Journal of Environmental Management 219 (2018) 103–114

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Effects of agricultural land use on sediment and nutrient retention in valley-bottom wetlands of Migina catchment, southern Rwanda

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A R T I C L E I N F O

Article history:
Received 19 January 2018
Received in revised form
17 April 2018
Accepted 22 April 2018

Keywords:
Water quality
Catchment management
Agriculture
Land use
Sediment retention
Nutrient retention
Wetlands

A B S T R A C T

Factors affecting the retention and export of water, sediments (TSS), nitrogen (TN) and phosphorus (TP) were examined in the Migina river catchment, southern Rwanda from May 2012 to May 2013. Landscape characteristics and seasonal changes in land use and land cover (LULC), rainfall, discharge, and area-specific net stream yields of TSS, TP and TN were measured monthly in 16 reaches of the Munyazi sub-catchment with five valley bottom LULC categories (grass/forest, ponds/reservoirs, ploughed, rice, and vegetables). Valley bottoms dominated by grass/forest and ponds/reservoir types were generally associated with positive net yields of nutrients and sediments, while those with agricultural land covers had a net negative yields, resulting in net export. Water was retained only in reaches with ponds/reservoirs. Seasonally, there was a strong relationship between net yield and discharge, with 93%, 60% and 67% of the annual TSS, TP and TN yields, respectively, transported during 115 days with rain. During low flow periods, all LULC types had positive net yields of TSS, TP and TN (suggesting retention), but during high flow periods had negative net yields (suggesting export). Significant effects of hillside land use on sediment and nutrient yields were also found. Stream and river water quality in Rwandan valley bottoms are at risk of further deterioration due to declining natural ecosystems (grassland and forest) and increasing agricultural and urban development. It is important to adopt appropriate land management practices (minimal tillage, optimization of water use, strategic implementation of retention ponds and vegetation buffer zones) to intercept TSS, TP and TN in runoff from storm water and agricultural areas. Special attention is needed for critical periods of the year when farming activities (e.g. land preparation, fertilizer application) coincide with high flow events.

1. Introduction

In Sub-Sahara Africa, land degradation threatens many livelihoods, and is estimated to cost 3% of Africa's annual agricultural gross domestic product (Jansky and Chandran, 2004). In Rwanda, land degradation and associated soil and nutrient losses reduce the capacity to feed the nation by 40,000 Rwandans each year (NISR, 2008). Soil loss was estimated at 10 t ha^{-1} y^{-1} or 120–136 kg of nitrogen, phosphorus and potassium (NPK) ha^{-1} y^{-1} (Henao and Baanante, 1999; World Bank, 2005). Erosion and nutrient loss also leads to water quality problems, and is the main source of nutrient and sediment pollution in surface water, groundwater and wetlands (WWAP, 2009).

In East Africa, erosion and nutrients from fertilized farms and urban areas are the major causes of eutrophication and ecosystem degradation of Lake Victoria. The Migina river in the uppermost catchment of the Nile River is a tributary of the Akagera River, the main surface inflow to Lake Victoria. The typical catchment landscape consists of a series of rugged medium-high to high steep mountains, draining into narrow valley bottom wetlands. With an average population density about 450 persons km^{-2}, pressure on land in the Migina catchment is high, and soil degradation widespread. Conversion of valley-bottom wetlands for agricultural production, that has being ongoing for a number of years, is set to increase further as a consequence of the Rwandan government's food security policies (MINAGRI, 2009, 2010). While effects of soil loss and nutrient exports on the eutrophication and sedimentation of rivers and lakes like Akagera River, Lake Cyohoha, as well as Lake

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https://doi.org/10.1016/j.jenvman.2018.04.094
0301-4797/

Victoria are already apparent, there is a need for more detailed knowledge on how current land use practices affect water quality, and how valley-bottom wetlands can mitigate that.

The contribution of valley-bottom wetlands to water quality regulation depends on the complex interactions between hydrological flowpaths from the hillsides to the streams (surface runoff and groundwater flows) and biogeochemical processes (Burt and Pinay, 2005; Lohse et al., 2009). Nutrient retention by floodplain wetlands through ecological and biogeochemical processes has been demonstrated in European and American wetlands (e.g. Johnson et al., 1997; Verhoeven et al., 2006). Little is known about the role of wetlands in African catchments (Dunne, 1979; Hecky et al., 2003; de Villiers and Thiart, 2007), where wet and dry seasons are more pronounced and where land-use conversion sometimes follows seasonal patterns which makes the generalized land use classifications that are commonly used less appropriate. A water quality study in Migina catchment showed that the relationship between water quality and discharge is influenced by the land use in the valley bottom, with reaches dominated by rice and vegetable land covers more prone to sediment and nutrient loss than those with intact wetland vegetation or water bodies like ponds or reservoirs (Uwimana et al., 2017). However, that study only looked at water quality differences and did not consider the size and characteristics of reaches on sediment and nutrient retention.

The strong seasonal and spatial variation in the Migina valley-bottom farming systems is likely to have an impact on sediment and nutrient dynamics. The agricultural land passes through different land cover stages seasonally, as farmers follow a rotation of land preparation, planting, weeding, fertilizing and harvesting. Studies in other parts of the world have shown that the chemistry of streams is influenced by both hydrological pathways (from hillslopes through floodplains to streams) and the chemical and biological processes of soils and vegetation (Burt and Pinay, 2005). Sediment and phosphorus (P) transport generally depend on overland flows, while nitrogen (N) transport is more related to subsurface flows (Jordan et al., 1997; Pärn et al., 2012). In agricultural catchments, both N and P can be washed into surface waters by overland runoff shortly after the application of fertilizers and manures, or during livestock grazing. N transport through groundwater, often in the form of nitrate, is slower (Howden et al., 2011). Factors determining the movement of N, P and sediments include frequency and intensity of rainfall, land use and land cover, soil type (hydraulic conductivity and erodibility), slope length and angle, and processes like leaching, adsorption, and denitrification (Burt and Pinay, 2005; Lohse et al., 2009; Pärn et al., 2012).

Field measurements of these processes are absent in Rwanda and generally scarce in Africa, where many catchments are ungauged, sampling sites are difficult to access and water quality is not monitored regularly. In the Migina catchment both land use and stream flow are subject to strong seasonal fluctuations, and a better understanding of how these relate to land use patterns in driving sediment and nutrient dynamics is important for supporting catchment planning. This is relevant not only in Rwanda but in many other African countries with similar landscape features and similar challenges of food security, water quality degradation and climate variability. The overall objective of this study is to relate trends in the retention of total suspended solids (TSS), total phosphorus (TP) and total nitrogen (TN) to valley bottom land use & land cover, in the context of seasonal rainfall and landscape features in the Migina catchment, Rwanda. Specific objectives were to (1) describe landscape features (catchment area, soil, slope and population density) and quantify changes in seasonal valley bottom land use & land cover dynamics in selected reaches of Migina catchment; (2) assess seasonal variation in the rainfall and fluxes of TSS, TP and TN; and (3) examine the relationship between TSS, TP, and TN yield and land use & land cover in the valley bottoms.

2. Material and methods

2.1. Study area and period

Migina catchment (Fig. 1a and b) is located in Rwanda's Southern Province. It has an area of 261 km^2 and is shared between Huye, Gisagara and Nyaruguru Districts (29°42′- 29°48′ E; 2°32′- 2°48′ S). The geology in the area is typical granites, quartzites and schists. Weathering and ferralization of these rocks has resulted in ferrallitic soil with clay deposits in the valley bottoms. The soil on the steep hillsides is composed of clayey and sandy material typical of ferralitic soil with good drainage, while the valley bottom soil consists of clay intermixed with organic detritus typical of Histosols (Twagiramungu, 2006; Van den Berg and Bolt, 2010). Migina river is 40.4 km long and fairly straight in most of its course, with a channel of about 1 m deep and 1.5 m wide in the upstream to 3 m deep and 4 m wide downstream. A long-term average runoff coefficient of 0.25 was estimated for Migina catchment (Munyaneza et al., 2011), and during two rainfall events more than 80% of the total discharge was generated by subsurface flows (Munyaneza et al., 2012). Maximum altitude in the catchment is 2247 m, with the valley floors ranging from 1400 to 1900 m. The climate in the catchment is temperate tropical humid, influenced by the proximity to the equator at 2° to the north, by Lake Victoria in the East, and by the altitude, with a pronounced dry period between June and September. Average temperature was 20 °C with low thermal amplitude. Rainfall distribution in 2009–2011 was fairly uniform across the catchment (coefficient of variation of 7%), with annual rainfall about 1200 mm (Munyaneza et al., 2014).

Agriculture dominates land use and land cover (LULC) in both the valley bottoms and hill slopes. Valley bottom LULC includes rice farms, vegetables (maize, beans, potatoes, carrots, tomatoes), clay, silt and sand mines, grassland, and fishponds and dams (standing water). Between crops, plots may be left fallow or ploughed. On the hill slopes, bananas are the main crop and cover the soil more or less the whole year. Land cover within the crop growing season in the valley bottom can change from completely bare soil resulting from hoeing to a dense canopy at the end of the season. Sixteen river reaches with different LULC combinations in the valley bottoms were selected in the Munyazi sub-catchment (Fig. 1c) because it represents all major LULC types in Migina catchment. Seasonal LULC patterns in the valley bottom land surrounding each reach were monitored monthly in the period May 2012–May 2013 along with the TSS, TP and TN concentrations before entering and after passing through the valley-bottom lands (Table 1). In the following text, the term "reach" is used for a river section with the associated valley-bottom land.

2.2. Data collection

2.2.1. Reach characteristics, population density and land use

A Digital Elevation Model (DEM, 10 × 10 m resolution, Fig. 1a) produced by the UR-CGIS (Centre for Geographic Information Systems & Remote Sensing, University of Rwanda) in 2008 was used to delineate the study area and identify the hydrological networks, determine the reach areas, slopes and length of the valleys. Hydrogeomorphic modifications in the sub-catchment exist in the form of reservoirs (Save Dam), fishponds (Rwasave fish farm with 103 fishponds; and Karubanda fish farm with 10 ponds) and small water intake points. Soil types were classified using field observation and literature review (Verdoodt and van Ranst, 2006). The population density in each reach was determined by interpolation