initial abstraction coefficient, which is variable (0.1–0.3 S) depending upon the value of AMC conditions (λ=0.3 for AMC-I; λ=0.2 for AMC-II and λ=0.1 for AMC-III) (Gupta & Panigrhy, 2008). All the parameters, except λ, are with dimensional (L). Equation 4 has a physical restriction that $P>\lambda S$. Those months with $P \leq 0.1S$, $P \leq 0.2S$ and $P \leq 0.3S$ respectively for AMC-I, AMC-II and AMC-III are ignored from the runoff computation since they are not effective.

Results and discussion

Temporal dynamics of surface runoff

The depths of runoff computed using the SCS-CN model in ArcInfo GIS (grid based) for the different years considered are presented in Table 1. Table 1 also displays the runoff responses of the different LUC units during the periods of interest. The result reveals that runoff shows great temporal variability depending on the patterns of rainfall in all the periods considered. Deforestation in favour of bushy woodlands (open) impacted the time series of runoff.

Table 1. Average surface runoff depth (mm) for the different LUC units

Land use/cover	1973	1986	2000	2007	2008	Av. Runoff Potential	Response Class/Rank
Bushy woodland (open)	64.5	60.4	88.5	98.6	511.0	78	5
Shrubland	78.1	179.7	222.9	224.6	821.0	176	3
Forestland	22.1	19.6	53.5	45.3	330.2	37	7
Swamp/ lava	219.7	301.2	324.8	310.3	830.1	289	2
Farmland	88.4	86.6	103.0	123.8	586.3	100	4

Grassland	41.5	39.3	76.1	64.0	531.1	55	6
Water (Lake)	315.6	439.2	448.2	550.3	950.0	438	1
Weighted Mean Q	37.2	79.3	108.3	119.80	329.2		
Weighted Mean CN	61.2	68.2	73.7	74.2	74.4		
Weighted Mean r_c	0.11	0.17	0.22	0.19	0.33		

* CN- Curve number; Q-runoff depth; r_c- runoff coefficient

Effect of land cover changes on surface runoff

The mean average runoff coefficient (r_c) of the watershed calculated from the simulated runoff is in the range of 0.07 to 0.22 (1960-2007) (Table 1). However, r_c value as high as 0.33 is obtained during the extreme wet year (2008), indicating the effect of extreme climatic condition on the amount of runoff generated. The obtained result ($r_c = 0.19$) for the recent time (2007) is almost comparable with the r_c value ($r_c = 0.18$) obtained by Dilnesaw (2006) for the Upper Awash Valley. Average r_c value of 0.14 was also obtained for Lake Ziway catchment (Ayenew et al., 2007).

The analysis of mean runoff depth predicted by the SCS-CN model (Table 1) reveals that vegetation cover and runoff have an inverse relationship: decreasing vegetation cover resulted in increased surface runoff from 37.2 mm in 1973 to about 120 mm in 2007. This is actually expected since a good vegetation cover (like forest) reduces the CN and eventually the runoff response (Gupta & Panigrahy, 2008). Canopy cover is responsible for the inverse relationship between vegetation cover and runoff as it affects interception depth, permeability and surface roughness, which inhibits overland flow and increases infiltration and storage (Hernandez et al., 2000). Hence, the decrement of vegetation cover in the area facilitates overland flow by hindering infiltration and storage.

The spatial maps of annual rainfall and runoff for the year 2000 are shown in Fig. 2. The effect of vegetation cover condition on the runoff processes in the lake catchment is clearly observed from the figures. Forestland, for example, having highest rainfall (566.2 mm) due to its topographic favour generated the lowest runoff (53.5 mm) owing to its lowest CN index (Table 1). Conversely, Abadir farm receives relatively almost the lowest rainfall (434.2 mm), but generates higher annual runoff (108 mm) compared to forestlands. Furthermore, wetland//lava flow receive almost the lowest rainfall amount (453.9 mm), but are characterized by relatively high runoff potential (328 mm). These conditions imply the significant impact of pedogeographic characteristics and vegetation cover on the runoff response of the Lake catchment.

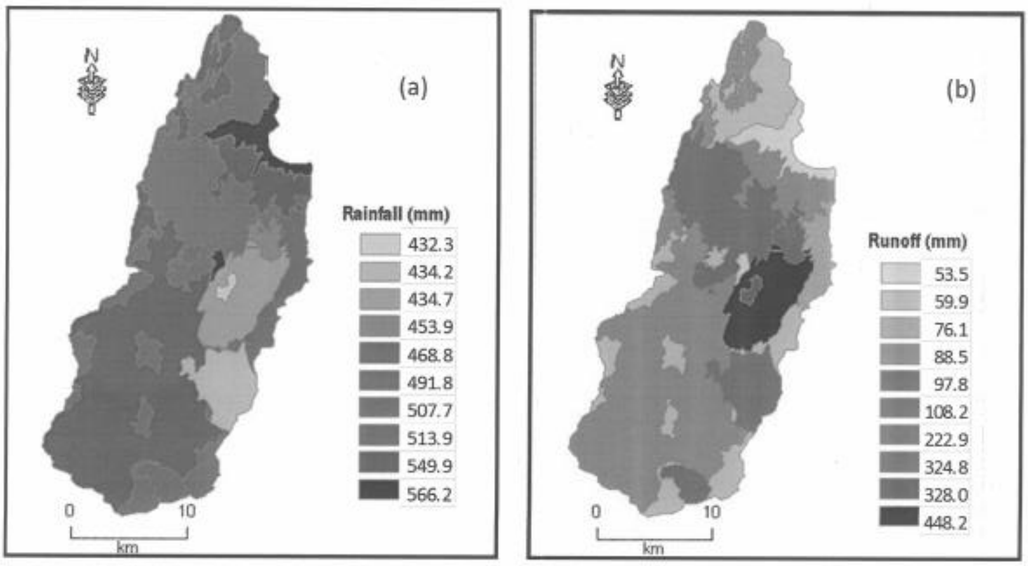

Figure 2. Spatial variability of annual rainfall (a) and surface runoff (b) (year 2000)

Implications of increased runoff to the region

The lake catchment has undergone significant LUC change (from 42.2% to 6% in 2008) (Dinka, 2012a). Deforested lands are exposed to the impacts of raindrops, which might accelerate the detachment, removal and transport of soil particles and the associated consequences (Dinka, 2012a). Conversion of native tropical forests to other land cover types might produce permanent changes in the annual stream flows. The significant LUC changes in the region could lead to different environmental consequences such as land degradation and flooding. The significant changes in the LUC are expected to result in increased surface run-off, evapotranspiration, erosion rate and sediment yields. The change in the regimes of surface run-off is contributing to the expansion of the lake (Dinka et al., 2014).

The lake expansion is affecting the ecosystem, irrigation development, railway and highway structures, pastoralism, etc (Dinka, 2012b). Dinka (2012a) report indicated that about 18 924 ha of forest and 4730 ha of grazing lands were lost in the period between 1973 and 2008. The majority of loss grassland areas were inundated by the lake water. The lake expansion analysis made by Dinka (2012b) indicated that the lake inundated about 45.8 km^2 in the past about a century (1960-2010), resulted in volume increment of about 280 million m^3. Groundwater inundations also are most likely to occur in the region due to the fact that the lake water has interaction with the groundwater system of the area. If the past expansion trend of the lake continues in the future, it can be expected that the lake would inundate parts of Matahara town, Fantalle Village, and Matahara Sugarcane Plantation. Under extreme circumstances, the lake has the potential to join Awash River in the near future, thereby challenging irrigation development within Awash river basin and the socio-economics of the region. This characteristics of the lake is attracting the attention of researchers, policy makers and decision makers. In cognizant to the possible threat of the lake expansion to the environment and socio-economics of the region, the government is making the necessary efforts to limit the expansion of the lake. Since the surface runoff is one of the contributing factors for the lake expansion, any measures (especially vegetation and mechanical) to reduce surface runoff and increase infiltration are highly recommended. Sustainable lake water management measures are crucial and highly recommended by the author.

Conclusion

The study result indicates that Basaka Lake catchment have been experiencing significant LUC change since 1960s, which in turn resulted in change of regimes of surface runoff regimes of the region. Since surface runoff and soil loss are interrelated, significant amount of soil loss from the catchment and deposition of sediments in the lake is expected. The reduction in vegetation cover also resulted in decrement of canopy and interception losses, soil fertility and hence, increase of runoff coefficient of the lake catchment from 0.07 in 1960s to about 0.23 in 2000s. Moreover, debris, top soil and various forms of contaminants are most likely flowing into Lake Basaka through the process of runoff, thereby changing the regimes of lakes water balance. Therefore, it is of major importance to take into account possible future LUC evolution when forecasting the hydrologic behaviors of the lake catchment.

Note

The study has revealed the potential risky areas for surface runoff, which is extremely important for the water balance computation and appropriate lake water management. The identified potential highly contributing areas (CAs) for these hydrologic processes give clue where LUC practice has to be done to limit, if not avoided, their impacts on the Lake water balance and its catchment. Areas producing more runoff need special priority for the implementation of soil erosion control measures. This study provides an insight to the dynamics in hydrologic processes of the watershed since the inception of the Lake expansion and hence, can be related to the expansion as a cause-effect relationship. Finally, the author would like to suggest more attention to be given to the sustainable management of the lake water and its catchment mainly because of its increasing environmental and socioeconomic problems.

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