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Analysis of infield rainwater harvesting and land use change impacts on the hydrologic cycle in the Wami River basin

Frank Joseph Wambura[a,c,d,*], Ottfried Dietrich[a], Frieder Graef[b]

[a] Institute of Landscape Hydrology, Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany
[b] Institute of Land Use Systems, Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany
[c] Institute of Earth and Environmental Sciences, University of Potsdam, Potsdam, Germany
[d] Department of Urban and Regional Planning, Ardhi University, Dar es Salaam, Tanzania

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ABSTRACT

The management of water resources in a river basin experiencing the expansion of agricultural activities requires a proper understanding of impacts on its hydrologic cycle. This study focused on the analysis of impacts of infield rainwater harvesting (IRWH) and future agricultural expansion as land and water uses change (LWUC) on the hydrologic cycle in the Wami River basin (Tanzania) using the Soil and Water Assessment Tool (SWAT). In the SWAT model, IRWH was implemented by fragmenting rainwater harvesting hydrological response units (HRUs) from cropland HRUs and assigning them as potholes for rainwater impoundment. LWUC was implemented by customizing land cover types and their corresponding model parameters in all original HRUs, and introducing projected water uses in the model. The study thus demonstrated the successful modelling of IRWH and land use change in the SWAT model using HRU fragmentation and customization approaches, respectively. The results indicated that IRWH applications in croplands led to a large increase in evapotranspiration (ET) and the soil water content, and a decrease in percolation, especially in the dry years. However, the average annual streamflow showed negligible changes when IRWH was implemented, even in 50% of current low-coverage croplands in the river basin. Thus, IRWH applications in the river basin are recommended. The results also indicated that LWUC caused huge changes in ET, the soil water content, percolation and the streamflow from the river basin. The average annual streamflow was predicted to decrease by 26% due to LWUC. However, land use change alone without projected water uses was predicted to cause a minor decrease of about 1% in the average annual streamflow. Therefore, further studies on the eco-hydrology of the river basin under various water use scenarios are recommended prior to the expansion of agricultural areas.

1. Introduction

The interactions between hydrologic cycles and agricultural activities, i.e., cultivation and livestock-keeping in river basins, have received increased attention in recent years (Bharati et al., 2008; Speelman et al., 2008; Tijani et al., 2014). In order to improve food security in Sub-Saharan Africa, countries have engaged in the expansion of agricultural areas and the intensification of technologies which increase crop yields (Graef et al., 2014; MLHHSD, 2009). In Tanzania and especially in the Wami River basin, some strategies and plans include the intensification of rainwater harvesting for small-scale farms and the expansion of agricultural areas for cultivation and grazing (MLHHSD, 2009).

Recently, rainwater harvesting has drawn attention in many regions in Sub-Saharan Africa as a sustainable and economical water source (Kahinda et al., 2010; Ndomba and Wambura, 2010; Welderufael et al., 2013), especially for small-scale farming. Infield or in-situ rainwater harvesting (IRWH) consists of small pits or furrows that are dug within farms for collecting rainwater in order to increase the soil moisture and consequently the crop yield (Welderufael et al., 2013). The IRWH technique has shown a significant increase in the maize yield of up to 80% compared to conventional tillage practice in the Makanya catchment, Tanzania (Makurira et al., 2007). In the Wami River basin, IRWH is also expected to be extended to small-scale farmers in order to increase their crop yields. Currently, IRWH has been selected as one of the food value chain upgrading strategies studied by the Trans-SEC (Innovating Strategies to Safeguard Food Security Using Technology and Knowledge Transfer: A People-Centred Approach) research project for increasing food security in the Wami River basin (Graef et al., 2014). However, intensifying IRWH practices at a basin level may increase or

* Corresponding author at: Eberswalder Str. 84, 15374, Müncheberg, Germany.
E-mail addresses: fwambura@zalf.de, wamburafj@aru.ac.tz (F.J. Wambura).

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decrease water availability in other places (Andersson et al., 2011; Makurira et al., 2009; Ngigi et al., 2008; Ngigi, 2003). Therefore, understanding the impacts of different levels of IRWH application before its intensification is crucial for the sustainability of the ecosystem in a river basin.

Tanzania has a potential arable area of about 44 million hectares (URT, 2007). In the Wami River basin, the potential area already identified for cultivation, grazing and settlement is about 71% of the river basin area (MLHHSD, 2009). However, any land use change (LUC) may also have impacts on the hydrologic cycle and consequently affect the ecosystem downstream of the river basin (Baker and Miller, 2013; Schilling et al., 2008; Wagner et al., 2013). In most cases, LUCs are accompanied by an increase in water abstractions, i.e., water use change (WUC). This is because LUCs resulting from the expansion of agricultural and industrial areas also increase the water demand (Cofie and Amede, 2015; Maeda et al., 2011). In the past, the impacts of land and water uses change (LWUC) on water resources were largely neglected or considered byproducts of advancement (Scanlon et al., 2005; Schilling et al., 2008). Recent evaluations of historical effects in the Wami River basin have shown that the expansion of arable land for agricultural practices that contributed to a shift in land and water uses in the past continue to shape the direction of land and water uses in the future (FBD, 2006; Madulu, 2005; Wambura et al., 2017). Therefore, prediction of consequences of future land and water uses on water resources is vital.

The modelling of IRWH and LWUC is useful in the ex-ante assessment of their impacts on the hydrologic cycle of a given river basin (Glendenning and Vervoort, 2011; Ouessar et al., 2009; Welderufael et al., 2013). Due to various applications of the Soil and Water Assessment Tool (SWAT) in river basins in Sub-Saharan Africa, including the Wami River basin in Tanzania (Mulungu and Munishi, 2007; Ndomba et al., 2008; Nobert and Jeremiah, 2012; Wambura, 2014; Wambura et al., 2015), we selected it as the modelling environment for the IRWH and LWUC scenario simulations.

The objective of this research was to analyse the impacts of IRWH and LWUC on the hydrologic cycle in the Wami River basin. The research aimed at using more convincing process-based approaches in implementing IRWH and LUC in the SWAT model. The analysis focused on changes in evapotranspiration (ET) and the soil water content due to IRWH in individual croplands in different parts of the river basin, as well as the general impacts of both IRWH and LWUC on the streamflow from the river basin.

2. Material and methods

2.1. Study area

The Wami River basin, with an area of approximately 41,170 km^2, is located between 5°00′–7°27′S and 36°00′–39°00′E in east-central Tanzania (Fig. 1). Elevation within this river basin ranges from 0 to 2360 masl. The river basin is separated into two major parts by the Eastern Arc Mountains (EAMs), which comprise the Rubeho, Ukaguru, Nguru and Nguu mountain ranges. The predominant soils in the river basin are loam (38%) and sand-clay-loam (41%) (FAO-ISRIC, 2003). The land use classes are predominantly bushland (23%), woodland (44%) and grassland (20%) (FAO, 1997). The ranch (savannah grassland), cropland (under small-scale farming) and irrigation areas cover about 1%, 7% and 2% of the river basin, respectively. Natural forests, which are predominantly located along the EAMs, cover about 3% of the river basin area (FAO, 1997).

In the Wami River basin, the average rainfall ranges between 692 and 1388 mm per year (from Tanzania Meteorological Agency 2000–2010). The river basin has two major rainfall zones: a unimodal rainfall zone with one heavy rainfall season from October to April (ONDJFMA) in the upstream part and a bimodal rainfall zone in the downstream part. The bimodal rainfall zone has two rainfall seasons: a light rainfall season between October and December (OND) and a heavy rainfall season between March and May (MAM). A transition between bimodal and unimodal rainfalls occurs in the midstream part of the river basin. The average daily temperature in the river basin ranges between 24 and 31 °C (from Tanzania Meteorological Agency 2000–2010). The average actual ET in the river basin ranges between 368 and 1614 mm/year (from MODIS ET 2000–2010, Mu et al. (2011)), with higher ET downstream than upstream.

The hydrologic cycle in the Wami River basin is affected by the domestic water demand, irrigation, recently introduced rainwater harvesting agriculture, ranches, and an increasing demand for charcoal, fuel wood and timber (Doggart and Burgess, 2005; IUCN, 2010; Madulu, 2005). Most of the abstracted water is used for irrigation of sugarcane and rice plantations (Wambura, 2014; Wambura et al., 2015). In the year 2010, irrigation activities in the river basin accounted for an average of 96% of the total abstracted water (Wambura, 2014; Wambura et al., 2015). Moreover, the small-scale farming activities in the Wami River basin follow the rainfall seasons of OND and MAM as well as the dry period between June and September or October (Mourice et al., 2015).

2.2. Data for scenario development

The slopes were computed from a 90 m Shuttle Radar Topography Mission elevation model (Jarvis et al., 2008). The baseline land use at a scale of 1:250,000 was obtained from the FAO database (FAO, 1997). The proposed land use map used the future land use plan from the National Land Use Framework Plan 2009–2029 (NLUFP 2009–2029) (MLHHSD, 2009). To project water uses in sub-basins in the year 2029, we used water use data (domestic, livestock, irrigation and industrial water uses) and projection parameters from the study by Wambura et al. (2015).

2.3. Basic model for scenario simulation

The hydrological model used was the previously calibrated and validated SWAT model of the Wami River basin from the study by Wambura et al. (2018). It was set up using topography (90 m digital elevation model, Jarvis et al. (2008)), soil (scale of 1:2,000,000, FAO-ISRIC (2003)) and land use (scale of 1:250,000, FAO (1997)) data. As a result, 45 sub-basins and 2034 hydrological response units (HRUs) were obtained from the model setup (Wambura et al., 2018). The average size of the HRUs was about 20 km^2 and there were 371 original cropland HRUs. In the model, land use of cropland was scheduled for plant growth from mid-October to mid-June of the following year and the harvest period was in the remaining months (Wambura et al., 2018). The climate data used in the model were temperature and precipitation data (Tanzania Meteorological Agency; Weedon et al. (2014)), and baseline water use data (Wambura et al., 2015) were used to abstract water from simulated flows. The maximum canopy storage and critical depth of shallow groundwater parameters in the model were parameterized by the spatial pattern of long-term average ET and shallow groundwater levels inferred in the study by Wambura et al. (2017), respectively.

The model was calibrated using the first two thirds of the time series of monthly streamflow (2000–2007) at the 1G2-Mandera gauging station (Wami–Ruvu Basin Water Office) (Fig. 1) and the spatial pattern of long-term average monthly ET (from MODIS ET, Mu et al. (2011)). In the calibration, the Nash-Sutcliffe efficiency and the index of volumetric fit of the hydrograph achieved were 0.67 and 0.93, respectively (Wambura et al., 2018). The correlation coefficient of the spatial calibration of average ET achieved was 0.71. The model was also validated using the last third of the time series of monthly streamflow (2007–2010) at the 1G2-Mandera gauging station. The Nash-Sutcliffe efficiency and the index of volumetric fit of the validation hydrograph achieved were 0.74 and 0.81, respectively (Wambura et al., 2018).