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Sustainability in the Food-Water-Ecosystem Nexus: The Role of Land Use and Land Cover Change for Water Resources and Ecosystems in the Kilombero Wetland, Tanzania

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Abstract: Land Use Land Cover Change (LULCC) has a significant impact on water resources and ecosystems in sub-Saharan Africa (SSA). On the basis of three research projects we aim to describe and discuss the potential, uncertainties, synergies and science-policy interfaces of satellite-based integrated research for the Kilombero catchment, comprising one of the major agricultural utilized floodplains in Tanzania. LULCC was quantified at the floodplain and catchment scale analyzing Landsat 5 and Sentinel 2 satellite imagery applying different adapted classification methodologies. LULC maps at the catchment scale serve as spatial input for the distributed, process-based ecohydrological model SWAT (Soil Water Assessment Tool) simulating the changes in the spatial and temporal water balance in runoff components caused by LULCC. The results reveal that over the past 26 years LULCC has significantly altered the floodplain and already shows an impact on the ecosystem by degrading the existing wildlife corridors. On the catchment scale the anomalies of the water balance are still marginal, but with the expected structural changes of the catchment there is an urgent need to increase the public awareness and knowledge of decision makers regarding the effect of the relationship between LULCC, water resources and environmental degradation.

Keywords: floodplain; LULCC; satellite-based maps; SWAT; Tanzania; water resources; wetland

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1. Introduction

The work presented here is the result of cooperation amongst three projects. The first is the GlobE: Wetlands in East Africa project funded by the German Ministry of Education and Research and the German Ministry for Economic Cooperation and Development, focusing on the sustainable agricultural use of East-African wetlands with a special focus on the geomorphic wetland types floodplain and inland valley (https://www.wetlands-africa.uni-bonn.de/). The second is the European Horizon 2020 project Satellite-based Wetland Observation Service (SWOS) that develops a service for providing users with remote sensing based information products (http://swos-service.eu/). The third is the Kilombero and Lower Rufiji Wetlands Ecosystem Management Project (KILORWEMP) funded by

Belgian and European aid and executed by the Tanzanian Ministry of Natural Resources and Tourism and the Belgian Development Agency. All three projects focus on the sustainable use and management of wetland ecosystems and the use of satellite-based maps and products. This collaboration directly contributes to the GEO-Wetlands initiative that was recently established as part of the 2017–2019 Work Programme of the Group on Earth Observations (GEO) through a partnership led by several SWOS partners together with the Ramsar Convention Secretariat, the European Space Agency and others.

Globally, wetlands are one of the most endangered and fastest declining ecosystems, but there are few spatially inclusive and comprehensive quantitative studies on global wetland degradation and loss [1–4]. Several global conventions and Multilateral Environmental Agreements therefore strive for their protection and sustainable use and require high quality data and information about their status and trends [5,6]. Understanding wetland hydrology at multiple scales is crucial to assess the impact of on-site and off-site water resources management measures on diverse wetland ecosystem services. This implies the analysis of catchment-wetland interactions to determine altered wetland water inflows based on local climate variability and land use changes of the upstream catchment and furthermore the impact of wetland use on downstream riparian [7]. Applying historic land-use data, Piao et al. (2007) [8] have demonstrated on a global scale that land-use change has an overall significant impact on hydrological runoff regimes. Furthermore, they have shown that land-use change has had the strongest impact in tropical regions with an even higher share than expected of climate change. Therefore, Integrated Water Resources Management will only provide sustainable solutions with a focus on the complete green-blue water approach [9]. With the growing water demand, especially from agricultural activities, there is an accumulative risk that additional water demands of various sectors cannot be satisfied during the hydrological cycle of the year [10]. The 2030 agenda framed 17 sustainable development goals (SDGs) including a total of 169 targets highlighting the key role of climate and natural resources like water, soil and ecosystems providing the basis for sustainable development. There is a strong need to balance the tradeoffs between the different SDGs and the related targets [11,12]. Water is one of the key links between the SDGs as an integral part of human development and ecosystem needs [13]. With respect to the food-water-energy nexus, Bhaduri et al. (2015) [14] postulate an urgent need in solution-oriented integrated research on land, water and energy efficiency which is indeed also essential for the sustainability in the food-water-ecosystem nexus under the framework of the different SDGs and their related targets. Overall estimates of increased future water use in sub-Saharan Africa (SSA) primarily concentrate on the energy (hydropower) and agricultural sector [15]. Focusing on the sustainability assessment of the food-water-ecosystem nexus for wetland ecosystems, it is essential to apply an integrated catchment-wetland approach to identify the impact of land use changes on the catchments and the wetlands' water budget in particular and hence on the water-related ecosystem services, again regulating ecosystem health and agricultural practice. There are numerous recent hydrological grid-based model developments and applications assessing the impact of global change, including Land Use Land Cover Change (LULCC), on the water resources at various scales [16–19]. High quality remote sensing based land use/cover maps serve as important spatial input data for the application of such grid-based hydrological models at the catchment scale and especially for developing and analyzing LULCC scenarios. At the catchment scale, information about LULCC is required especially when the focus is on studying the impact on related wetlands. Earth observation, however, is recognized as a means to provide consistent and comprehensive information to complement monitoring, management and ground-based knowledge [20–22].

The SSA region recorded an extensive conversion of natural vegetation to agriculture in the past decades [23]. This is particularly evident for the IGAD (Intergovernmental Authority on Development in Eastern Africa) region where over the last two decades various land cover change processes, mainly driven by demographic growth, caused high losses of natural vegetation and an increase in agricultural areas [24,25]. In Tanzania, several studies have been conducted to explore LULCC and its impact at regional and local levels [26–29]. They show that already some 10 years ago, LULCC was taking place largely driven by human activity and often with negative consequences for wildlife. The recent introduction of an agricultural green growth approach in the Southern Agricultural Growth Corridor (SAGCOT)—covering one third of the mainland of Tanzania including three key development clusters in the Kilombero, Ihemi and Mbarali region—has driven an international focus on the region and will doubtlessly have an impact on agricultural land use practices and hence on overall land use dynamics [30]. These key clusters are characterized by their great agricultural potential, extensive forests, wildlife, protected areas and by their poorly developed infrastructure. This paper focuses on the potential and challenges of satellite-based integrated research on water resources and related ecosystems in the Kilombero floodplain and its contributing catchment, representing one of the SAGCOT key development clusters in Tanzania [31]. The objectives of this study are to outline and discuss the prospects of these integrated scientific results for supporting national decision and policy making, reporting on Multilateral Environmental Agreements as well as required capacity building and awareness raising activities.

2. Study Site

The Kilombero river is a tributary of the Rufiji river, one of the major basins in Tanzania, and is situated in the south-eastern part of the country (Figure 1). The Kilombero catchment covers an area of 40,240 km^2 with elevation ranges between 200 and 2500 m.a.s.l. [32]. The broad floodplain of the main Kilombero river comprises about 7967 km^2 [33] and is framed by the north-western Udzungwa mountains and the Mahenge Mbarika mountains in the south-east. The plain is geologically described by sedimentary basin infillings forming a seasonal alluvial floodplain geomorphic wetland type dominated by fluvisol soils [34]. The regional climate is characterized as sub-humid tropical with an average daily temperature of around 22–23 °C and annual precipitation of about 1200–1400 mm [35]. The bimodal rainy pattern comprises a short rainy season (November–January) and a long rainy season (March–May) with a distinct dry season from July until October. The Kilombero river is a natural shaped river with a high yearly discharge variability of about 92–3044 m^3/s [36]—as observed at the Swero gauging station situated at the outlet of the catchment—and regular flooding of the wetland during the long rainy season. Land use and cover of the wetland are strongly attributed to the flooding duration, height and extent of the Kilombero river and its tributaries. The 2012 national population census [37] counted over 670,000 people living in the two districts of Kilombero and Ulanga, which occupy the valley and immediately adjoining hilly regions. Annual population growth was estimated respectively at 3.9% and 2.4% against a national rate of 2.7%. Over the last five decades, the valley (especially its NW section) has been a magnet for infrastructure development (including the TAZARA railway), resettlement, immigration and consequently an expansion of rural centers and farming [38]. A few large commercial firms and a large number of small farms grow mostly rice, maize and sugarcane. Furthermore, the floodplain is used for fisheries and cattle grazing [39]. The wetland ecosystem also provides other direct livelihood inputs like forest products, thatch grass, brick making, bush meat and domestic water [40]. In 2000, Tanzania ratified the Ramsar Convention of Wetlands of 1971. This agreement stipulates wise use of wetland resources, thereby maintaining the ecological character of the site while contributing to people's welfare [41]. In April 2002, the Kilombero Valley Floodplain Ramsar Site was designated under the Ramsar Convention as a wetland of international importance. This designation was justified by a range of ecological services, functions and values provided by the wetland, including the presence of the wetland dependent Puku Antelope *Kobus vardonii* listed as near threatened in the IUCN Red List of Threatened Species; and its role as a dry season wildlife refuge for seasonally migrating species [42] moving between the Udzungwa mountain range in the North (where the Udzwungwa National Park and Kilombero Nature Reserve are situated) and the vast Selous Games Reserve situated to the south-west of the floodplain.

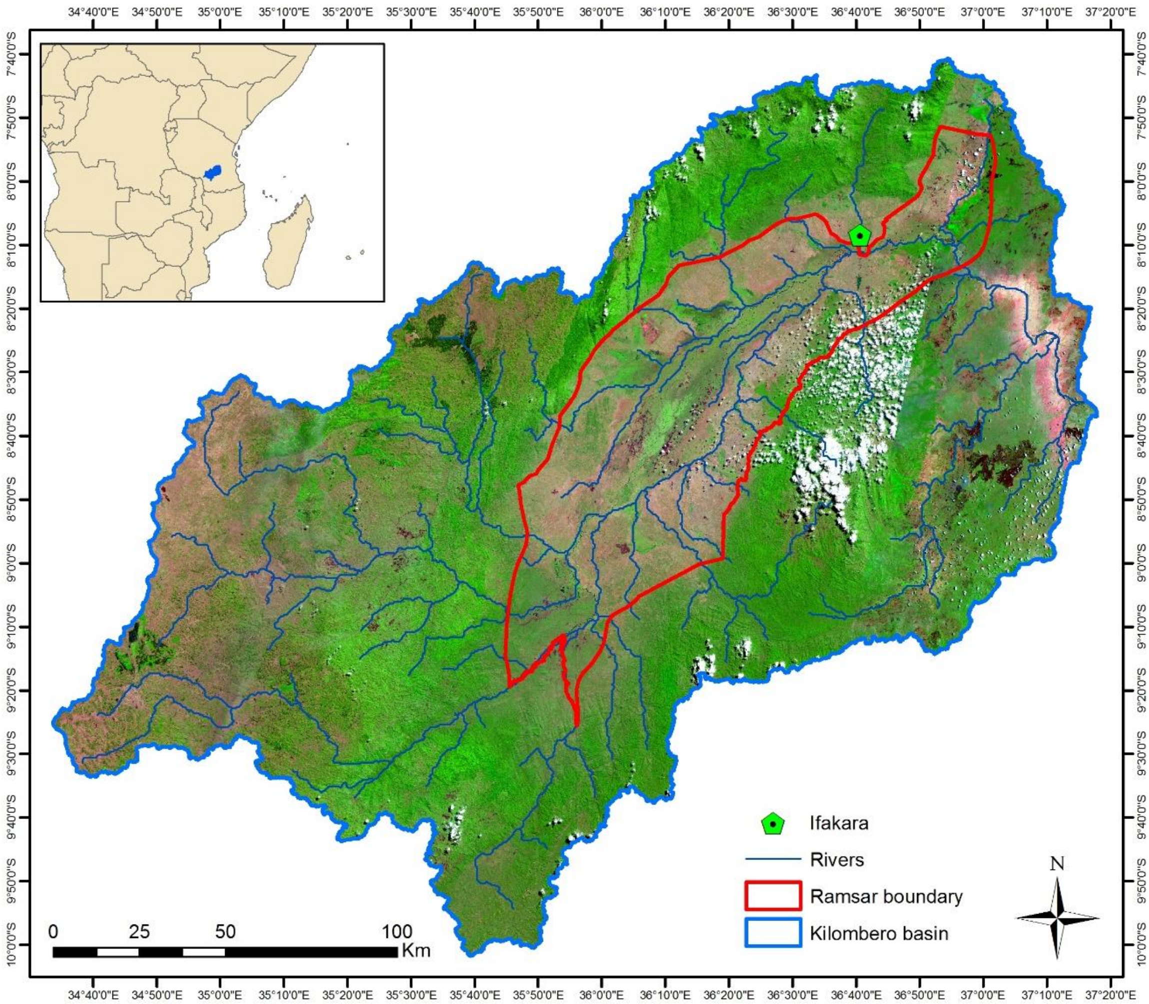

Figure 1. Sentinel-2 image of the study area. RGB: 12, 8A, 4.

3. Methods

3.1. Land Use and Land Cover Classification and Change Assessment

3.1.1. LULC Changes in the Kilombero Floodplain

Using the Shuttle Radar Topography Mission digital elevation model (SRTM DEM) and optical satellite images from different time steps and sensors, the study area was mapped at the floodplain scale. Three time steps were considered where most of the changes were expected to occur: 1990, 2004 and 2016. Since the area is not covered by a single pass of sensors, multiple images had to be used. Table 1 lists the images analyzed in this study. For 1990 and 2004 the Landsat 5 Thematic Mapper (TM) was used. The most recent time step (2016) was covered by multiple Sentinel-2 data [43]. The Landsat TM has six optical and shortwave infrared image bands with a spatial resolution of 30 m. Sentinel-2 has thirteen optical and shortwave infrared spectral bands; four at 10 m spatial resolution, six at 20 m spatial resolution and three at 60 m spatial resolution, the latter being used mainly for atmospheric correction and cloud masking. The spectral properties of Sentinel-2 and Landsat 8 are comparable in the visible, near infrared and short-wave infrared spectral region. Due to its larger spatial coverage of 290 km—compared to the 185 km of Landsat—and its higher spatial resolution, we preferred Sentinel-2 over Landsat 8 for the 2016 time step.

Table 1. Images used for the LULC maps of the Kilombero floodplain.

1990 (Landsat 5)	2004 (Landsat 5)	2016 (Sentinel 2)
1 June 1991	7 May 2004	6 December 2015
11 July 1990	17 July 2004	26 December 2015
		24 May 2016
		13 June 2016

Oblique and vertical photos taken during two flight campaigns in January and June 2016 were included for training the 2016 images. The campaigns were conducted over parts of the catchment that are of importance for local authorities and the project goals. The images deliver high spatial resolution and geo-tagged photographs. Local experts assisted in their interpretation, thereby minimizing errors of misinterpretation. The photo interpretation of Landsat, Google Earth (https://www.google.com/intl/de/earth/) and Bing (https://www.bing.com/maps) images was applied to train the 1990 and 2004 satellite images. Because one of the primary goals of the study was to quantify the expansion of agricultural areas, the area was divided into four coarse classes: open to close forest, arable land (including industrial and subsistence farming), water and wetland. This last class comprises natural non-forested areas that are seasonally flooded. The classification of built-up areas is challenging because buildings are often made of natural materials such as clay, and relatively low-density settlements blend with farmed areas. Therefore, built-up areas covered only small areas of the catchment and this class was omitted from the LULCC analysis, although the growth of the main centers such as Ifakara and the belt of settlements along the main transport infrastructure is considerable. The classification was performed using the SWOS toolbox. This software was specifically developed for the segment-based classification of wetlands. The classification process applied here includes segmentation of the satellite images and a supervised, segment-based maximum likelihood classification algorithm implemented in the SWOS toolbox. Similar methodologies have been used in other wetland monitoring projects [44], and the latest version of it is currently being applied over 25 wetlands covering a wide range of biogeographic regions. Validation was performed using 400 randomly distributed points in CollectEarth [45]. We calculated LULC area estimations for each class for each time step, following the recommendations developed by Olofsson et al. (2014) [46]. The error matrices are expressed in area proportions rather than in unit counts, and error adjusted area estimations are calculated for each class. LULCC analysis was performed via post-classification comparison (PCC) [47] of the LULC maps.

3.1.2. LULC Changes at the Catchment Scale

As contributing catchments have an essential impact on the hydrological functioning of a wetland as well as on its water and energy balance, it is crucial to monitor long-term LULCC at catchment scale. For wetlands in tropical and subtropical Africa, frequent cloud cover often hampers the performance of more conventional compositing and classification approaches for optical satellite imagery, particularly when high spatial resolution is required [48]. Synthetic Aperture Radar (SAR) systems are therefore often preferred over optical systems, in particular when seasonal dynamics are to be considered [49–51]. Their availability, however, is limited since consistent operational image acquisitions have not been taken until recently. With Sentinel-1, operating as a two satellite constellation, data are continuously available and free of charge [52,53].

Historic data records are restricted to specific observation periods and regions. Therefore, optical data from different periods have been used to assess long-term LULCC. In order to obtain complete spatial coverage of the Kilombero catchment and to account for intra-annual water and land use dynamics, all available Landsat scenes from a three-year epoch around 1994, 2004, and 2014 were subjected to the calculation of temporal metrics [45]. This method follows the assumption that images of dry periods with low water tables as well as rainy season images with high water tables are included.

The use of temporal metrics became popular during the past years due to data availability and its efficiency in LULC assessment [54]. Temporal metrics are capable of suppressing outliers due to remaining artifacts originating from inaccurate cloud masking. Accurate cloud masking, however, is desired. Landsat surface reflectance higher level data products [55,56] were acquired from the USGS downloading platform Earth Explorer (https://earthexplorer.usgs.gov/). Cloud masking was performed using the pixel quality file appended to each dataset. It contains information about cloud cover and is generated based on the Fmask algorithm [57,58]. The catchment area delineation was based on the SRTM digital elevation model (DEM) applying the DEM processing tool of the Soil and Water Assessment Tool (SWAT, [59]). From multi-temporal statistical metrics the Normalized Difference Vegetation Index (NDVI, [60]), the Normalized Difference Water Index (NDWI [61]), and Tasseled Cap components describing brightness, greenness and wetness [62–65] were calculated. Combined with the SRTM digital elevation model (DEM) and derivatives (slope, surface roughness, topographic wetness index [66]), an input dataset for a Random Forest (RF) classification was composed. RF is a supervised ensemble classifier developed by Breiman [67,68], reported to be stable with limited or imbalanced input data [69], not to overfit [68,70] and to generally yield high accuracies in land use and land cover classification (e.g., [71–73]). Field observations, flight campaigns and Google Earth were used as reference for model training and validation. We made use of a hierarchical classification scheme containing two levels, with Level 1 comprising only four main classes (forest vegetation, non-forest vegetation, non-vegetated, water), and Level 2 including ten sub-classes (montane forest, closed woodland, open woodland, teak plantation, cropland, grassland, bare soil, swamp, built-up and water). For the classification at the catchment scale only the more detailed Level 2 classifications of each time step were applied.

LULCC were assessed by PCC, i.e., a simple pixel-by-pixel comparison of two classifications of different periods (1994–2004, 2004–2014). A fourth time step was classified as a 1970s LULC map. Due to limited data availability the number of land use classes had to be reduced and a much simpler approach was used. In fact, only three images acquired in two years (1973 and 1979) suitable for classification could be identified. The resulting classification served as the base land use map for the hydrological model calibration and validation period (1958–1970).

3.2. The Impact of Land Use and Land Cover on Water Resources at the Catchment Scale

3.2.1. The SWAT Model Setup for the Kilombero Catchment

SWAT (Soil and Water Assessment Tool) [59] is a semi-distributed ecohydrological model which is able to simulate the water balance from small catchments [74] up to the continental scale [75] for a variety of climatic conditions including tropical climate [76]. The physical based modelling of the SWAT model implies data intensity (Table 2) but the semi-distributed approach in combination with the integrated plant growth routine enables SWAT to simulate the impacts of land use changes on water resources [77].

Table 2. Data description and sources of the SWAT model.

Data Type	Digital Elevation Model (DEM)	Soil	Land Use	Climate	Discharge
Resolution	90 m	1 km	60 m (1979); 30 m (1994, 2004, 2014)	Observed (precipitation) modelled (0.44°) with CORDEX—Africa (temperature, rel. humidity, wind speed, solar radiation)	Station data comprising 34,000 km^2
Source	SRTM [78]	Harmonized World Soil Database (HWSD) [79]	(Own product, see Section 3.1.2)	CORDEX-Africa [80]	Rufiji Basin Water Office [36]

3.2.2. Model Configuration and Performance Evaluation

Due to limited discharge data availability, the model was calibrated for the time period 1958 to 1965 and validated from 1966 to 1970 at the Swero gauging station comprising 34,000 km^2 of the Kilombero catchment. The results for the calibration and validation period are very good according to Moriasi et al. 2007 [81] (Table 3). Input data is given in Table 2 while both the calibration and validation period were exclusively run with the 60 m (1979) land use map.

Table 3. Summary of the quantitative model performance analysis for daily resolution. The p-factor (0–1) is the amount of observed data bracketed by the uncertainty band of the simulations and the r-factor (0–∞) expresses the width of the uncertainty band and should be below 1 [82]. R^2 is the coefficient of determination, NSE the Nash-Sutcliffe efficiency [83], PBIAS [84] is the percent bias and KGE the Kling–Gupta Efficiency [85].

Simulation period	p-Factor	r-Factor	R^2	NSE	PBIAS	KGE	Mean_Sim (Mean_obs) [mm] Discharge	StDev_Sim (StDev_obs) [mm] of Discharge
Calibration	0.62	0.45	0.86	0.85	0.3	0.93	535.28 (537.11)	578.56 (572.50)
Validation	0.67	0.56	0.80	0.80	2.5	0.89	508.53 (521.32)	496.61 (508.19)

The water balance (Table 4) indicates the significance of groundwater flow which was also represented in the high sensitivity of groundwater controlling parameters during the model calibration and is in sync with the high aquifer productivity of the mountainous parts of the catchment [86].

Table 4. Water balance components for the calibration period (1958–1965).

Water Balance Components	Mean Annual [mm]
Precipitation	1306
Evapotranspiration	757
Surface runoff	41
Lateral flow	55
Base flow	221
Recharge to the deep aquifer	222

4. Results

4.1. LULCC at Floodplain Scale

The results of this study show that the floodplain experienced major LULCC over the past 26 years (Figures 2 and 3, Table 5). Most of the changes occurred along the perimeter belt of the valley floor and the boundary of the Ramsar site, predominantly showing the expansion of agricultural areas at the expense of natural wetland area. The central part of the floodplain is still not used for crops, mainly because of the high frequency of floods.

Fire is one means of management in the Kilombero region. Agricultural areas but also natural grasslands are regularly burnt in expectation of the rainy season to boost grass growth during the following growing season. Hence, fire prone areas can be seen from the satellite images even though they are not classified here. Jones et al. (2012) [87] reported the recent loss of functionality of two wildlife corridors; Nyanganje and Ruipa. They connected the Selous Game Reserve to the South-East with the Udzungwa Mountains National Park to the North-West. The LULC analysis indicates that these areas were still connected in 1990, with only a few areas classified as arable land. In 2004, the proportion of arable land increased and spread between forests and wetland area. The 2016 result reveals that direct connectivity between the wetland along the Kilombero river and the Udzungwa and Selous protected areas is no longer existent. According to the maps, only the southern tip of the Ramsar site was not agriculturally utilized in 2016. Despite a relatively high forest loss, mostly non-forested natural areas have been converted into agriculture. From 1990 to 2004, wetlands, water bodies and natural grasslands were reduced from 6598 km^2 (±1404 km^2) to 3911 km^2 (±718 km^2). By 2016, they were further reduced to 2237 km^2 (±263 km^2). Whereas arable land increased slightly from 2082 km^2 (±655 km^2) in 1990, to 2511 km^2 (±638 km^2) in 2004 and 5704 km^2 (±788 km^2) by 2016. Due to the large coverage of forested areas and persistent cloud coverage at higher altitudes, forest losses/gains were inconclusive during the first period. During the second period, forests and open forests were estimated to go from 14,408 km^2 (±718 km^2) in 2004 to 12,922 km^2 (±751 km^2) by 2016.

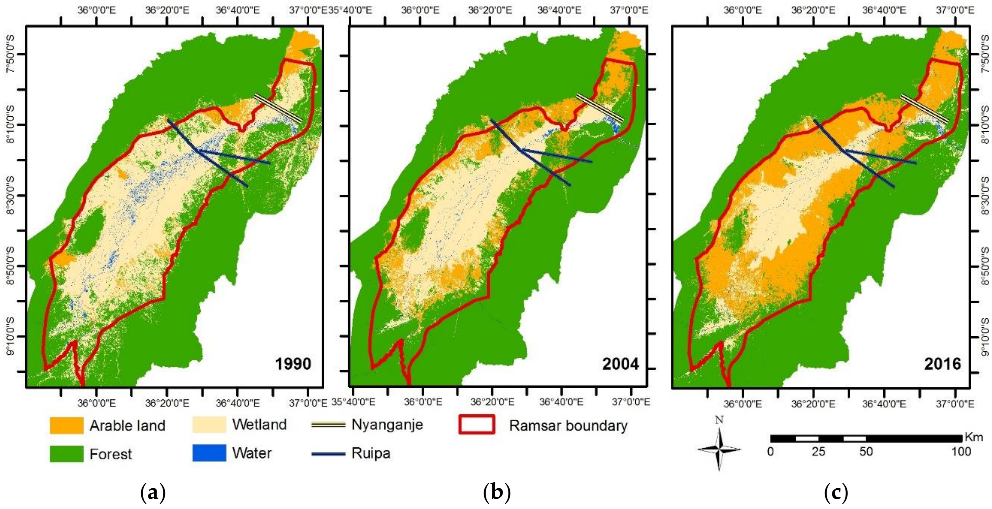

Figure 2. LULC maps of the Kilombero floodplain for 1990 (**a**), 2004 (**b**) and 2016 (**c**). Individual overall map accuracies were >80%. Wildlife corridor locations for Ruipa and Nyanganje were extracted and modified from Jones et al. (2012) [87].

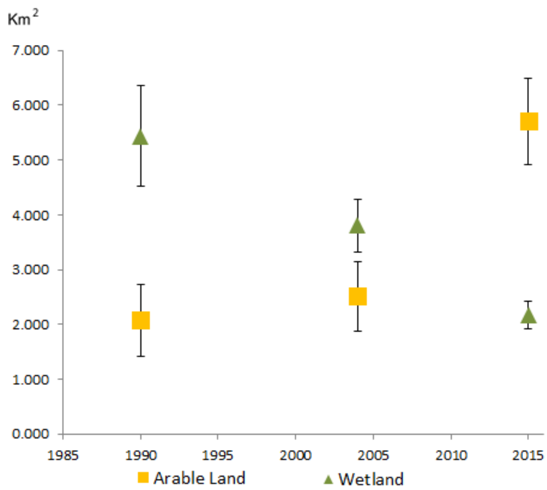

Figure 3. Area estimated for wetlands and arable land across the study period, with their estimated errors at a 95% confidence interval.

Table 5. Area proportions of each LULC class (floodplain scale).

LULC Class	1990 (km^2)	2004 (km^2)	2016 (km^2)
Arable Land	2082	2511	5704
Wetland	5436	3809	2166
Forest	12,177	14,408	12,922
Water	1162	102	71

4.2. LULC Changes at the Catchment Scale

The analysis at the catchment scale provides more thematic details since more land use classes were defined. Specifically, forests are subdivided in subclasses comprising natural forest types such as montane forest, closed woodland, open woodland and anthropogenic forest types such as teak plantations. LULC conversion north of the Kilombero river is largely determined by topography. The steep slopes of the Udzungwa mountain range are inappropriate for crop cultivation, though a few banana plantations can be found. Therefore, conversion mainly takes place for crop cultivation in the floodplain area reaching further towards the Kilombero river, and partly along the forest fringes. Natural grasslands north of the river almost completely disappeared in 2014 (Figure 4). South of the Kilombero river, topography has less impact on land use decisions and conversion reaches both further into the floodplain and also further away from the river towards the woodlands. Primary forests are increasingly converted in smaller patches to teak plantations. Teak plantations can also be found at the slopes of the Udzungwa mountains north of the Kilombero river but at a much smaller extent. Area proportions of each LULC class from the 1970s to 2014 are depicted in Table 6 and change detection statistics between 1994–2004 and 2004–2014, respectively, are shown in Table 7. The highest uncertainty is expected in the category "changes within natural classes" since these represent subtle transitions between classes that are spectrally (and often ecologically) similar. Changes listed in this category can be either attributed to natural processes or to classification errors. Classification errors are less likely in the conversion classes since those conversions are spectrally more intense than changes between similar classes and thus better detectable by means of remote sensing. Besides, the temporal dynamics, i.e., the combination of phenology and management, of natural classes and crops differ substantially since natural surfaces are usually not managed or at least they are managed in a different way. As the approach used in this study accounts for temporal dynamics, we assume the detection of conversions is realistic. However, classification errors are likely in parts of some protected regions classified as cropland, e.g., in the classification of 2014 of the Selous Game Reserve.

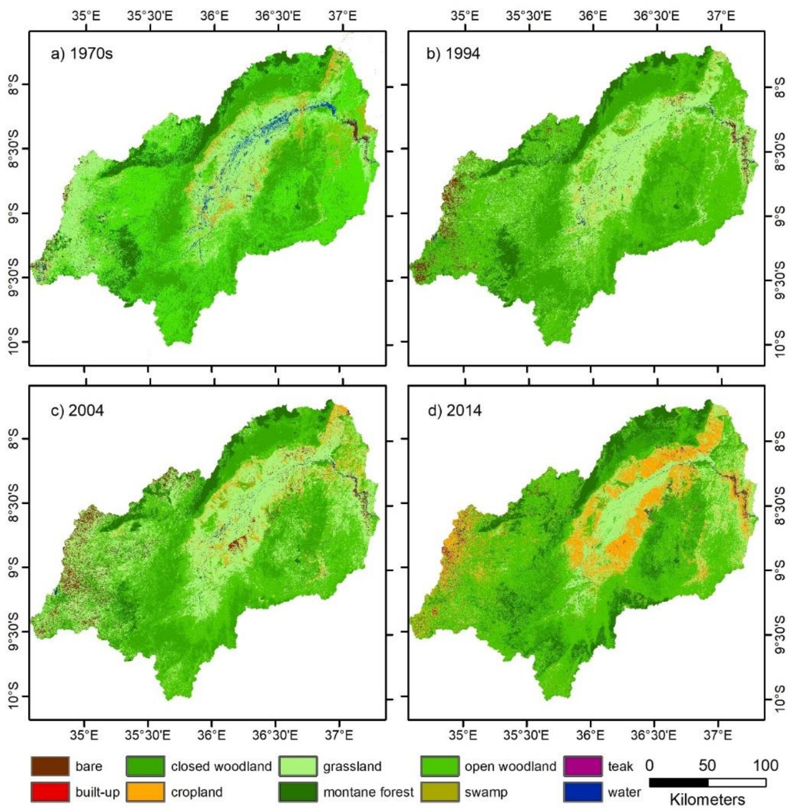

Figure 4. LULC classifications for four time steps: (**a**) 1970s, (**b**) 1994, (**c**) 2004 and (**d**) 2014.

Table 6. Area proportions of each LULC class (catchment scale).

LULC Class	1970s (km^2)	1994 (km^2)	2004 (km^2)	2014 (km^2)
Cropland	1414.38	473.33	1293.50	5603.18
Grassland	9162.49	9489.96	13,139.04	6827.92
Open Woodland	16,771.86	17,660.93	14,222.44	17,394.11
Closed Woodland	8377.62	8662.76	7486.78	4609.35
Montane Forest	3138.89	2542.89	1901.42	4681.38
Teak	n.a.	35.72	70.30	154.32
Swamp	164.01	114.68	206.62	333.00
Bare	445.73	1094.82	1695.90	485.77
Built-Up	n.a.	9.23	40.62	78.43
Water	890.26	155.79	183.49	72.64

Table 7. Change detection statistics based on post-classification comparison results of the Kilombero catchment.

1994–2004	Area (km^2)	2004–2014	Area (km^2)
Conversion to cropland	1968.94	Conversion to cropland	5744.11
Grassland to cropland	1093.15	Grassland to cropland	4981.32
Open woodland to cropland	838.67	Open woodland to cropland	762.79
Swamp to cropland	37.12		
Conversion to teak	97.14	Conversion to teak	176.4
Bare soil to teak	0.31	Bare soil to teak	0.88
Grassland to teak	10.57	Grassland to teak	24.56
Open woodland to teak	86.26	Open woodland to teak	113.64
		Closed woodland to teak	37.32
Changes within natural classes	12,496.49	Changes within natural classes	12,808.00
Open woodland to grassland	5378.69	Open woodland to grassland	1316.24
		Closed woodland to open woodland	2401.3
Grassland to bare soil	1835.23		
Swamp to grassland	39.05		
Bare to open woodland	136.51	Bare to open woodland	554.43
Bare to grassland	3268.5	Bare to grassland	93.94
Grassland to open woodland	1838.51	Grassland to open woodland	4128.38
		Closed woodland to montane forest	2888.71
		Open woodland to closed woodland	1425.00
Other changes	1156.97	Other changes	0.00
Cropland to grassland	945.24	-	
Cropland to open woodland	211.73	-	

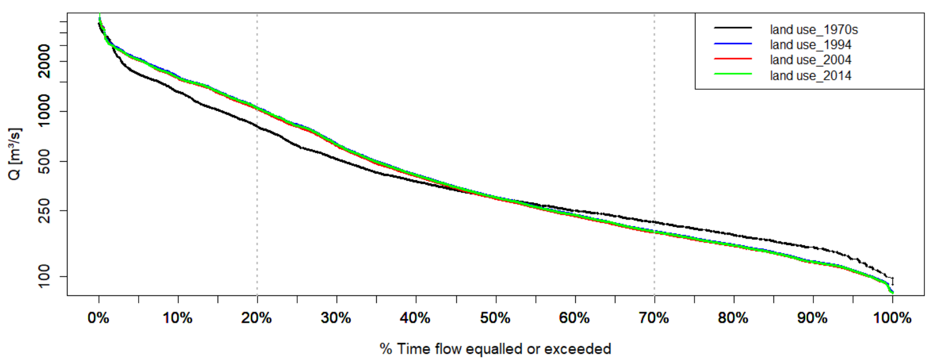

Figure 5. Flow duration curves of the four land use setups from the 1970s up to 2014 for the whole catchment. Climate data (1958–1970) in all four scenarios is not modified to attribute all changes in exceedance probabilities to alterations in land use inputs.

The flow duration curves of the land use change scenarios from 1994 to 2014 do not show significant changes in exceedance probabilities (Figure 5) whereas a more detailed look at single components of the water balance (Table 4) illustrates changes in all runoff components and in all four land use scenarios (Figure 6). It can be seen that baseflow, overall water yield (baseflow, lateral runoff and surface runoff), and the deep aquifer recharge increase compared to the 1970s scenario, though not in a chronological order with regard to land use changes. Surface runoff decreases in the 1994 land use scenario and increases for the following scenarios of 2004 and 2014. Lateral runoff and evapotranspiration decrease in all scenarios compared to the reference scenario.

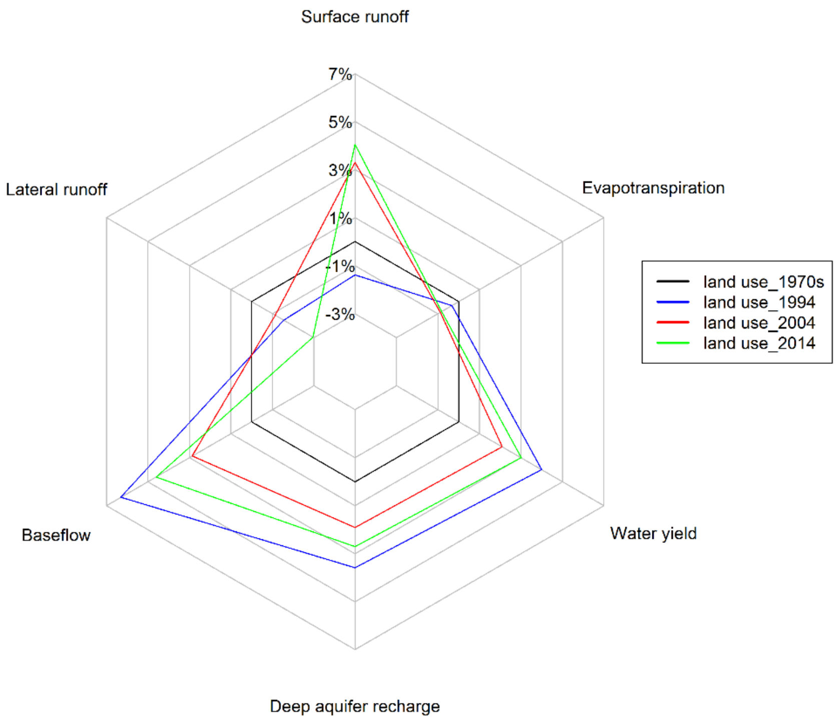

Figure 6. Percentage shifts in water balance components (Table 4) for the whole catchment and investigation period (1958–1970) through the application of different land use maps.

5. Discussion

5.1. The Potential, Uncertainties and Limitations of LULCC Analysis and SWAT Application

Land use classification is based on transferring continuous spectral signals into discrete classes [46]. This generates errors that must be reported in order to evaluate the validity of the maps or the models using the LULC data. In our case, water, wetlands and arable land were rather homogeneous classes. However, the forest class was spatially often very heterogeneous, with areas of open forests mixed with patches of grasslands or arable land. This caused the estimations of forested areas to be less accurate, especially for the 1990 map due to lack of quality training and validation data. Considering these limitations, the high rates of agricultural expansion at the expense of wetlands first are still very obvious, especially during the period 2004–2016. At the catchment scale the impact of the changes for the period 1994–2014 seem to be negligible at first glance concerning the flow duration curve (Figure 5). However, the flow duration curve displays the ranked discharge values of 15 simulation years for each land use scenario. Hence there is no temporal information when discharge thresholds are exceeded and only the percentage of data exceeding certain thresholds is shown. Nevertheless, a shift from the 1970s scenario to the more recent land use scenarios (1994 to 2014) can be observed. The simulated changes in land use patterns from the 1970s compared to other scenarios result in decreasing low flows and increasing high flows as shown in Figure 5. These changes in low flows and high flows affected the overall hydrological regime of the Kilombero river. On the one hand, increasing high flow events had an impact on the inundation height and duration during the rainy season and on the other hand, decreasing low flows were directly linked to the surface groundwater interaction in the floodplain during the dry season, altering the depth to groundwater table dynamics and hence the overall soil water availability. On a seasonal scale this shift probably influenced already implemented and planned cropping schemes, especially with respect to the planned intensified agricultural cultivation [31]. This potential impact on agricultural management was emphasized when analyzing single components of the water balance. In addition to the above mentioned changes from the 1970s scenario it was apparent that shifts in the water balance can be observed among the scenarios from 1994 to 2014 (Figure 6). This is especially true of the increase in surface runoff and the decrease in baseflow which was caused by the conversion from open woodland into cropland/grassland [88] resulting in an overall increase of high flow events and a decrease of low flow events respectively (Figure 5). Furthermore, the high evapotranspiration rate of the 1970s scenario was related to the overestimation of the land use class open water in the floodplain area (Figure 4) because available Landsat images were exclusively from the wet season. However, the conversion of open woodland to cropland and grassland decreased actual evapotranspiration rates. This was mainly observed in the land use change scenario from 1994 to 2004 (Figure 6) with a major shift from open woodland to grassland (Tables 6 and 7). In general, this analysis indicates that the observed changes led to decreased actual evapotranspiration and baseflow whereas surface runoff increased, altering the hydrological regime of the Kilombero river. However, the simulated components of the water balance (Figures 5 and 6) were aggregated by areal means over the entire simulation period. Future research should focus on smaller timescales such as seasonal changes as well as more detailed spatial analyses. Spatially distributed analyses will probably show clearer results with respect to changes of the hydrological system as this first integrated catchment approach. As already demonstrated by the spatial and temporal data availability for the setup of the SWAT model for the catchment (Table 2) there is a temporal and resolution based mismatch of operational climate and hydrological data and globally available geo and climate data sets resulting in an overall increase in the uncertainty of the model results. Beyond LULCC analysis, the calibrated and validated hydrological model for the Kilombero catchment can be further applied to climate change (e.g., CORDEX-Africa [80]) or infrastructure measure (e.g., hydropower or irrigation reservoirs) scenarios quantifying the impact on the water balance and runoff components. This is relevant for the impact assessment analysis of the water management scenarios that are driven by the expected expansion of the agricultural growth corridor (SAGCOT). Furthermore, the simulated discharge of the Kilombero river can serve as a boundary condition for a hydrodynamic model (e.g., LISFLOOD, [89]) to simulate inundation depth, extent and dynamics for the floodplain, which is crucial for sustainable agricultural management of the wetland. The high resolution LULC map of the SWOS floodplain study would serve here as spatial input data parametrizing the surface roughness of the floodplain. However, to obtain high resolution spatial and temporal inundation maps that can be applied for further management measures on a local scale, the application of the hydrodynamic model for the floodplain would further require a high resolution digital elevation model like TanDEM-X data sets [90], ideally corrected with high accuracy ground truth elevation data.

5.2. Science-Policy Interface and Capacity Building

Site level analysis, reviews and planning processes in and about Kilombero Valley have emphasized environmental change and ecological threats arising from LULCC in the catchment including the intensification of human activities, in particular within and around the valley floor [91]. We have presented the first comprehensive multi temporal LULCC analysis of the Kilombero catchment. The results provide evidence that LULCC is taking place: a large-scale conversion of natural grasslands and forests to cropland and plantations has been the prime driver of change across the higher elevation valley floor and the wider catchment. Although our analysis does not provide direct evidence of land use practices such as grazing and seasonal burning which are observed locally [92], nor of their ecological impacts, it documents how habitat fragmentation and loss have undermined pre-existing wildlife connectivity across most sections of the wetland. Based on our preliminary assessment, the implications of LULCC on the water balance of the catchment and the overall water availability of the wetland may be classified as marginal but it has a strong impact on agriculture.

Human population growth, agriculture expansion and intensification, and infrastructure development have changed Kilombero Valley over the last decades. A wildlife dominated land use combined with semi-subsistence agriculture and fisheries has been replaced by a complex and ever evolving agrarian economy, more and more integrated with national and global value chains. The preservation of key wetland ecosystems services and function will increasingly require authorities and stakeholders to choose among possible land use tradeoffs and to contextualize local choices within the catchment scale. The availability of spatially and temporally distributed data and analysis of LULCC is essential to inform local and national decision making on land use, to enable environmental monitoring and to support national reporting on global conventions and frameworks (e.g., Ramsar Convention on Wetlands; Sustainable Development Goals). Local and national planning processes are required to reflect and translate LULCC analysis in forms and processes amenable to local stakeholders and decision making which will support sustainable development in the SAGCOT area.

6. Conclusions—Ways Forward

The new GEO-Wetlands initiative facilitates cooperation between different projects under the common goal of improving the mapping, monitoring and assessment of global wetland extent, status and trends. Close cooperation between projects and teams from different regions and backgrounds is important for achieving ambitious global targets that are set by conventions and frameworks. In the framework of the Sustainable Development Goals, indicator 6.6.1. "Change in the extent of water related ecosystems over time" requires information of high temporal and spatial resolution. Earth observations make significant contributions that also directly support the Ramsar Convention on Wetlands. As MacKay et al. already reported in 2009 [21], EO can play a significant role for wetland monitoring on different scales. The scientific and technical developments since then has increased the capabilities of remote sensing even further.

In SSA countries it is often difficult to utilize the full potential of available satellite data and hydrological model applications, despite the growing accessibility and quality of remote sensing data and sophisticated hydrological modelling applications. Frequent and persistent limitations include technical capacity bottlenecks in planning agencies and the fact that LULCC and hydrological analysis is often delivered through transient and externally funded projects. We posit that the development of partnerships such as the one underpinning this study may provide an institutional mechanism to overcome some of those limitations. The potential value of the partnership transcends the mere pooling of multi-sector expertise and rests in the blending of different and complementary institutional agendas. In this case the partnership has joined a global environmental monitoring initiative, a regional research initiative and a site-specific development intervention embedded in the national wetland management system.

The productive outcome from the initial opportunistic agenda shared by the partners has opened up further potential: the use of the results of the environmental analysis in the local planning processes currently deployed on-site to strengthen the management of the Ramsar Site; the dissemination of key evidence of LULCC change among local stakeholders to increase awareness of change at landscape scale and to mitigate conflicts over land use decisions; the feeding of the experience into the development of standardized methods, best practice guidelines and training material on various scales to improve wetland degradation assessment and overall wetland management in SSA; utilization of the evidence generated into the national and international reporting system for the SDG indicator 6.6.1 and the related national reporting on water related ecosystems.

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