

PARTICIPATORY MONITORING AND VALUATION OF HYDROLOGICAL
ECOSYSTEM SERVICES IN TROPICAL MOUNTAINOUS LANDSCAPES OF
KENYA

NAOMI KARIMI NJUE

A dissertation submitted by M.Sc. Naomi Karimi Njue to the Institute of Natural Sciences at the
Department of Landscape, Water and Biogeochemical Cycles of the Justus Liebig University
Giessen for the degree of

Doctor of Natural Sciences (Dr. rer.nat.)

Referees:

Prof. Dr. Lutz Breuer Justus Liebig University Giessen

Prof. Dr. Jan Siemens Justus Liebig University Giessen

Submitted: 14 November 2023

Abstract

Tropical montane forests provide water-related ecosystem services (WES) that are crucial for human well-being and sustainable development, yet these ecosystems are among the most threatened globally by conversion to other land uses and climate change. Despite their importance and vulnerability, the lack of hydrometric data and inadequate incorporation of socio-cultural values in decision-making processes makes it more difficult to plan for sustainable land use and water resources management in the tropics. To contribute towards this monitoring and knowledge gap, this dissertation examines the potential of using participatory approaches in monitoring and valuation of WES. First, a comprehensive systematic review based on a synthesis of 71 scientific studies on citizen science in the context of hydrology was conducted to understand the scope and future prospects of integrating citizen science in hydrological monitoring. There has been a significant growth in the application of state-of-the art approaches of citizen science in hydrology over the past decade, with successful implementation and contributions especially to water quality assessments. In the second part of this dissertation, a contributory citizen science water quality and level monitoring network was established at six sites within the Sondu-Miriu River Basin, a mesoscale catchment in South-West Mau, Kenya with the aim to evaluate suspended sediment dynamics. A two-year dataset generated by citizen scientists revealed that suspended sediment concentrations were highest in agricultural landscapes, and lowest in sub-catchments with high forest cover, indicating the impacts of land use patterns on suspended sediment dynamics in the region and the direct role of forested areas in providing important services in term of sediment regulation that affect the society. Data on suspended sediment and water level collected by citizen scientists using turbidity tubes and water level gauges validated with data from automatic stations at two sites, revealed a similar temporal pattern. Finally, the third part of the dissertation focusses on socio-cultural valuation of WES based on a household survey. Water provisioning, climate regulation, water purification, water regulation, and groundwater recharge were perceived as the top five most important services for societal well-being and highly vulnerable. The findings of this dissertation show that citizen science is a promising, cost-effective participatory strategy that can support hydrological monitoring and research in remote tropical mountainous regions. Additionally, socio-cultural valuation can be a useful tool for identifying relevant ecosystem services. This can help guide the prioritization and design of more effective and locally adaptive management strategies that promote sustainable livelihoods and environmental sustainability.

Table of contents

List of tables	VII
List of figures	VIII
1. Extended Summary.....	1
1.1 Introduction.....	1
1.2 Objectives	6
1.3 Methodology.....	8
1.3.1 Review of citizen science in hydrology	8
1.3.2 Monitoring and valuation of WES in Mau Forest Complex, Kenya.....	9
1.3.2.1 Study area	9
1.3.2.2 Citizen science monitoring program.....	13
1.3.3 Household survey	16
1.4 Summary of results	18
1.4.1 Objective 1: Citizen science in hydrology	18
1.4.2 Objective 2: Spatial and temporal patterns in water quality and quantity.....	21
1.4.3 Objective 3: Socio-cultural values of WES.....	24
1.5 Implications and recommendations for future research.....	27
2. Citizen science in hydrological monitoring and ecosystem services management: State of the art and future prospects	31
2.1 Introduction.....	31
2.2 Overview.....	33
2.2.1 What is citizen science?	33
2.2.2 Early developments	34
2.2.3 Successful examples.....	35
2.3 Citizen science in hydrology.....	35

2.4	Methodology.....	37
2.5	Results and discussion	39
2.5.1	Overview of the reviewed articles.....	39
2.5.2	Scope of monitoring	40
2.5.3	Spatial and temporal extent	41
2.5.4	Citizen involvement and training	42
2.5.5	Information flows and communication channels	43
2.5.6	Water level and discharge	44
2.5.7	Precipitation.....	45
2.5.8	Water quality	46
2.5.9	Social media	49
2.5.10	Data credibility and application of citizen science data	50
2.5.11	Data transmission	51
2.5.12	Future developments	52
2.6	Conclusions.....	52
3.	Monitoring of suspended sediments in a tropical forested landscape with citizen science	59
3.1	Introduction.....	59
3.2	Materials and Methods.....	61
3.2.1	Catchment description.....	61
3.2.2	Citizen science recruitment and training	63
3.2.3	Field data acquisition and transmission.....	66
3.2.4	Analysis of level of engagement	67
3.2.5	Calibration	68
3.2.6	Data validation	69
3.2.7	Quality control and assurance	70

3.2.8	Statistical analyses.....	70
3.3	Results and Discussion	71
3.3.1	Relationship between turbidity and suspended sediment concentration	71
3.3.2	Validation of citizen science data.....	72
3.3.3	Participation rate.....	75
3.3.4	Method of engagement.....	79
3.3.5	Spatial and temporal trends of suspended sediment concentrations	80
3.4	Conclusion	84
4.	Valuation of water-related ecosystem services: Implications for sustainable management of tropical montane forests	87
4.1	Introduction.....	87
4.2	Materials and methods	90
4.2.1	Study area	90
4.3	Household survey	92
4.3.1	Survey design	92
4.3.2	Household selection	94
4.3.3	Implementation.....	95
4.4	Data analysis.....	95
4.5	Results.....	96
4.5.1	Socio-demographic characteristics.....	96
4.6	Socio-cultural valuation of WES	97
4.6.1	Perceived roles of forests in provisioning of WES	97
4.6.2	Perceived importance of WES	99
4.6.3	Prioritized WES.....	100
4.6.4	Linkages between importance of WES and perceived trends	101

4.6.5	Socio-demographic and environmental variables on the perception of ecosystem services.....	102
4.7	Willingness to pay	106
4.8	Discussion.....	107
4.8.1	Socio-cultural values of WES provided by forests	107
4.8.2	Vulnerability of ecosystem services.....	108
4.8.3	Contrasting perceptions of WES: Does proximity to the forest matter?.....	110
4.8.4	Factors influencing the perceptions of WES.....	111
4.8.5	Potential for payment for ecosystem services	112
4.9	Conclusion and management implications	112
	References	125
	Acknowledgement.....	149
	Declaration	151

List of tables

Table 2.1	Data extracted from the articles in the final study pool.	39
Table 2.2	Citizen science-based water monitoring in Sondu Catchment, Kenya.	48
Table 2.3	Contribution of citizen science in hydrology through social media.....	49
Table 3.1	Catchment characteristics of the monitoring subcatchments in the Sondu-Miriu river basin, Kenya.	65
Table 3.2	Diversity in gender, age, education level and distance to the monitoring station of the 19 trained citizen scientists.....	66
Table 3.3	Demographics of the 19 trained citizen scientists in relation to the level of engagement based on the total number of valid measurements contributed over the entire monitoring period between September 2017 to September 2019 (Very active: >100, active: 50–100, moderately active: 20–50, less active: < 20).	77
Table 4.1	Characteristics of the sampled households across the three zones under study, in the South-West Mau.....	94
Table 4.2	Socio-demographic and environmental characteristics of the households. For continuous variables mean±standard deviation are provided, for categorical values the number of respondents in each category and the corresponding percentage relative to the total number of participants in each zone. NA values have been excluded and as a consequence, percentages do not always sum to 100%. The significance level is indicated as follows: * p<0.05, ** p<0.01 and *** p<0.001.	96
Table 4.3	Perceived importance of provisioning, regulating and cultural ecosystems services across the zones (Mean ± SD; the different letters indicate significant differences among the zones).....	99
Table 4.4	Logistic regression results showing the socio-economic and environmental factors influencing the perceived importance of WESs in the South-West Mau. Coefficients from the model with standard errors (in parentheses) are provided. The significance level is indicated as follows: * p<0.05, ** p<0.01 and *** p<0.001	104

List of figures

Figure 1.1	Cascade model showing stepwise hydrological ecosystem services provision by the forests and the relationship between the social-ecological systems. Adapted from Carvalho-Santos et al. (2014) and Haines-Young & Potschin. (2010)7
Figure 1.2	Maps of the study area in the Sondu-Miriu river basin: (A) location of the study area showing the network of the citizen science stations for water level and water quality monitoring and automatic stations used for validation, as well as the three areas (Lower, Middle and Upper) where the household survey was carried out, and (B) land use types across the Sondu-Miriu basin. 10
Figure 1.3	Examples of the land use in the study area: (A) Natural forest, and commercial tea plantations with woodlots of Eucalyptus species, (B) Mosaic of smallholder tea farms, croplands and small woodlots, (C) Smallholder agriculture area with crop fields, pasture lands, urban centre and degraded riparian zones, (D) Erosion along river banks in the smallholder agriculture area due to animal access. 13
Figure 1.4	(A) Citizen science water quality and water level monitoring station, installed with water level gauges and a signboard with instructions on how to collect and submit water level data, (B) citizen scientists taking turbidity measurements using turbidity tubes, and (C) scale on the turbidity tube. 15
Figure 1.5	Geographical distribution of the citizen science studies and scope of monitoring (Njue et al., 2019). 18
Figure 1.6	Time series of suspended sediment concentration and observed water level transmitted by citizen scientists and measured by automated stations at sites (A) KUR and (B) CMT in the Sondu-Miriu river basin over the monitoring period between September 2017 to September 2019. Adapted from Njue et al. (2021)...24
Figure 1.7	Perceived importance and trends of WES among the three zones, determined by altitudinal position relative to the forest in the South-West Mau, Kenya based on household survey (n=217). Significant differences in perceptions of importance among zones are identified with different letters. The symbols indicate the increasing or declining perceived trends for the water-related ecosystem services.26

Figure 2.1	Typology of citizen science-based program showing levels of involvement and influence. After Bonney et al. (2009) and Shirk et al. (2012).....	36
Figure 2.2	Overview of review methodology.....	39
Figure 2.3	Citizen science-based studies in hydrological research between 2001-2018 (n=71).	40
Figure 2.4	Distribution of studies and scope of hydrological monitoring per country.....	41
Figure 2.5	(a) Spatial and (b) temporal scales of citizen science projects.....	42
Figure 3.1	Map of the study area showing (A) elevation (SRTM digital elevation model 30 m resolution; USGS, 2000), citizen science stations and automatic water monitoring network and (B) land use within the Sondu-Miriu River Basin.....	62
Figure 3.2	Relationship between suspended sediment concentrations (SSC) (mg L^{-1}) and turbidity measurements using (A) turbidity tubes (Tu) at the six monitoring sites and (B) automated station (AS) at two monitoring sites (KUR and CMT) in the Sondu-Miriu river basin, Kenya.	72
Figure 3.3	Comparison of the suspended sediment concentration (mg L^{-1}) calculated based on calibrated turbidity measurements collected by citizen scientist and automated stations between September 2017 and September 2019 for (A) KUR and (B) CMT in the Sondu-Miriu river basin, Kenya. The dashed line represents the 1:1 relationship.	74
Figure 3.4	Relative difference between citizen scientists measured SSC (mg L^{-1}) using turbidity tubes and the SSC (mg L^{-1}) obtained from turbidity data recorded by an <i>in situ</i> UV-Vis sensor at the corresponding automated station for (A) KUR and (B) CMT. The grey boxplots show the relative difference for all participants at a given site. Participant number corresponds to the participant ID shown in Figure 3.6. ..	74
Figure 3.5	Participation of citizen scientists in data collection and cumulative for the monitoring period from September 2017 to September 2019 in the Sondu basin, Kenya: (A) total number of measurements per month B) Lorenz curve representing inequality in data collection by all participants.....	76

Figure 3.6 Temporal distribution of data collected by all participants at all the monitoring sites for the monitoring period from September 2017 to September 2019. Level of engagement is based on the number of measurements (*n*) contributed per month.78

Figure 3.7 Variation in suspended sediment concentrations across the monitoring sites for the sampling period September 2017 to September 2019. The lower and upper lines of the boxplots correspond to the 1st and 3rd quantile (Q_1 and Q_3), respectively, while the solid horizontal line inside the box represents the median value (Q_2). The lower and upper whiskers show the minimum and maximum values within 1.5 times the interquartile range, while the circle markers represent extreme values outside of that range. Significant differences among sites are indicated with different letters ($P<0.05$).81

Figure 3.8 Time series of suspended sediment concentration and observed water level transmitted by citizen scientists at five sites and measured by automated stations at sites KUR and CMT in the Sondu-Miriu river basin over the monitoring period between September 2017 to September 2019.83

Figure 4.1 Conceptual framework linking forest ecosystems with livelihood and well-being through the flow of water-related ecosystem services.90

Figure 4.2 Map of the study area showing locations of the sampled households in the South-West Mau, Kenya.91

Figure 4.3 Perception of the role of forests in providing various WES (left) and the mean score for each WES (right) in the South-West Mau ($n=217$). The Y-axis presents individual WES per zone (L=lower, M=middle, and U=upper zone) and X-axis denotes the proportion of participants.98

Figure 4.4 Comparison of perceived importance of WES and trends between the three zones ($n=217$). Significant differences in perceptions of importance among zones are identified with different letters. If no letters are provided, there were no significant differences among zones. The symbols indicate whether participants in each zone perceived a generally increasing or declining trend for the WES, respectively... 100

Figure 4.5 Scatter plots of the perceived importance (Y-axes) and trends of water-related ecosystem services (X-axes) based on participants’ responses across the three zones in the South West Mau (n=217). The quadrants indicate perceptions of WES as very important-decreasing (critical), very important-increasing (important but not vulnerable), not important-decreasing (vulnerable but not important), and not important-increasing (less relevant). The five most important WES are represented in different colors and ranked from the most to least important based on the number of times they were mentioned by participants. 101

Figure 4.6 Proportion of participants showing willingness to pay for WES (a) and reasons for those not willing to pay (b)..... 106

1. Extended Summary

1.1 Introduction

Forests are among the most valuable ecosystems that provide a wide range of ecosystem services, of which hydrological or water-related ecosystem services (WES) are considered the most fundamental for human well-being and sustainable development (Brauman et al., 2007). Forests are well-known for their role in regulating the hydrological cycle, water quantity, quality and timing of discharge (Brauman et al., 2007; Bruijnzeel, 2004; Calder, 2002; Ellison et al., 2017). They also provide protective functions against soil erosion and flooding and offer cultural benefits such as recreational and spiritual experiences (Brauman et al., 2007). However, given the growing proportion of the population depending directly on natural forest resources for their livelihoods and the changing climate, these ecosystems are under increasing pressure from land use change, particularly to agriculture (FAO, 2020). The hydrological effects of land use and climate change are often reflected in spatial and temporal changes in surface and groundwater quality, water flow regimes, intensification of soil erosion, sedimentation and extreme hydrological events, that ultimately have negative impacts on water resources and quality of life (Caldas et al., 2018; Pacheco and Sanches Fernandes, 2016; Truong et al., 2018). With water demand projected to increase by 20-30% over the next two decades (Burek et al., 2016) and water scarcity expected to affect two-thirds of the world's population by 2025 (FAO, 2013), this poses a significant bottleneck to achieving sustainable development and poverty reduction as enshrined in the 2030 agenda (United Nations, 2015).

Although the hydrological role of forest is well documented, only 12% of the world's forests are managed with water conservation as a primary objective (Springgay et al., 2021). This could be an indication that the WES provided by forests are often undervalued and not fully taken into account in conservation policies and decision-making processes (Hohenthal et al., 2015; Springgay et al., 2021). Yet, the sustainable management of forested landscapes, while balancing trade-offs from other land use decisions designed to meet immediate societal needs for provisioning services such as food, fibre, and timber, remains a major challenge (Grizzetti et al., 2016). The forest ecosystems and human societies are interconnected through intricate social-ecological systems that are characterized by many interactions and feedbacks between different users and landscapes (Scholte et al., 2015). Thus, to support the evidence-based decision-making needed for landscape planning

and sustainable management of forested watersheds this requires quantification of WES of forest using biophysical indicators such as water quality and quantity, as well as socio-cultural values indicators. This is essential because the state and supply of ecosystem services depends not only on ecosystems properties (supported by underlying biophysical structures and processes), but also on the societal demand for these services, which are strongly shaped by the socio-cultural values (Martín-López et al., 2014; Villamagna et al., 2013). The socio-cultural values placed upon ecosystems and their associated services are context-and place specific, and how these services are perceived has the potential to influence ecosystem use and management decisions (Scholte et al., 2015). As a consequence, this can result in pressures or management decisions that produce feedback mechanisms that shape the organization of ecosystems (structures, processes and functions) and ecosystem service provisioning, with consequences for human well-being (Haines-Young and Potschin, 2010). For instance, depending on how people value the provision of clean water by forests, this may influence their willingness to actively support conservation initiatives or pay for ecosystem services to ensure sustained supply and quality of water.

From a biophysical perspective, regular and long-term monitoring of water quantity and quality at multiple spatial and temporal scales can provide comprehensive hydrological datasets and information fundamental for sustainable water resources management. Such data can be used to characterize catchment behaviour, quantify human impacts on hydrological and ecosystem responses, and understand trends for improving predictive models for future projections (Ochoa-Tocachi et al., 2018; Tetzlaff et al., 2017). However, such datasets are not widely available, in part because robust and representative hydrological monitoring systems do not exist in many parts of the world, due to inadequate infrastructure and technical capabilities (Buytaert et al., 2016; Hannah et al., 2011; Nardi et al., 2020). Besides, the costs associated with establishing a dense hydrometric monitoring network are prohibitive, thus limiting most regional and national monitoring programs from conducting regular and long-term hydrological monitoring at scale, especially in developing countries (Buytaert et al., 2014; Lowry and Fienen, 2013; Mazzoleni et al., 2017).

While advanced approaches such as remote sensing and hydrological models are increasingly being used to fill this data gap, they are still limited by spatial and temporal resolutions, require detailed ground-based observations for validation and substantial training to operate (Ochoa-Tocachi et al., 2018; Starkey et al., 2017). High-frequency and long-term hydrological data are increasingly

obtained using fixed automatic monitoring systems, owing to recent advances in *in situ* sensor technology, but their application to a large number of monitoring sites and use in tropical regions is relatively very low (Jacobs et al., 2018). Besides the high cost of installation, fixed automated monitoring requires engagement of technical personnel, routine maintenance and security as they are prone to wear, vandalism and theft (Gomani et al., 2010). This can be logistically challenging and costly, which is a barrier for implementation in regions where there are limited financial resources (Danielsen et al., 2005; Mazzoleni et al., 2017). Recently, participatory approaches such as citizen science have gained attention as a cost-effective alternative for long-term monitoring of local and global environmental change, particularly in the fields of ecology, biogeography and environmental sciences (Dickinson et al., 2012; Johnson et al., 2014; Silvertown, 2009).

Citizen science is a participatory approach that seeks to involve the general public in the scientific research process such as defining research design, collection, analysing, interpretation and dissemination of data, often in collaboration with or under the guidance of scientists (Bonney et al., 2009a). There is a growing evidence of the potential of citizen science to reduce monitoring costs and provide valuable and reliable datasets with improved spatial and temporal coverage that would otherwise not have been possible (Bonney et al., 2009a; Silvertown, 2009). These data can be useful to fill scientific data gaps and for the calibration and testing of hydrological models, especially in data-scarce regions (Weeser et al., 2019). Such models can, for example, be used to investigate future land use and climate scenario or make reliable projections for developing water management strategies. At the same time, citizen science provides opportunities for collaboration with local people which can foster empowerment, learning and public scientific literacy as well enhance a more polycentric governance and natural resources management (Bonney et al., 2009a; Buytaert et al., 2016). As a result, the citizen science concept is now becoming integrated in policies and decision-making processes (Haklay, 2015). Current technological developments have given rise to robust, simple and low-cost monitoring devices (Newman et al., 2012). This provides unprecedented opportunities for data collection using citizen science in the field of hydrological sciences to advance biophysical quantification of WES (Buytaert et al., 2014; Zheng et al., 2017).

Participatory approaches are also crucial to understand the socio-cultural values of WES. Integration of socio-cultural values in the assessments of ecosystems services has recently gained policy relevance as a powerful way to better inform decision-making processes that support

sustainable natural resources management (de Groot et al., 2010; Scholte et al., 2015). A socio-cultural approach to value hydrological ecosystem services provided by forests can help in the identification and prioritization of relevant services, based on societal demand and preferences (Schröter et al., 2017; Vollmer et al., 2022). It also reveals the underlying socio-ecological interactions that can help to visualise potential trade-offs and synergies which is essential in the management of ecosystems to avoid social conflicts (Martín-López et al., 2014). Such information would not only serve as a basis for developing locally adaptive monitoring and management approaches, but also increase the effectiveness and legitimacy of management decisions (Velasco-Muñoz et al., 2022).

Many low-income countries lack the resources for comprehensive biophysical monitoring and socio-cultural valuation of WES. As a consequence, there is not sufficient data and knowledge to inform sustainable forest and water management in regions that are strongly affected by land use and climate change, leaving a lot of people extremely vulnerable to the impacts of these changes. This dissertation aims to address this knowledge gap by evaluating participatory approaches to quantify biophysical and socio-cultural values of WES, using the Mau Forest Complex in Kenya as a case study. The Mau Forest Complex is considered one of the most important water towers in Kenya. It is also the largest remaining indigenous tropical montane forest in East Africa, providing freshwater to over 5 million people living downstream (UNEP, 2008). However, the Mau Forest is under constant threat of conversion to smallholder agriculture and settlements (Brandt et al., 2018; Jebiwott et al., 2021). As a result, about 25% of the Mau Forest Complex, i.e. approximately 699 km² of forest area, was lost between 1984 and 2020, disrupting the hydrological services at local level (Jebiwott et al., 2021). Significant hydrological changes are being observed in rainfall patterns, flow regimes and groundwater recharge (Mango et al., 2010; Mati et al., 2008; Mwangi et al., 2020), as well as in water quality deterioration because of high nutrient and sediment levels in streams (Jacobs et al., 2017; Stenfert Kroese et al., 2020b). The adverse impacts of these changes are felt most at the local level, where people are directly dependent on these resources and services for their livelihood and well-being (Acharya et al., 2019; Dorji et al., 2019; Gebrehiwot et al., 2014). While biophysical assessments of WES are essential for quantifying ecological values, many parts of the catchment remain ungauged or poorly gauged (Kundu and Olang, 2008; Weeser et al., 2018), and existing studies lack information on socio-cultural values (Langat et al., 2021). As a result, there is scarcity of comprehensive datasets, as well as inadequate consideration of important

social perspectives of ecosystem service values in management decisions, hampering effective water resources and watershed management.

This study applies the ecosystem services approach embedded in the cascade framework adapted from Carvalho-Santos et al. (2014) and Haines-Young & Potschin (2010) (Figure 1.1). The cascade illustrates the stepwise provision of WES by forests linking ecosystem properties to functions and services (supply side), the resulting contributions to human well-being (i.e., benefits that people experience) and value (demand-side), as well as feedback mechanisms generated through human pressures and management decisions (de Groot et al., 2010; Haines-Young and Potschin, 2010). For example, forest biophysical structures (i.e., vegetation density and root system) promote forest soil porosity, thus enhancing the infiltration and surface runoff processes. These processes underpin the capacity of forest ecosystem (function) to store, regulate flows, trap sediments, and break down pollutants. These functions provide ecosystems services such as water flow regulation and water purification, which translates into improved water availability and less sediments in rivers thus resulting in a reliable supply of clean water for domestic uses that contributes to aspects of human well-being (benefits). The benefits can be valued using biophysical, socio-cultural or economical terms (value). The framework thus provides a way to quantify how forest ecosystems support the provision of WES and how society benefits and values these services from a socio-ecological perspective.

Within the adapted framework shown in Figure 1.1, this dissertation focuses on quantifying the biophysical and socio-cultural values of WES using participatory approaches. For biophysical assessment, this study focused on water levels and suspended sediment concentrations in river networks as indicators for ecosystem function and the services ‘water supply’ and ‘erosion prevention’ (Carvalho-Santos et al., 2014). Water levels and suspended sediment measurements were monitored using citizen science (Njue et al., 2021). Perceived benefits and values attached to different WES were assessed using socio-cultural indicators. This would not only help to understand the spatial and temporal dynamics of water quantity and quality provision but also the demand of WES from the society and their willingness to contribute to their management thereof. In addition, this contributes to the existing knowledge of how WES assessments can be enhanced through participatory approaches. In particular, this study provides insights into the relevance of

citizen science in hydrology and the integration of socio-cultural valuation in the assessment of ecosystem services.

1.2 Objectives

The main aim of this dissertation is to assess the potential of participatory approaches in monitoring and valuation of WES in the Mau Forest Complex. This aim is subdivided into three objectives, which will be addressed in three separate chapters in this dissertation:

Objective 1: To assess the application and contribution of citizen science in hydrological monitoring and ecosystem services management based on the current literature (Chapter 2);

Objective 2: To demonstrate the use of citizen science to assess spatio-temporal suspended sediments dynamics as an indicator for the ecosystem service of ‘erosion prevention’ (Chapter 3);

Objective 3: To evaluate the socio-cultural values of WES provided by forests and their implications for local forest and water resources management (Chapter 4).

In addition to advancing scientific knowledge on the potential of citizen science in hydrology and its application to socio-cultural valuation in ecosystem services studies, the knowledge gained from this study can also contribute to designing incentive-based mechanisms that promote co-management of water and forest resources and land use planning as well as sustainable livelihoods.

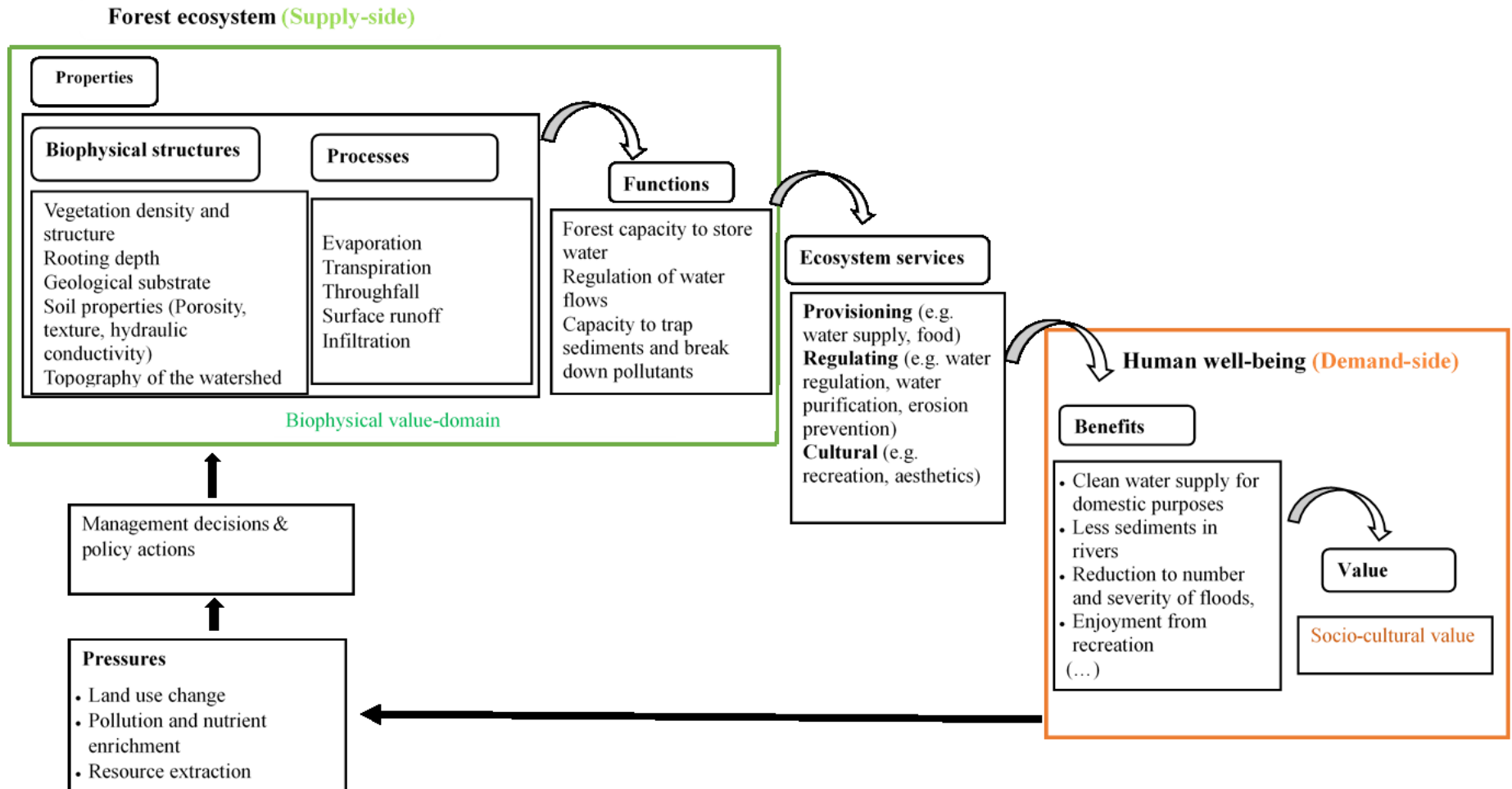


Figure 1.1 Cascade framework illustrating stepwise WES provision by forests and the linkages between the biophysical (supply-side) and social systems (demand- side) via the flow of WES, and the feedback mechanisms resulting from pressures and management decisions. Adapted from Carvalho-Santos et al. (2014) and Haines-Young & Potschin (2010).

1.3 Methodology

1.3.1 Review of citizen science in hydrology

To evaluate the potential and prospects of citizen science in hydrological sciences, a comprehensive systematic review of recent empirical studies was conducted (Chapter 2). The literature search was conducted using Google Scholar and Web of Science bibliographic databases, following a multistep procedure. The first step aimed at identifying empirical research using citizen science approaches in hydrology with a focus in water quantity, water quality and/or precipitation monitoring. All identified literature published in English language between 2001 and 2018, in the form of full articles in peer-reviewed academic journals, book chapters, program websites, and technical reports were considered. Boolean search strings were used to construct search queries using keywords with related terms including ("citizen science" OR "participatory monitoring OR "participatory sensing" OR "human sensing" OR "human computing" OR “crowdsensing” OR "crowd sensing" OR “crowd sourcing” OR "crowdsourcing" OR "public participation" OR “community based monitoring” OR "volunteer based monitoring") AND (rainfall OR precipitation OR "water level*" OR "water quantity" OR "water quality"). To broaden the search, the backward and forward reference method were applied which involved examining and reviewing papers cited in the articles selected in the first step. The full search process yielded 281 records.

Subsequently, these records were further screened to extract empirical studies that contained relevant evidence about the involvement of citizen scientists in the hydrological research process, and those that explicitly reported on the methodology and approaches used in the research process, as well as on the quantitative analysis of the data generated by citizen scientists. The selection criteria were based on the inclusion-exclusion approach described by Talavera et al. (2017), which included review of abstracts, reading full articles, and quality analysis. Studies with no clear active involvement of citizen scientists and those that used synthetic data to imitate citizen science were deliberately excluded from the criteria.

Through the iterative search process, 71 empirical studies were identified for full-text review and quantitative synthesis, which formed the basis for the detailed literature analysis of this study. In doing so, the aim of this review was to assess the concept and current scope of citizen science in hydrological sciences. This was followed by evaluating the design and applications of citizen science considering nature, structure and level of engagement, to understand how effectively citizen

science approaches have been implemented in practice, which was complemented by case studies. This review also explored the implications, motivation, challenges, data quality control measures, identifying key factors for success and opportunities in the integration of citizen science in hydrology for future research. The study aimed to answer two research questions: (1) How is citizen science contributing to hydrological research, and (2) What is the future scope of citizen science in hydrology?

1.3.2 Monitoring and valuation of WES in Mau Forest Complex, Kenya

To further explore the potential for participatory approaches in the assessment of WES, a ‘contributory’ citizen science-based monitoring program was implemented and a household survey was conducted for biophysical and socio-cultural valuation of WES, respectively (Chapter 3 and Chapter 4).

1.3.2.1 Study area

Biophysical monitoring of water resources was carried out in the Sondu-Miriu river basin in western Kenya. The basin is located between latitudes 0°17' and 0°22' south and longitudes 34°45' and 35°45' east, covering an area of approximately 3,470 km² (Figure 1.2). It forms the fourth largest Kenyan river basin draining into Lake Victoria (Masese et al., 2012). The river originates from the South-West Mau, the largest block in the Mau Forest Complex. The area is characterised by undulating topography, generally sloping from east to west, with elevations ranging from 2,900 m a.s.l. at the top of the Mau Escarpment to about 1,140 m a.s.l on the shores of Lake Victoria.

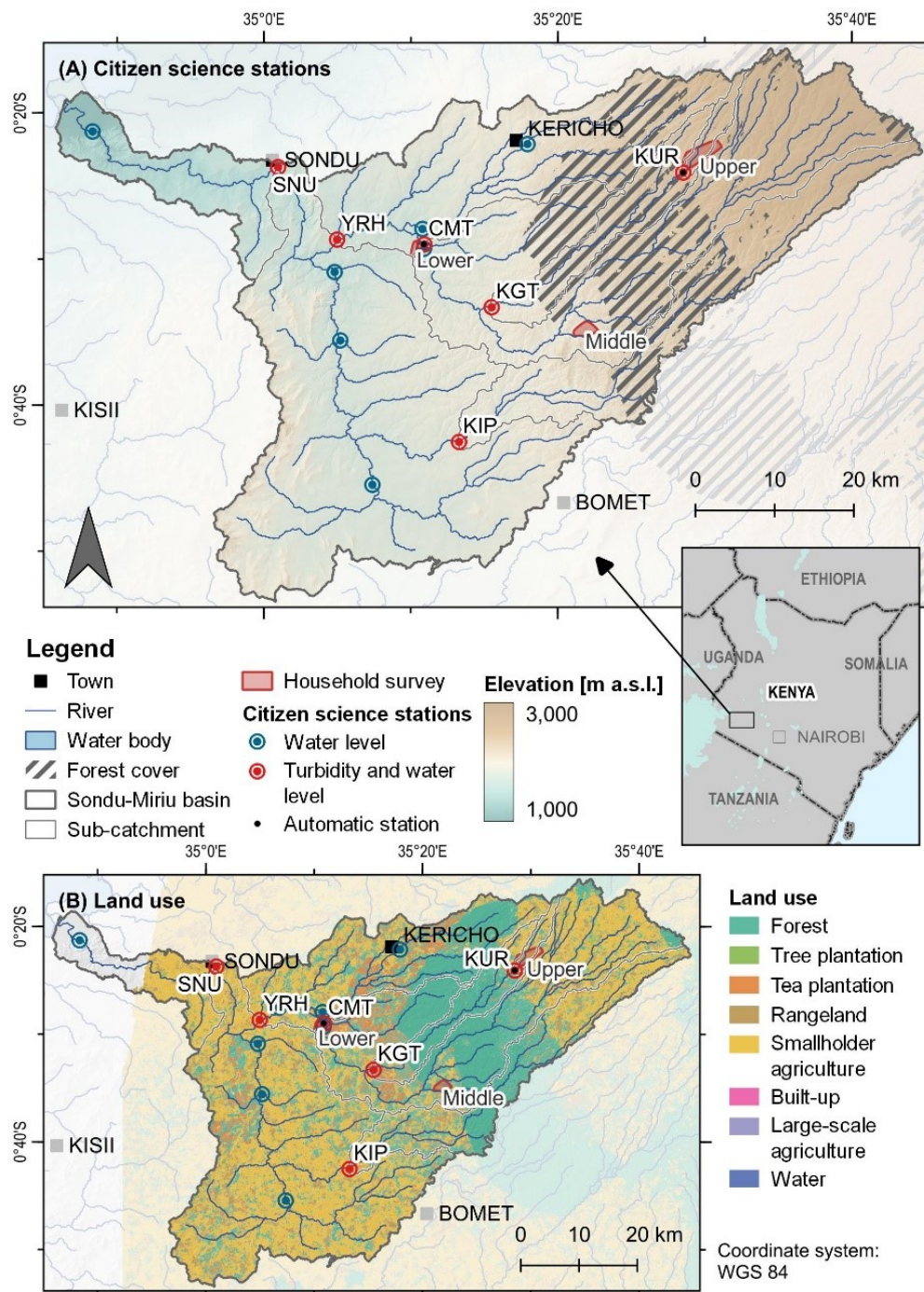


Figure 1.2 Maps of the study area in the Sondu-Miriu river basin: (A) location of the study area showing the network of the citizen science stations for water level and water quality monitoring and automatic stations used for validation, as well as the three areas (Lower, Middle and Upper) where the household survey was carried out, (B) land use types across the Sondu-Miriu basin with acronyms of the six monitoring sites.

The area is characterized by diverse land use types (Figure 1.2B; Figure 1.3). The upper part is located above 2,400 m a.s.l. in the north-eastern region and is dominated by smallholder agriculture, where food crops such as maize, potatoes and cabbages are grown for subsistence on small farms averaging less than 2 ha, and livestock kept as an alternative source of income. Woodlots of exotic tree species consisting of mainly *Eucalyptus* and *Cypress* species intersperse with croplands. The natural forest covers the central part, which is part of the South-West Mau forest block, classified as an Afromontane mixed forest (Kinyanjui, 2011). It transitions from a broad-leafed evergreen above 1,950 m a.s.l. to a thicket of bamboo mainly *Arundinaria alpine* and grassland vegetation at about 2,300 m a.s.l. (Jacobs et al., 2017; Kinyanjui, 2011). The eastern upland side of the South-West Mau was largely affected by forest excisions recorded in 2001 where 27.3% (22,797 ha) of the forest area were excised for settlement and farmland (UNEP, 2008). The intensity of forest disturbance resulting from firewood extraction, charcoal burning, livestock grazing, forest fires and illegal logging is also greatest near the forest edge at higher elevations (Brandt et al., 2018). This has led to the establishment of tea buffer zones along the eastern and western forest boundaries, not only to protect the forest from further encroachment and deforestation, but also to provide alternative livelihoods for the communities adjacent to the forest (NTZDC, 2016).

From the edge of the forest to the west (below 2,100 m a.s.l), the land opens up to a rich upland agricultural area of about 20,000 ha which is dominated by commercial tea plantations alternating with exotic tree plantations consisting mainly of *Eucalyptus* spp. and *Cypress* spp., usually used as firewood for tea processing (Figure 1.3A). The region is the largest producer of tea in Kenya, which is the third largest foreign exchange earner in the country and a major contributor to local livelihoods (Kenya Water Towers Agency, 2020). The riparian forests adjacent to the commercial tea plantations are well maintained and have dense native vegetation that act as a buffer zone along rivers with a maximum width of 30 m (Njue et al., 2016). The certification programs in the tea sector encourages large and small scale tea producers to adopt sustainable agriculture practices such as conserving and restoring forests, implementing boundary planting and restoration with native species (Milder et al., 2015). Adjacent the commercial tea plantations, the area transitions to a landscape characterised by a mosaic of tea on small farms (<1 ha), annual food crops parcels, fodder crops, dairy farming, and small portions of *Eucalyptus* and *Cypress* woodlots (Jacobs et al., 2017; Milder et al., 2015).

The lowland areas towards Sondu town (<1,800 m a.s.l.) are characterised by a mixed land use dominated by smallholder agriculture, pastureland and more rural, peri-urban and urban settlements with high population and better access to the market (Figure 1.3C). The crops grown in this region are tea, bananas, coffee, maize, beans, sunflower and pineapples depending on the sub-zone. In smallholder agriculture areas, most of the natural vegetation along the riparian zones and on the farms has been replaced with exotic trees such as *Eucalyptus* spp. This is due to the increased demand for Eucalyptus as it is the preferred source of timber for construction and fuel for tea processing in the region. In some areas, encroachment of floodplains for cultivation due to fertile soils and frequent access to rivers by livestock and people further contribute to the degradation of the riparian zones and riverbank erosion (Figure 1.3C-D).

The annual rainfall distribution of the study area is characterised by bi-modal rainfall pattern which is influenced by the Intertropical Convergence Zone (ITCZ), and modified by local altitudinal differences (Camberlin, 2018). The long rainy season occur between April and July, the short rains between October and December, followed by a dry season from January to February with monthly rainfall <75 mm month⁻¹ (Jacobs et al., 2017). The area also experiences intermediate rains between the long and short rainy seasons, such that the area is often characterised by one long cropping season. Precipitation, temperature and evapotranspiration within the study area vary with altitude. The uplands zone around the central part of Kericho, where tea is grown, receive the highest annual rainfall of about 2,000 mm yr⁻¹ while the lowland zones receive about 1,000 mm yr⁻¹ (Obati, 2007). The mean annual temperature range from 16°C in the upland areas to 22°C at lower altitudes, with June and July being the coldest months with minimum temperatures, and maximum temperatures observed in February during the dry season (Stephens et al., 1992; Vuai et al., 2012). The potential evapotranspiration rate increases from 1,400 mm yr⁻¹ to 1,800 mm yr⁻¹ from higher elevations (>1,900 m a.s.l.) to lower elevations (1,800 m a.s.l.) (Weeser et al., 2019).

The study area is dominated by deep (>1.8 m), fine textured and well-drained volcanic loamy soils with humic topsoil, classified as humic Nitisols (Jaetzold and Schmidt, 1983; Sombroek et al., 1982).

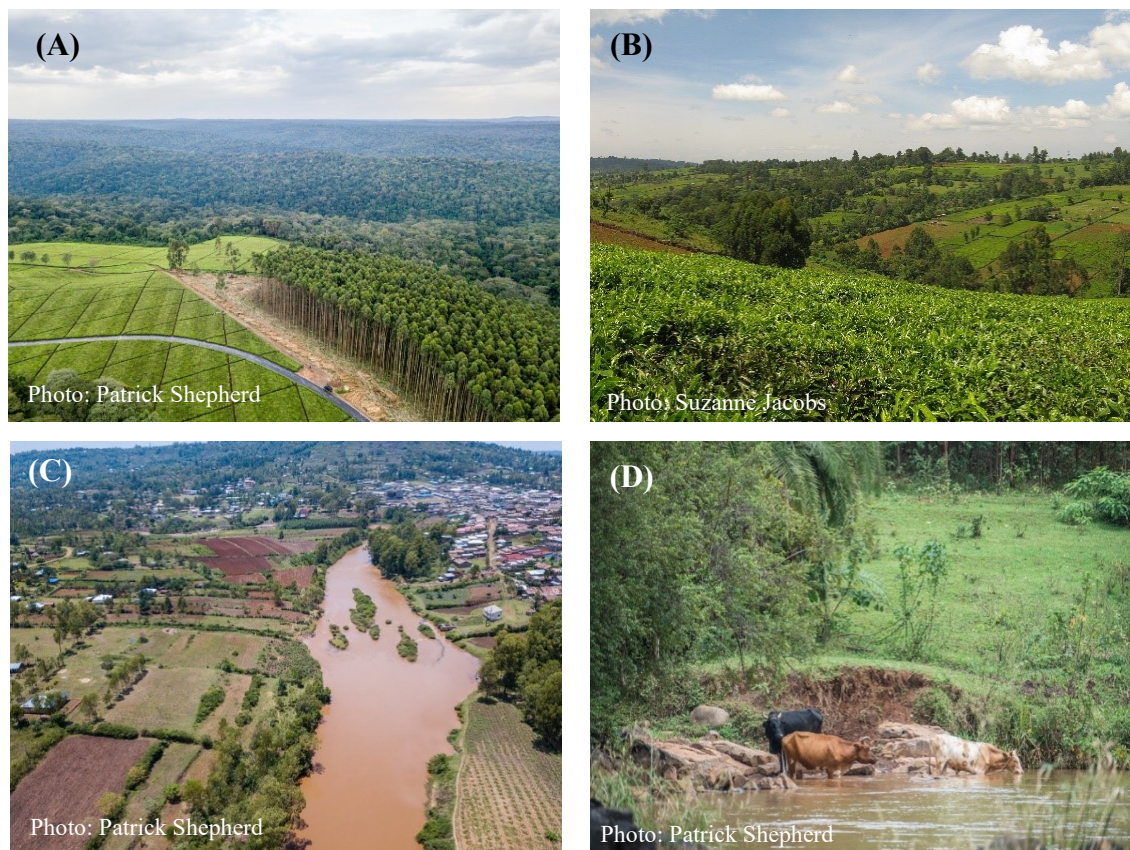


Figure 1.3 Examples of the land use in the study area: (A) Natural forest, and commercial tea plantations with woodlots of *Eucalyptus* spp, (B) Mosaic of smallholder tea farms, croplands and small woodlots, (C) Smallholder agriculture area with crop fields, pasture lands, urban centre and degraded riparian zones, (D) Erosion along river banks in the smallholder agriculture area due to animal access.

1.3.2.2 Citizen science monitoring program

For the citizen science based monitoring program, a monitoring network of six sites was established (Figure 1.2), considering among other factors, accessibility and proximity to potential citizen scientists (Chapter 3). The selected sites were among 13 sites that were established earlier for a citizen science water level monitoring program, all of which had water level gauges installed (Weeser et al., 2018). In each site, the citizen scientists were trained to monitor turbidity and water level. To assess the quality of citizen science-based generated data, two sites were located next to automatic monitoring stations equipped with a radar sensor (VEGAPULS WL61, VEGA GrieshaberKG, Schiltach, Germany) and a UV/Vis spectrometer probe (spectro::lyser, s::can

Messtechnik, Vienna, Austria) that measured water level and turbidity, respectively, at 10-min interval (Jacobs et al., 2018).

At the beginning of the project, sensitization meetings were organized at each site with members of the local community to promote the project idea and identify potential participants who would be willing to participate and contribute to the water level and quality monitoring program. In addition, the sensitization meetings also included interactive focus group discussions to understand local knowledge and perceptions on water quantity and quality issues. The meetings also provided an opportunity for capacity building and creation of awareness on the importance of community-based monitoring programs in generation of data for research, policy, conservation and land management at local level. A total of 19 citizen scientists (~3 participants per site) were recruited and trained during a one-day training event organized at each site. During the training, citizen scientists were introduced to the water sampling and water quality measurement procedures, reading of water levels, data recording and submission, and quality control. Each participant was equipped with the necessary material for the monitoring activity, including a turbidity tube, a water-sampling device made from locally available materials, and a training manual with a set of instructions on water level and turbidity monitoring procedures, with pictures and examples for better presentation and understanding. The manual was written in both Swahili and English to reduce language barriers.

Turbidity was used as a surrogate for suspended sediment concentrations, and was measured using a modified Wagtech turbidity tube (Total Ex-Works Wagtech Projects, Thatcham UK). The citizen scientists performed the turbidity measurements, by pouring small amounts of the river water sample in the turbidity tube until the pattern fixed on the bottom of the tube could no longer be seen when viewed from above. To estimate the turbidity value, the citizen scientist then read the value on the scale on the side of the tube corresponding to the level of the water column in the tube. In cases where the water level mark was between two scales, turbidity was estimated by taking a fractional value between the scales marks, assuming a linear scale (Mitchell et al., 2007). Turbidity level was recorded as zero only when the pattern on the bottom of the tube was still visible even when the turbidity tube was filled completely, indicating that the measurements were below the detection limit of the turbidity tube scale. In addition to turbidity measurements, citizen scientists took water level data by reading the value from a water level gauge installed at the site (Figure 1.4).

Citizen scientists were asked to repeat turbidity measurements twice before submitting the data to reduce measurement error and to submit both turbidity and water level data at least twice per week.

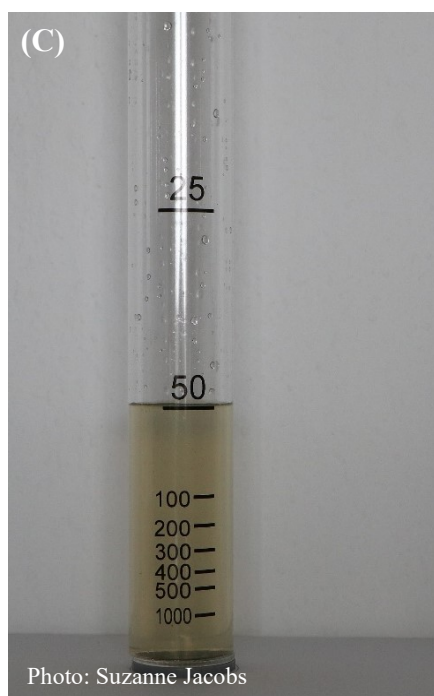


Figure 1.4 (A) Citizen science water quality and water level monitoring station, installed with water level gauges and a signboard with instructions on how to collect and submit water level data, (B) citizen scientists taking turbidity measurements using turbidity tubes, and (C) scale on the turbidity tube.

Following the approach described by Weeser et al. (2018), citizen scientists submitted data by sending a text message via their cell phone to a central server. The text message contained the value of water or turbidity levels and a site-specific ID, as specified in the manual. For the server to be able to process the content of the message, an individual text message had to be sent for each type of value. The transmitted data were then parsed and interpreted by a script (using the open-source programming languages Python and JavaScript) to link the measurements with the specific monitoring station and parameter. Processed data were stored in a database, and an automated feedback built into the central server provided an immediate response to the participants as detailed in Weeser et al. (2018). In addition to submitting the data to the central server, citizen scientists recorded the data onto a standard form in the field that helped with quality review and control. For quality control and assurance, the turbidity tubes were first calibrated in order to convert turbidity measurements into suspended sediment concentrations (SSC). This was achieved by relating the turbidity values obtained using turbidity tube and spectro::lyser to simultaneous measurements of SSC obtained from suspended sediment samples prepared using fine sediments collected from the riverbed at each sampling site. The calibration process is described in Chapter 3. Subsequently, the SSC data generated by the citizen scientists were compared and validated with the data recorded by the automated stations.

1.3.3 Household survey

To assess social perceptions of and value for WES provided by tropical montane forests, as well as people's willingness to contribute to the management of these services, a survey with 217 households living around the South-West Mau forest was carried out (Chapter 4). The sample households were drawn through a multi-stage sampling procedure. First, the study area was stratified into upper, middle and lower zones in order to gather contextual and spatial data that would be representative of the local socio-economic and environmental conditions from across the study area while also taking into consideration the potential influence of proximity to the forest on the perceptions of WES (Figure 1.2). Three sub-locations (the lowest administrative unit at local level), one from each zone, were selected purposefully based on their proximity to the forest (up to 15 km). In the next stage, 11 sample villages, (3-4 villages from each sub-location) were selected randomly. Finally, a total of 217 households of the study were randomly selected from the 11 villages based on the estimated total number of households provided by each respective local

administrative officer. Given the relative homogeneity of households per zone, we adopted a sampling intensity of 15-20% (Ketema et al., 2021). Out of the total 217 households sampled, 73 households were located in the upper zone, 72 in the middle zone, and 72 in the lower zone, respectively. This sample size was representative at 95% confidence level, yielding a sampling error margin of 6%.

Data were collected using a semi-structured questionnaire developed in LimeSurvey (<https://www.limesurvey.org/>) and adapted in the Offline Survey application for Android smartphones (<https://www.offlinesurveys.com/>). The questionnaire consisted of three sections eliciting information on: 1) participants' socio-demographic characteristics such as gender, age, education level, years of residence, household size, source of income, annual income, and land size, 2) perceptions of the WES provided by the forest, and, 3) the participants' environmental behaviour. The survey questions addressed 15 WES that were selected based on review of previous studies (Grizzetti et al., 2016; MEA, 2005; Paletto et al., 2021; Springgay et al., 2019; Turkelboom et al., 2013). The services were classified into three categories according to the ecosystem services classification system identified in the Millennium Ecosystem Assessment (MEA, 2005) and organized around the cascade model (Haines-Young and Potschin, 2010) (Figure 1.1). These services included provisioning (water and food provisioning), regulating (water purification, erosion prevention, soil fertility maintenance, flood protection, water regulation, groundwater recharge, climate regulation), and cultural services (recreation, aesthetics, religious and spiritual values, social relations, sense of place, education and knowledge systems). Statements regarding the role of forests in providing these particular WES were developed based on hypothesized relationships between forests and hydrological services (Calder, 2002; Dave et al., 2017; Gebrehiwot et al., 2014; Wilk, 2000). The participants' environmental behaviours were evaluated based on whether 1) they belonged to any community-based organizations involved in conservation activities, 2) they had received information or training on forest and water conservation, 3) they had implemented any conservation measures on their farms and, 4) their willingness to pay for conservation purposes to ensure clean water. A detailed questionnaire is provided in Appendix 4.3

The questionnaires, which had been pretested prior to the survey, were administered in April 2022 through face-to-face interviews. The interviews were conducted either in Swahili or in a local

language (the former being a national official language) by trained field enumerators. Each individual interview lasted between 45 and 60 minutes.

1.4 Summary of results

1.4.1 Objective 1: Citizen science in hydrology

The reviewed studies showed that the application of citizen science in generating scientific data in the hydrological context has gained tremendous popularity over the past decade and especially since 2014 onwards. These approaches were more prevalent in high-income regions, with North America and Europe having the highest representation at 45% and 20%, respectively, while Australia had the lowest representation at 4%. Although the uptake of citizen science in hydrology in low-income countries is still at its infancy, we recognize that it is gradually increasing, as demonstrated by a representation of Africa and Asia in 10% and 9% of the studies, respectively (Figure 1.5).

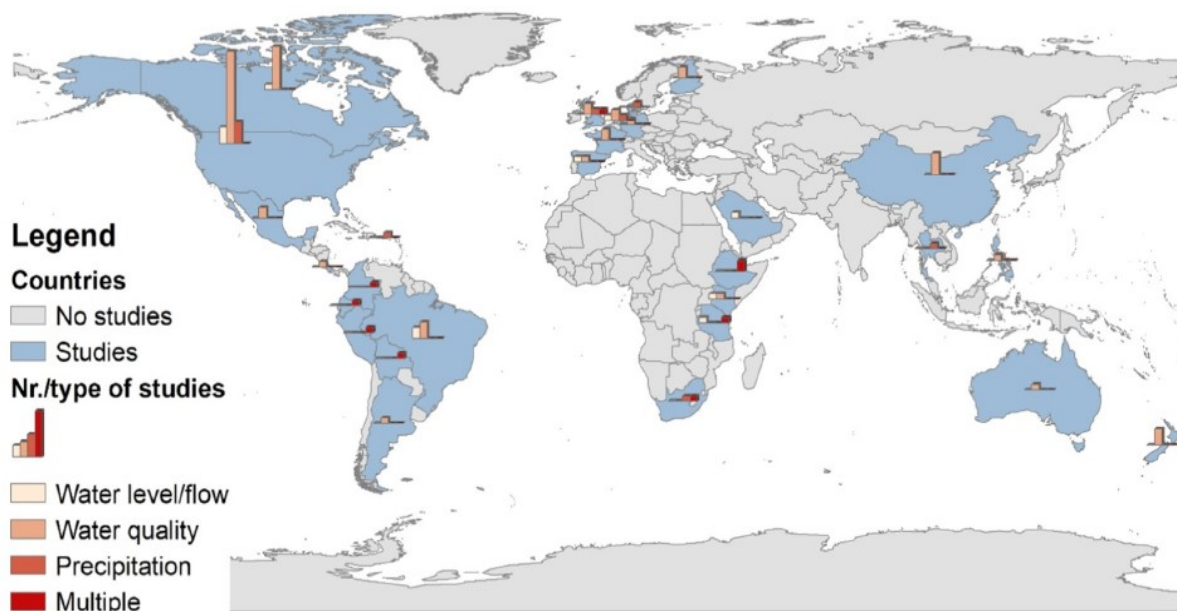


Figure 1.5 Geographical distribution of the citizen science studies and scope of monitoring (Njue et al., 2019).

The scope and scale of monitoring, as well as the degree of citizen participation in citizen science initiatives, varied depending on the nature of the program. Most of the studies reviewed focussed on water quality monitoring (63%) including in-situ measurements of nutrient concentrations

(nitrates and phosphates), turbidity, biological indicators (benthic macroinvertebrates), as well as visual assessment of environmental conditions (e.g., signs of pollution, water colour and surroundings), both at local and global scale. Some of the projects in the U.S. such as CrowdHydrology and the Community Collaborative Rain, Hail and Snow network (CoCoRaHS) involve citizen scientists in monitoring of water levels and precipitation (Lowry and Fienen, 2013; Reges et al., 2016). Other projects with a similar approach in low-income countries include Weeser et al. (2018) in Kenya, Gomani et al. (2010) in Tanzania, and Kongo et al. (2010) in South Africa.

The spatial scale of monitoring networks ranged from monitoring at a single-site to monitoring at multiple sites spread across a city, country, entire watersheds, provinces, or states. The temporal scale varied from 1-day to more than 11 years of monitoring. More than 60% of the programs monitored for 1-5 years and had fewer than 100 sites. Only 5 programs monitored more than 300 sites and fewer than 10 programs had longer monitoring periods of more than 10 years. The Florida Lakewatch and Alabama Water Watch (AWW) are successful examples of long-term volunteer water quality monitoring programs, that have worked with thousands of citizen scientists for more than ten years to study the dynamics of freshwater ecosystems, providing information at large spatial scales (>1500 water bodies) (Deutsch & Ruiz-Córdova, 2015; Hoyer et al., 2014; Thornhill et al., 2018). On a global scale, FreshWater Watch, an established citizen science project, has collected valuable freshwater quality data at 27,000 data points in more than 20 countries (<https://freshwaterwatch.thewaterhub.org/>), and with around 146 countries participating in World Water Monitoring Day (EarthEcho, 2015).

Most citizen science programs followed a contributory model (73%), i.e., scientists designed the study and citizens primarily contributed to data collection. 23% were collaborative projects that relied on a higher level of interaction between citizen scientists and professionals, while 4% were co-created projects that primarily involved citizen scientists in the overall process of scientific inquiry. Several studies (n = 55) had clear pathways of data acquisition and management that were either automated, semi-automated, or manual, while others relied on a combination of approaches. For example, CrowdWater (Kampf et al., 2018), Creekwatch (Kim et al., 2011), Crowdmap (Ross and Potts, 2011), and Mping (Elmore et al., 2014) have developed non-intrusive, cost-effective, web-enabled smartphone-based digital infrastructures with GPS location capabilities to crowdsource valuable hydrologic data including water levels, streamflow rates and precipitation,

for both research and watershed management. Such applications allow the submission of images and videos with geo-located date and time-stamped information, which are more informative and intuitive than other crowdsourcing methods. Nonetheless, in remote regions where internet connectivity is limited, some studies crowdsourced water level data through simple SMS-text messaging (Lowry and Fienen, 2013; Weeser et al., 2018) or by manually recording data on sheets and sending via email (Walker et al., 2016).

Although camera-based systems are well suited for continuous hydrological monitoring of streamflow (Royem et al., 2012) and water quality mapping (Goddijn-Murphy et al., 2009), especially in studying ephemeral streams in remote areas, their applications in hydrology are still limited. To overcome challenges associated with physical installation of flow gauging stations, such as water level gauges, sensors or camera-based systems in remote regions, virtual staff gauge approach can be deployed to monitor and estimate water levels (Seibert et al., 2019). With the growing number of smart devices and people connected to the internet, opportunistic sensing supported by the Internet of things (IoT) is becoming easily adapted in citizen science frameworks for diverse monitoring purposes in hydrology, such as in crowdsourcing large amount of hydrometeorological data from personal weather stations (Vos et al., 2017). In addition, the mining and analysis of volunteered geographic information from social media (e.g., Facebook, YouTube and Flickr) is an emerging frontier for hydrological sciences that has been applied for real-time mapping, estimating flow rates, and validating models for the prediction and better understanding of extreme hydrological events (Li et al., 2018).

Regarding credibility and reliability of data, there is growing body of evidence from numerous studies demonstrating that citizen scientists generate high-quality hydrological data that are comparable to data collected by professional scientists or using standard methods. For example, crowdsourced data on water levels (Lowry and Fienen, 2013; Weeser et al., 2018), atmospheric and rainfall time series datasets (Vos et al., 2017), and water quality data based on benthic macroinvertebrate, water temperature and dissolved oxygen monitoring (Fore et al., 2001; Safford and Peters, 2018), compared favourably to data collected using conventional methods or by professionals. This is proof for the reliability of citizen science data. To support the validity and reliability of data generated by citizen scientists, most programs provided training for participants (82%), and 90% adopted rigorous quality assurance/quality control measures. The studies used

measures such as automatic data quality control, training of participants, developing standardised and replicable sampling protocols, calibration of monitoring tools, as well as validation of data with standard methods or comparison with professionally collected data to identify outliers (Burgess et al., 2017; Jollymore et al., 2017; McGoff et al., 2017; Weeser et al., 2018).

Furthermore, several studies have demonstrated the applicability and assimilation of citizen science data in hydrological modelling (Wang et al., 2018; Weeser et al., 2019), and quantification of trends and seasonality of river nutrients (Abbott et al., 2018), rainfall and base flows in watersheds (Koskelo et al., 2012). Some organizations use citizen science data to validate radar precipitation estimations and measurements obtained from automated rain gauge networks (Smith et al., 2015; Zhang et al., 2014), and improve freshwater quality classification to support regulatory purposes (Loperfido et al., 2010). The aforementioned works suggests that through calibration and validation, citizen scientists are capable of collecting data of sufficient quality and quantity that can be utilized for hydrological research applications, to improve hydrological risk reduction, support sustainable water resource management, and broaden the understanding of the hydrologic cycle and climate variability, particularly in data-scarce regions.

1.4.2 Objective 2: Spatial and temporal patterns in water quality and quantity

To assess the spatial and temporal patterns of SSC, a 2-year dataset of water level and turbidity measurements (monitoring period from September 2017 to September 2019), collected using citizen science as part of a water quality and quantity monitoring program in the Sondu-Miriu river basin, was investigated (Chapter 3). Within the monitoring period, citizen scientists provided over 1,300 valid observations for turbidity for the six sites, with only 6% ($n = 80$) invalid data. The invalid data was due to typing errors such as submitting data with an incorrect site-ID or missing information such as no site ID or sending turbidity readings in place of water level readings.

The participation rate and sampling effort of citizen scientists in data collection varied over the course of the project. The findings revealed a Gini coefficient of 0.66, indicating a high degree of sampling inequality among participants. Gini coefficient is a statistical indicator frequently calculated to inform about the participant contribution distributions in citizen science projects (Sauermann and Franzoni, 2015; Scott and Frost, 2017), whereby a higher Gini coefficient of 1 expresses unequal sampling effort whereas the lowest Gini coefficient of 0 expresses equal

sampling among participants (Atkinson, 1970). 72% of the data came from around 22% of active participants, most of whom were under 35 years of age. Around 11% showed long-term commitment by consistently contributing data throughout the monitoring period. Participation was highest during the initial phase of the project. Around 35% of the participants dropped out of the program after 1-2 months of monitoring. Low participation rates at some sites and high rate of drop-outs can be attributed to declining interest, or to the prohibitive transmitting cost of 0.01 USD per text message incurred by the participants. The declining interest and overall increasing number of dropouts over time, was also observed in other long-term citizen science based projects (Deutsch and Ruiz-Córdova, 2015; Klang and Heiskary, 2000).

To estimate SSC from turbidity measurements for citizen science and automated stations data, a site-specific calibration relationship relating SSC to turbidity was empirically derived using linear regression models as described in chapter 3. For both citizen science and automated stations datasets, the relationship between turbidity and suspended sediment concentrations showed a strong linearity of $R^2 = 0.91$ and $R^2 = 0.94$, respectively, and there was no significant difference between the slopes of each site-specific calibration ($p \Rightarrow 0.1$). Comparison of SSC data estimated from turbidity data collected by citizen scientists using turbidity tubes and from automated stations using a UV-Vis sensor at the KUR and CMT sites (see Figure 1.2), revealed a high correlation of 0.95 and 0.94, respectively. However, the results showed that citizen scientists at KUR tended to underestimate SSC values by ~30 %, whereas the citizen scientists at CMT overestimated low SSC values by ~10%. One possible reason for this could be the low repeatability due to the detection limits of the turbidity tubes, given the coarse turbidity scale readings especially in the lower and upper ranges, making it difficult to accurately estimate SSC within the measurement ranges. This could potentially lead to over- or underestimation of actual turbidity values due to the differences in site-specific characteristics (Anderson and Davie, 2004; Scott and Frost, 2017). In addition, the differences in SSC estimates may be due to sampling errors resulting from observer variability and biases, a challenge frequently reported with citizen science approaches (Miguel-Chinchilla et al., 2019; Thornhill et al., 2016).

A spatial comparison reveals that of the six monitored sites, SSC were significantly higher at SNU ($109 \pm 94 \text{ mg L}^{-1}$), a subcatchment dominated by agriculture, rangeland with a low forest vegetation (36%) and lowest at KGT ($50 \pm 24.7 \text{ mg L}^{-1}$), a sub-catchment with much higher forest cover (65%).

This indicates that agriculture may be the driving force for SSC loading in streams in the catchment, as observed in previous studies in the South-West Mau (Stenfert Kroese et al., 2020a). This could be caused by reduced infiltration rates and soil hydraulic conductivity properties in agricultural catchments, which is commonly associated with increased erosion rates and overland flows (Owuor et al., 2018).

Visual assessment of the hydrological time series of SSC and water levels from both citizen science-generated data and automated station data clearly showed similar seasonal patterns that closely matched the bi-modal precipitation pattern in the area, with SSC concentrations highest during April through July (long rains) and September through October (short rains) (Figure 1.6). This is consistent with other studies carried out in the area (Dutton et al., 2018; Stenfert Kroese et al., 2020a). Although both datasets showed a general trend in high and low flow conditions, the citizen scientists were not able to capture the same degree of variability in SSC concentrations as the automated stations, especially during the rainy season. Citizen scientists recorded very few high SSC values ($> 200 \text{ mg L}^{-1}$), suggesting that major sediment export events were not captured. Because high SSC values are associated with heavy rainfall and “bad weather,” it is likely that citizen scientists will avoid sampling under these extreme weather conditions. A similar temporal bias in sampling was reported in the FreshWater Watch monitoring network, where citizen scientists tended to sample sites more frequently in spring and summer months (Thornhill et al., 2016).

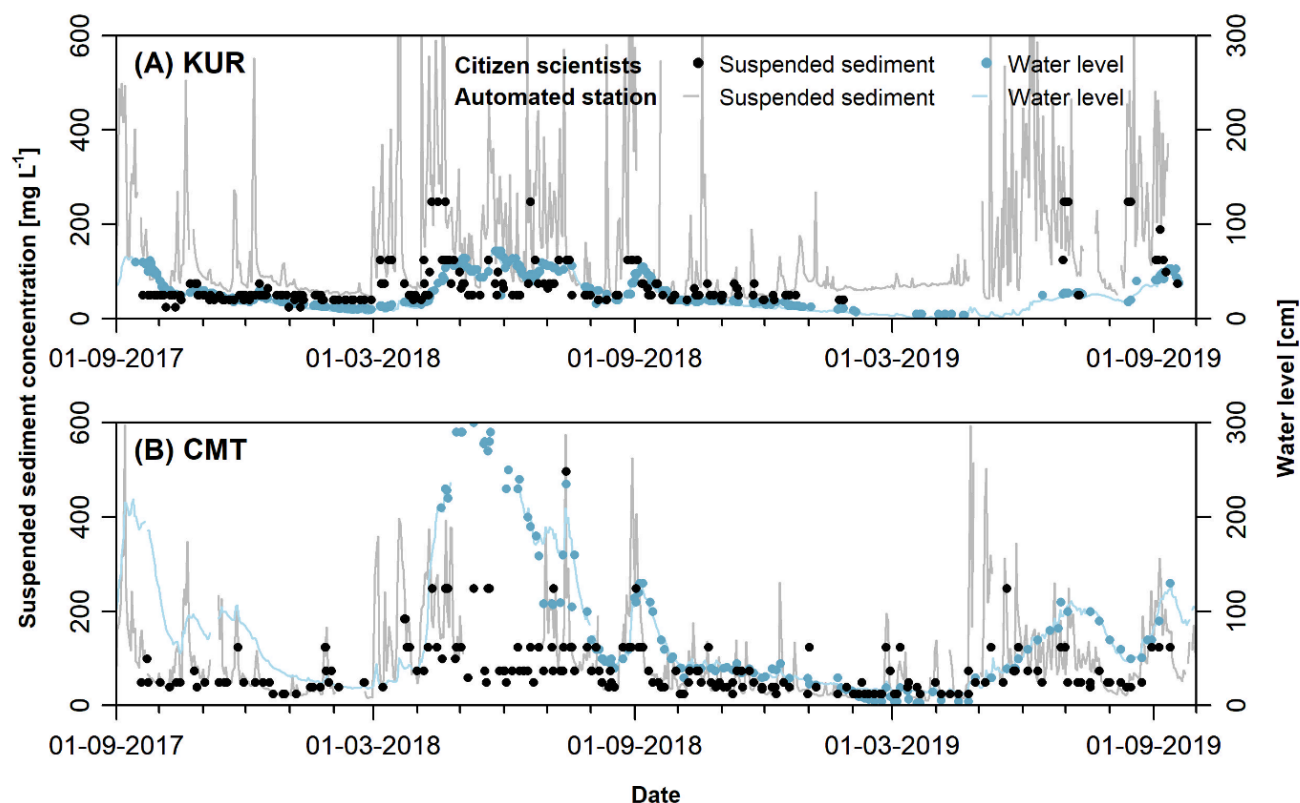


Figure 1.6 Time series of suspended sediment concentration and observed water level transmitted by citizen scientists and measured by automated stations at sites (A) KUR and (B) CMT in the Sondu-Miriu river basin over the monitoring period between September 2017 to September 2019. Adapted from Njue et al. (2021).

1.4.3 Objective 3: Socio-cultural values of WES

The results of the socio-cultural valuation revealed that 87% of the respondents believed that the South-West Mau forest provides a wide range of WES. Among the three categories of WES, regulating services had relatively higher perceived importance (4.22 ± 0.56), followed by provisioning services (3.57 ± 3.5) and cultural services (3.09 ± 0.93), on a scale of 1 (not important) to 5 (very important). Regulating services are essential for agricultural production, and since 88% of the participants depend on on-farm activities as their main source of income and livelihood, this may explain why these services were perceived as more important. Specifically, water provisioning, climate regulation, water purification, water regulation, and groundwater recharge were perceived as the top five most important services for societal and individual well-being, although the order was slightly different among the three zones in which the household survey was

conducted. Water provisioning was perceived as the most important WES for the rural households in the region, similar to findings reported by Miller et al. (2021). Provisioning of food was perceived as the least important among all the WES, as fishing is limited or non-existent in the area (Kapiyo et al., 2003).

Kruskal-Wallis tests revealed that the perceptions of importance for certain WES including food provisioning ($p < 0.001$), soil fertility maintenance ($p = 0.005$), flood protection ($p = 0.001$), groundwater recharge ($p = 0.02$), recreation ($p = 0.001$), aesthetics ($p < 0.001$), and religious and spiritual values ($p = 0.02$) differed significantly among the three zones (Figure 1.7). Previous studies reported that socio-cultural values are shaped by a complex set of factors related to biophysical, socio-economic settings and environmental awareness (Ketema et al., 2021; Miller et al., 2021). The study indicates that geographical location was an important factor influencing perceptions of WES. Generally, the perceived importance of all WES together, as well as for specific WES was significantly higher in the lower zone compared to the upper zone, despite being located further from the forest. The participants in the lower zone had lived longer in the area (30.5 ± 17.4 years) compared to those in the upper zone (16.9 ± 10.1 years), which could explain why they perceived more ecosystem services as important. The duration of residence in an area promotes sense of place due to experience, knowledge of the place and physical attachment to the environment (Muhamad et al., 2014; Shoyama and Yamagata, 2016). The higher perceived importance also suggests that the adverse effects of changes in ecosystem services may be more pronounced in the lower zones, making the participants more aware of the environmental issues (Ellison et al., 2017; Muhamad et al., 2014). The contrasting perceptions not only highlight the spatial heterogeneity in the supply and demand of the WES, but also potential trade-offs existing among services due to divergent interests, which is essential in the management of ecosystems (Zhang et al., 2021).

The provision of the five most important services was perceived to have declined over the past 10 years, which can be attributed to hydrological changes in the Mau Forest Complex as a result of land use and climate change (Jacobs et al., 2017; Mati et al., 2008; Mwangi et al., 2020; Owuor et al., 2018; Stenfert Kroese et al., 2020a). Furthermore, a change in the provision of the aforementioned services could also affect the provision of other services, such as religious and spiritual values and aesthetic values, which in turn may affect recreational opportunities, due to feedbacks and regime shifts among ecosystem services (Mahjoubi et al., 2022; Nyingi et al., 2013).

Because the delivery of most regulating ecosystem services is highly dependent on ecosystem organization (i.e., biophysical structures, processes, and functions), this finding emphasizes the prioritization of these services and the incorporation of their value into local and regional forest management and landscape planning decision-making.

Water purification, an indicator of water quality, was considered among the *critical* WES (i.e., perceived as both very important and with a declining trend), hence vulnerable to loss. As such, 82.5% of participants showed a high willingness to pay for conservation purposes to ensure the supply of clean water. Despite the high number of people willing to pay for ecosystem services, the majority (63%) were willing to pay less than 50 \$USD/month due to limited financial resources, as the majority (63%) of the participants were low-income earners, with an annual income of <1000 USD. This finding highlights the importance of considering the social perspectives and ecosystem service values in management decisions, as this could be used to design and implement effective and adaptive management strategies based on the needs and priorities of the local community.

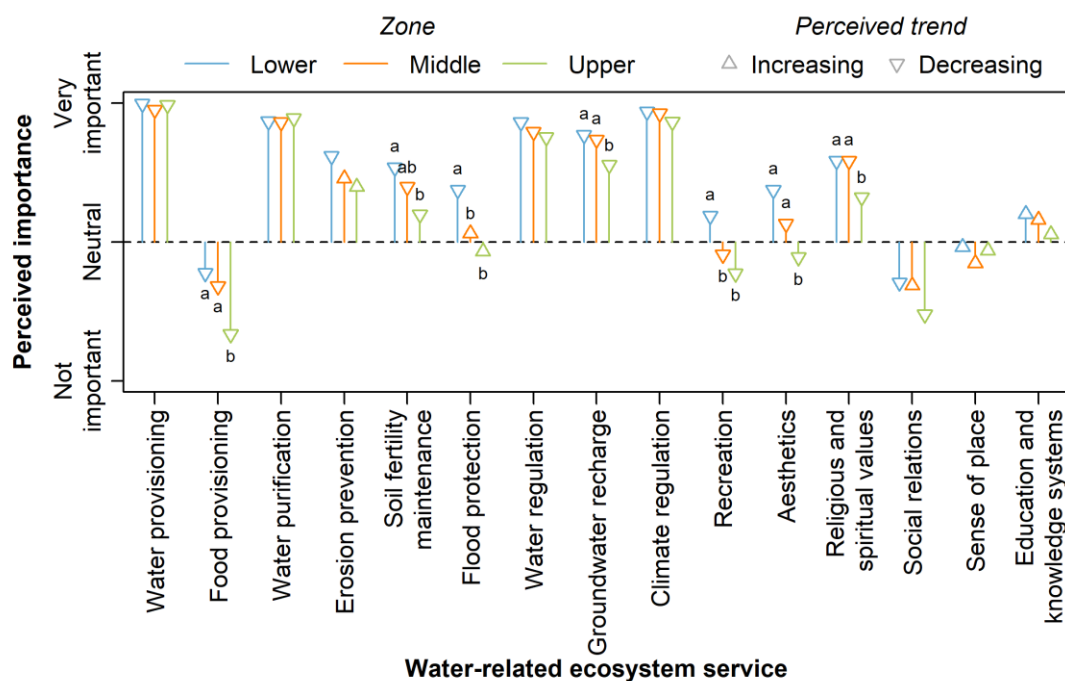


Figure 1.7 Perceived importance and trends of WES among the three elevation zones, in the South-West Mau, Kenya based on household survey (n=217). Significant differences in perceptions of importance among zones are identified with different letters. The symbols indicate the increasing or declining perceived trends for the WES. Adapted from Njue et al. (*in review*).

1.5 Implications and recommendations for future research

This work demonstrated that participatory approaches offer an alternative methodology to generate useful biophysical and socio-cultural information that can support decision making for sustainable management of natural resources. The growing number of studies and successful implementation of state-of-the-art approaches, particularly in monitoring water quantity, water quality and precipitation, demonstrate the potential and contribution of citizen science in hydrological research. Based on the review, it is also clear that active citizen science participation in hydrological monitoring can generate extensive datasets with broad spatial and temporal coverage that are of sufficient quality to support evidence-based decision-making, which is confirmed by the case study in the Sondu-Miriu river basin.

Water quality and quantity data generated by citizen scientists as part of a citizen science monitoring program in the Sondu-Miriu river basin provide significant insights into the spatial and temporal dynamics of suspended sediment and water fluxes. In the Sondu-Miriu river basin, soil erosion and sediment loads in rivers are a major concern. According to Masese et al. (2012), turbidity levels in the Sondu-Miriu river basin more than doubled over a 30-year period between 1988 to 2012. In Lake Victoria, into which the Sondu river drains, sediment was estimated to accumulate at a rate of 2.3 mm yr^{-1} , reportedly contributing to the eutrophication of the lake (Verschuren et al., 2002; Zhou et al., 2014). Recent biophysical studies carried out in the area have shown that agriculturally dominated catchments experienced the highest rates of soil loss and sediment yield, with small agriculture areas generating 6 times more suspended sediment annually than a catchment dominated by natural forest (Stenfert Kroese et al., 2020b). The amplification of soil loss and sediment inputs in the catchment is mainly attributed to changes in soil physical properties such as reduced infiltration rates and water retention capacity, due to the conversion of natural forests to agriculture and grazing lands (Owuor et al., 2018). Considering the current scenario of water degradation and the expected increase in soil erosion due to future deforestation, agricultural intensification and climate change, this makes it even more critical. Therefore, regular monitoring of turbidity and sediments on relevant spatial and temporal scales is crucial (Njue et al., 2021).

Turbidity tubes can be an effective and inexpensive monitoring tool for estimating relative sediment concentrations, but their low detection limits can result in under- or overestimation of

actual turbidity values (Njue et al., 2021). Nevertheless, the data can be useful to identify spatial differences and seasonal variations that provides baseline information that can support the development and implementation of targeted catchment-based management strategies to mitigate soil erosion and sediment delivery to water bodies. However, where the purpose of the data is to calculate sediment yields and to understand processes behind soil erosion, this method is not so suitable, as the timing of measurements might not be representative of all flow conditions and therefore lead to inaccurate estimates of soil loss. To further advance citizen science based hydrological monitoring, however, future citizen science projects could take advantage of smart technologies such as smartphone applications, sensor and camera-based monitoring systems with improved detection limits and resolution. Non-contact recording through photography or video-taping can probably improve the accuracy of citizen science measurements. Not only could this enhance the quality and usability of the generated data, it also offers opportunities to monitor a wider range of water quality parameters and thus provide a more comprehensive overview of the state of water resources in the region (Njue et al., 2019).

Despite the successful application of citizen science in biophysical monitoring of water resources (Breuer et al., 2015; Reges et al., 2016; Scott and Frost, 2017; Thornhill et al., 2017; Weeser et al., 2018), the integration of citizen science data into decision-making regarding water resources and ecosystem services management remains a challenge. This is due to criticisms of data credibility and quality (Catlin-Groves, 2012; Wilson et al., 2018). Such concerns not only hinder the use of citizen science data, but also prevent the full potential of citizen science from being realised. Generally, sampling biases and errors are frequently reported in citizen science approaches, such that data collected by citizens in comparison with traditionally collected data differ in terms of temporal and spatial coverage, volume and accuracy (Assumpção et al., 2018; Njue et al., 2021; Thornhill et al., 2016). Such errors encountered could be reduced through the implementation of rigorous quality assurance, such as standardised sampling protocols and training, thus unlocking the potential of data use for scientific and regulatory purposes (Wiggins et al., 2011). This could be further aided by the application of modern statistical tools as well modelling and simulation approaches to account and correct errors and biases associated with citizen science data (Bird et al., 2014; Isaac et al., 2014). The generation of high-quality data requires further attention, to create a trustworthy environment in which citizen science data are accepted as credible in the scientific community (Fritz et al., 2019).

The applicability of citizen science is further challenged by participation rates. Although sustained engagement of citizen scientists has important implications for data quality outcomes and project sustainability (Moor et al., 2019; Scott and Frost, 2017; Serret et al., 2019), active and long-term participation remains a challenge. In this study, for example, only a relatively small number of active citizen scientists contributed to the water quality data, and there were a high number of dropouts towards the end of the project. This was also observed for citizen science water level monitoring in the study area (Weeser et al., 2018). Interactive feedback and communication at different stages of the project cycle is a fundamental element of a successful citizen science program, as this not only serve to inform the participants about their collected data, scientific findings, and research outputs, but can also incentivize further engagement of citizen scientists, which promotes sustainability (Brouwer et al., 2018; Golumbic et al., 2020). Creating motivation mechanisms is also another important aspect for encouraging participation in any citizen science initiative (Pandeya et al., 2021). Therefore, future work could consider testing different methods of communication and feedback as well as data sharing to be able to develop engagement strategies that are tailored to the context of the project. In East Africa, where internet connectivity and access to technology are still limited, especially in remote regions, the use of smartphones may not be such a good option. Additionally, the use of free data submissions methods could minimise barriers to citizen participation. Particularly, adapting the project to the needs and interests of the participating group can promote sustained engagement and retention (Weeser et al., 2021). The degree and level of involvement of the participating group through the development of a participatory research can help align research with societal needs, which can greatly improve the societal acceptance and impact of research outcomes (Church et al., 2019; Golumbic et al., 2020). In this case, co-creation approach is most likely the most suitable for successful participatory research such as citizen science, as participants are actively involved throughout the development process and generate outputs that are relevant to them, which is a further incentive for continued participation.

Participatory methods and co-creation with a more bottom-up approach are important in management of natural resources as they can promote ownership and acceptance of management interventions by addressing issues relevant to the participants. Incorporating local socio-cultural values in planning and management decisions is also important to avoid social conflicts and trade-offs, as these values are context-dependent and differ depending on people's needs and priorities,

as outlined in Chapter 4. Highly valued services can serve as a strong incentive for people to participate in supporting management initiatives and environmental stewardship (Börner et al., 2017; Scholte et al., 2015). Therefore, identifying management interventions that particularly address critical WES might be a more suitable approach to improve natural resource conservation. Although there are other ways to explore on how to involve communities in biophysical and socio-cultural valuation as well as how to best take these socio-cultural values into account, it is promising that combining citizen science biophysical monitoring with community-based management approaches that incorporate their socio-cultural values might have high potential for the conservation and sustainable use of natural resources.

2. Citizen science in hydrological monitoring and ecosystem services management: State of the art and future prospects

This work is published in *Science of the Total Environment* as:

Njue, N., Kroese, J.S., Gräf, J., Jacobs, S.R., Weeser, B., Breuer, L., Rufino, M.C., 2019. Citizen science in hydrological monitoring and ecosystem services management: State of the art and future prospects. *Science of the Total Environment* 693, 133531. <https://doi.org/10.1016/j.scitotenv.2019.07.337>

2.1 Introduction

Provision of water is one of the most fundamental ecosystem services that underpins the societal wellbeing, which is often a significant bottleneck to sustainable development and poverty alleviation (Buytaert et al., 2014). Despite their importance, catchments in many parts of the world are under severe pressure associated with multiple stressors such as climate change and anthropogenic activities (Everard, 2012; Johnson et al., 2007). These stressors often affect negatively ecosystem health, including hydrological and biogeochemical processes compromising their resilience to cope with extreme events and disturbance (Falcone et al., 2010). Recent studies on environmental land use conflicts provide insights about the hydrological impacts related to the actual land uses that deviate from natural land uses (Araújo Costa et al., 2019; Valera et al., 2016). Development of land ignoring natural capability of soils trigger deterioration of surface water and groundwater quality (Pacheco and Sanches Fernandes, 2016; Valle Junior et al., 2014), change in water flow regimes (Truong et al., 2018), intensification of soil erosion (Pacheco et al., 2014), amplification of flooding (Caldas et al., 2018), decline in freshwater biodiversity and ecosystem services (Valle Junior et al., 2015). Consequently, these hydrological impacts pose significant threats to the sustainable use of water resources (Vanmaercke et al., 2014).

Dense networks for hydrological monitoring with high temporal and spatial resolution are needed to guide evidence-based decision making on sustainable water resources management (Mishra and Coulibaly, 2009; Ochoa-Tocachi et al., 2018). Comprehensive hydrological datasets provide fundamental information necessary to characterize catchment behavior, to make future projections based on models, to implement mitigation measures and to meet policy needs (Tetzlaff et al., 2017).

However, long-term hydrological monitoring networks using classical methods (e.g. manual and automatic grab sampling, automatic gauging stations, remote sensing technologies) come at substantial costs associated with installations, management, maintenance and engagement of technical personnel (Buytaert et al., 2014; Lowry and Fienen, 2013; Mazzoleni et al., 2017). Consequently, high costs of implementation often lead to sparse data collection and irregular monitoring. For instance, while remotely sensed data are becoming more readily available, they are still limited by low temporal resolution and involve large uncertainties that make hydrological assessments difficult (Ochoa-Tocachi et al., 2018). Thus, good quality and detailed ground-based observations are required for validation (Starkey et al., 2017). Grab sampling plans are usually too costly for any regional or national monitoring program (Hildebrandt et al., 2006), and sometimes short-lived hydrological events can be missed based on this approach (Jacobs et al., 2018). Fixed monitoring stations and equipment such as river gauging stations and *in situ* sensors are costly and are susceptible to corrosion, vandalism and theft and therefore require routine site maintenance and security (Gomani et al., 2010; Hannah et al., 2011; van Overloop et al., 2014). Sometimes, inaccessibility of remote locations limit the amount of data that can be collected with available resources (Zheng et al., 2018). Indeed, recent reviews have noted that hydrological data in many parts of the world are patchy and the lengths of the time series are insufficient to characterize and manage water resources, as many drainage basin remain ungauged or poorly gauged (Chacon-Hurtado et al., 2017; Mishra and Coulibaly, 2009). This implies that areas with limited monitoring networks, particularly the low-income countries, may take longer to attain sustainable water resources management (Buytaert et al., 2014).

There is a growing worldwide need to explore cost-effective data acquisition to generate knowledge for sustainable natural resource management (Buytaert et al., 2016; Loiselle et al., 2016; Pham et al., 2015). This need to develop novel approaches for monitoring environmental data is reflected in the recent growing attention to citizen science. Over the past two decades, citizen science has gained popularity around the world as a promising approach for long-term monitoring of local and global environmental change (Danielsen et al., 2005; Johnson et al., 2014; McKinley et al., 2017; Silvertown, 2009). Citizen science has the potential to enhance knowledge co-creation and science-based evidence that underpins the governance and management of natural resources, complementing conventional ways of monitoring while reducing monitoring costs and significantly improving data coverage, increasing social capital, empowering and supporting decision making

(Bonney et al., 2009a; Haklay, 2015; Silvertown, 2009). However, criticisms and concerns about the reliability and credibility of data collected have been highlighted as some of the factors impeding integration of citizen science data into decision making and causing slow acceptance within the scientific community (Catlin-Groves, 2012; Wilson et al., 2018). Consequently, citizen science may not realize its full potential in spite of the growth in open science and increasing number of scientific projects actively involving citizen scientists (Kullenberg and Kasperowski, 2016; Theobald et al., 2015; Wilson et al., 2018).

Citizen science covers a breadth of fields, having been more prominently and successfully applied in ecology, in biogeography and environmental sciences than in water science (Buytaert et al., 2014; Dickinson et al., 2012). Nevertheless, citizen science is emerging as a viable way to support research in hydrological sciences, especially in monitoring of precipitation, river water quantity and quality, soil moisture levels and flood risk management (Breuer et al., 2015; Loiselle et al., 2016; Lowry and Fienen, 2013; Weeser et al., 2018; Wilson et al., 2018). There are only a few notable examples of these approaches implemented in low-income countries, including Kenya (Weeser et al., 2018), Ethiopia (Walker et al., 2016), Tanzania (Gomani et al., 2010) and South Africa (Kongo et al., 2010), as compared to North America and Europe (Buytaert et al., 2014; Silvertown, 2009). While there is an increasing number of case studies and a growing body of research, a quantitative synthesis assessing emerging trends of citizen science initiatives in the context of hydrological sciences is lacking. Based on this background, this study aimed to provide a comprehensive review on the potential of citizen science and its application in the hydrological context and water resources management. We aimed to answer two research questions: (1) How is citizen science contributing to hydrological research, and (2) What is the future scope of citizen science in hydrology?

2.2 Overview

2.2.1 What is citizen science?

Citizen science is the involvement of the members of the public in different stages within the scientific research process such as collecting, categorizing, transcribing or analyzing scientific data (Bonney et al., 2009a). In 2013, the European Commission in their report “Green paper for citizen science” re-defined citizen science as “*general public engagement in scientific research activities*”

where citizens actively contribute to science either with their intellectual effort, or surrounding knowledge, or their tools and resources” (European Commission, 2013). Buytaert et al. (2014), described citizen science further as the process where members of the public perform research design, data collection and interpretation, sharing of knowledge and/or analyses alongside professional scientists. Terms such as volunteer-based monitoring (Deutsch and Ruiz-Córdova, 2015), crowdsourcing (Howe, 2006), community-based monitoring (Palmer Fry, 2011), citizen observatories (Liu et al., 2014), participatory sensing (Guo et al., 2014), participatory monitoring (Danielsen et al., 2005), and volunteered geographic monitoring (Elwood et al., 2012), are used to encapsulate many forms of public participation in science. The concept of citizen science varies in area of application, involving implicit or explicit data provision, collecting objective or subjective measurements, from bottom-up to top-down implementation, and using uni- or bi-directional communication paradigms between citizens and data processors (Wehn and Evers, 2015). What is common in all these concepts is the broader vision of involvement of the public in the co-generation of scientific knowledge that provides opportunities for learning and collaboration (Kullenberg and Kasperowski, 2016; Verbrugge et al., 2017). Eitzel et al. (2017) presents a review of the theoretical, historical, geopolitical and disciplinary context of the citizen science terminology.

2.2.2 Early developments

Although it is only recently that citizen science has gained wider recognition, it is not a new concept (Bonney et al., 2009a; Silvertown, 2009). Public involvement in scientific discovery has a long history that can be tracked at least to the 19th century and probably earlier (McKinley et al., 2017; Miller-Rushing et al., 2012). The earliest citizen science initiative begun in 1890 with the National Service in the US where volunteers reported daily measurements of air temperature and rainfall (Lee, 1994). The program has over one hundred years of continuous data at 500 stations and with more than 11,000 volunteers (Pfeffer and Wagenet, 2007). In the early 1900s, the Audubon Christmas Bird count in the US and the British Trust for Ornithology in the UK were founded. These bird surveys are the largest and longest-running successful forms of citizen-science initiatives, currently involving tens of thousands of participants having collected over one million records of species with metadata across the globe (Conrad and Hilchey, 2011; Hochachka et al., 2012; Silvertown, 2009). Since then, the application of citizen science has grown across disciplines, varying widely in terms of scale, size, scope, what is monitored, frequency, level of engagement

and costs of monitoring (Danielsen et al., 2005). Citizen scientists participate in a number of research activities including analyzing galaxies (Ponciano et al., 2014), air quality (Snik et al., 2014), invasive species (Gallo and Waitt, 2011), deforestation (Luz et al., 2014), water and soil monitoring (Deutsch et al., 2001), phenology and biodiversity (Fuccillo et al., 2015), and weather monitoring (Reges et al., 2016).

2.2.3 Successful examples

The significant growth of citizen science in natural sciences can be correlated with the increase in technological developments over the past 10-15 years including internet, gamification, robust and cheap sensing equipment, smartphones embedded with web-based mapping tools and global positioning systems (Buytaert et al., 2014; Catlin-Groves, 2012; Khamis et al., 2015). These developments have increased the feasibility of conducting large-scale citizen science projects by streamlining data collection, improving transmission and management of spatial data, automating quality control and expediting feedback communication, even in remote environments (Buytaert et al., 2014; Newman et al., 2012). Limited capacity and scope of monitoring due to decreased agencies budgets in recent decades (Carlson and Cohen, 2018), increasing public knowledge, democratization of science, and concern about anthropogenic impacts on ecosystems (Conrad and Hilchey, 2011), have further driven the need for citizen involvement in environmental monitoring and decision-making. Citizen science models can range from top-down to more bottom-up and participatory approaches depending on level of engagement (Conrad and Hilchey, 2011; Devictor et al., 2010; McKinley et al., 2012; Paul et al., 2018). Several frameworks exist for assessing the level of engagement in citizen science programs (Bonney et al., 2009a; Danielsen et al., 2009; Haklay, 2013; Shirk et al., 2012). The common forms of citizen participation can be categorized into five levels according to the level of influence and involvement in the scientific process, as illustrated in (Figure 2.1).

2.3 Citizen science in hydrology

The earliest prototype of citizen science in hydrology is the use of drift bottles in the 1960's and 1970's to study the patterns in surface water currents in the Caribbean sea. The Caribbean Fisheries Development Project released on a monthly basis and for nearly two years thousands of drift bottles in the sea with an enclosed card with instructions for the finder of the bottle to send back the bottle

with metadata on the date and place of recovery. The recovery rate was 9.6%, similar to the 7.4% return reported for bottles released off the north coast of Brazil (Brucks, 1971; Luedemann, 1967). These early projects lacked sophisticated platforms by which information was communicated, assembled, integrated and interpreted. Especially, the process of recruiting citizens and waiting for data were elaborate and could take a long time (Goodchild, 2007). The integration of hydrology within a citizen science framework is often difficult because hydrological measurements are complex, expensive, technologically demanding and require spatially and temporally distributed measurements (Paul et al., 2018).



Figure 2.1. Typology of citizen science-based program showing levels of involvement and influence. After Bonney et al. (2009) and Shirk et al. (2012).

Current technological improvements of monitoring equipment coupled with Volunteered Geographical Information (VGI) are improving the rate and quality of data collection through location-based, real-time mapping services (Newman et al., 2012), and this is paving the way for faster uptake and applications of citizen science in hydrology (Buytaert et al., 2014; Paul et al., 2018). Several citizen science initiatives for water resource monitoring have emerged worldwide, with networks of well-monitored sites thus improving the spatial coverage of monitoring (Ochoa-Tocachi et al., 2018). Current applications of citizen-led measurements of precipitation, river water

quality and quantity, soil moisture, ground water, lakes and oceans offer good examples of citizen science in hydrology. Most of these programs share a collective purpose to promote sustainable water resources management and encourage public participation in the scientific process (Miller-Rushing et al., 2012). These citizen science initiatives are reviewed in this paper.

2.4 Methodology

In this study we focused on applications of citizen science in monitoring water levels, water quality and/or precipitation as examples in hydrology. To collect information, we reviewed the literature including: peer reviewed articles, book chapters; program websites, and technical reports. Literature was extracted using Google scholar and Web of Science. Search terms were defined using keywords with synonyms or terms with related meaning (Figure 2.2). The Boolean search string method was used to construct search queries. To identify additional relevant articles, we also conducted a backward and forward reference searching examining and reviewing papers cited in the articles selected. Only papers within this scope were considered including: i) Studies that focused on citizen science in a hydrological context and that actively engaged citizen scientists in the scientific research process; ii) Documents published between 2001 and 2018 (both years inclusive), owing to the growth in popularity of citizen science and the emergence of technological developments (Buytaert et al., 2014). Within this period governments, academics, non-governmental and community organizations began to emphasize on the importance of citizen science in environmental monitoring (Jollymore et al., 2017); iii) Papers published in English.

The search yielded 287 articles related to citizen science-based hydrological monitoring. To obtain high quality sources that matched our objectives and that could help answer our research questions selection criteria were applied, which involved inclusion and quality analysis criteria adopted from the methodology by (Talavera et al., 2017). The criteria included:

Abstract check

Papers that did not provide relevant information in their abstracts were discarded at this stage (i.e. only reporting citizen science applications outside the scope of hydrological monitoring). Papers that passed the first criterion were retained.

Full article reading

Papers with minor aspects of our search terms (Figure 2.2) in their content were removed even when they contained the terms in the abstract. We assessed active involvement of citizens in hydrological research activities, and therefore deliberately excluded studies that employed focus group discussions, questionnaires and surveys of citizens because the citizens involved were the subject of the study and contributed passively.

Quality analysis

Three quality criteria were applied and papers that did not comply were excluded. Studies that used synthetic data to imitate citizen science or others that investigated the potential of citizen-science based technologies for the measurements of hydrological parameters with no clear active involvement or engagement of real citizen scientists were also excluded. However, studies on social media mining that is an emerging trend in this field and serve as a valuable source of data of hydrological relevance were included. The assumption was that this approach is participatory in the broader sense, even though participants are usually not aware of their contribution and participation (Michelsen et al., 2016).

The quality analysis were guided by the following questions:

- a. Does the study present a comprehensive application of citizen science in hydrological monitoring?
- b. Does the study show details of the methodology and technologies used to implement the monitoring?
- c. Does the paper present an analysis of the results?

After the iterative search process, 71 papers remained in the pool based on their scientific and technical content. We extracted general information and characteristics of the citizen science approach using a standardized data extraction sheet with predefined research questions (Table 2.1). We also screened the articles for reporting on opportunities and challenges in applying citizen science in hydrological monitoring.

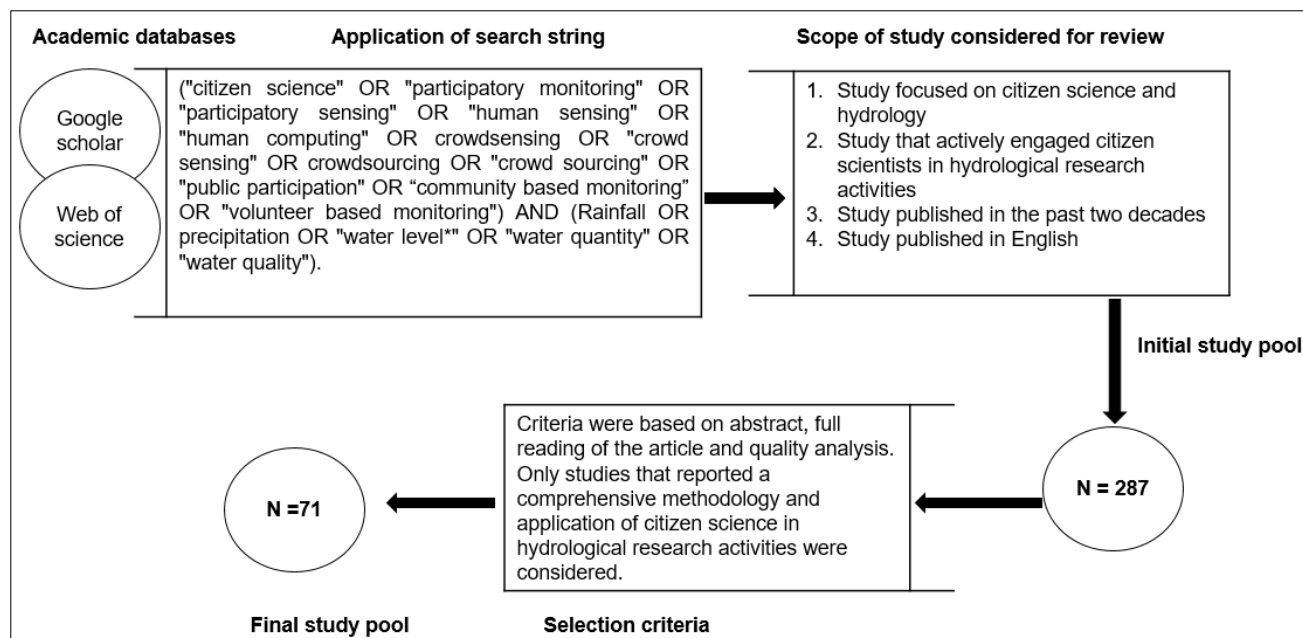


Figure 2.2 Overview of review methodology.

Table 2.1 Data extracted from the articles in the final study pool.

-
- Study reference and year of publication
 - Location of the study
 - Information on number of study sites/ participants and/ or measurements
 - Time scale of the study
 - Monitoring focus
 - Training program
 - Quality assurance plan
 - Communication and data transmission methods
 - Form of citizen participation (after Bonney et al., 2009; Shirk et al., 2012)
 - Name of the project
-

2.5 Results and discussion

2.5.1 Overview of the reviewed articles

The 71 studies reviewed reveal that the number of hydrological-oriented citizen science projects has increased in the last decade (Figure 2.3). The number of studies rose rapidly particularly since

2014, coinciding with emerging technologies, low-cost sensing equipment, and a rising interest in sustainable water resource management. The majority of the studies were carried out in high-income regions with North America and Europe being the most represented at 45% and 20%, respectively (Figure 2.4). Few studies engaging citizen scientists in hydrology were reported in Australia (4%), and low-income countries in Africa and Asia (10% and 9%, respectively). The uptake of citizen science in hydrology even in low-income countries is gradually rising, although it is still at its infancy. In such countries not only data are scarce, but the pressure on water resources is often already very high and increasing (Buytaert et al., 2016; Hannah et al., 2011). Further characteristics of the reviewed studies are presented in more detail in Appendix 2.1.

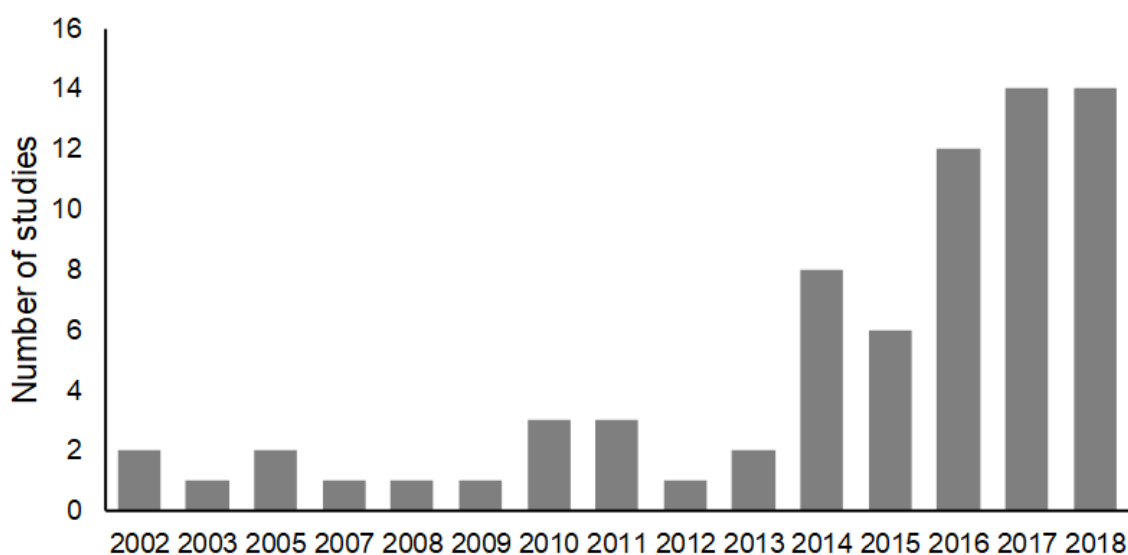


Figure 2.3 Citizen science-based studies in hydrological research between 2001-2018 (n=71).

2.5.2 Scope of monitoring

Programs ranged in the scope of monitoring from local to global scale. Most citizen science programs (63%) focused on the monitoring of water quality even though water level data are easier to collect than water quality parameters (Figure 2.4). This could be due to the increased global awareness of the deterioration of water quality. In addition, there are increasingly more low-cost test kits that measure a wide spectrum of basic water quality parameters, which was also reported by (Buytaert et al., 2014). Programs focused on water quality mostly collect physicochemical (e.g., nitrate, phosphate, turbidity, water color), biological (e.g., macroinvertebrates and *Escherichia coli*) and/or environmental conditions (e.g., land use in the surroundings of the sampling site, presence and number of potential pollution sources, conditions of the riparian vegetation). Some

of the programs were limited to the collection of water samples, with subsequent analysis of the samples in the laboratory (Breuer et al., 2015) in comparison to *in situ* measurements of the water quality parameter (Storey et al., 2016).

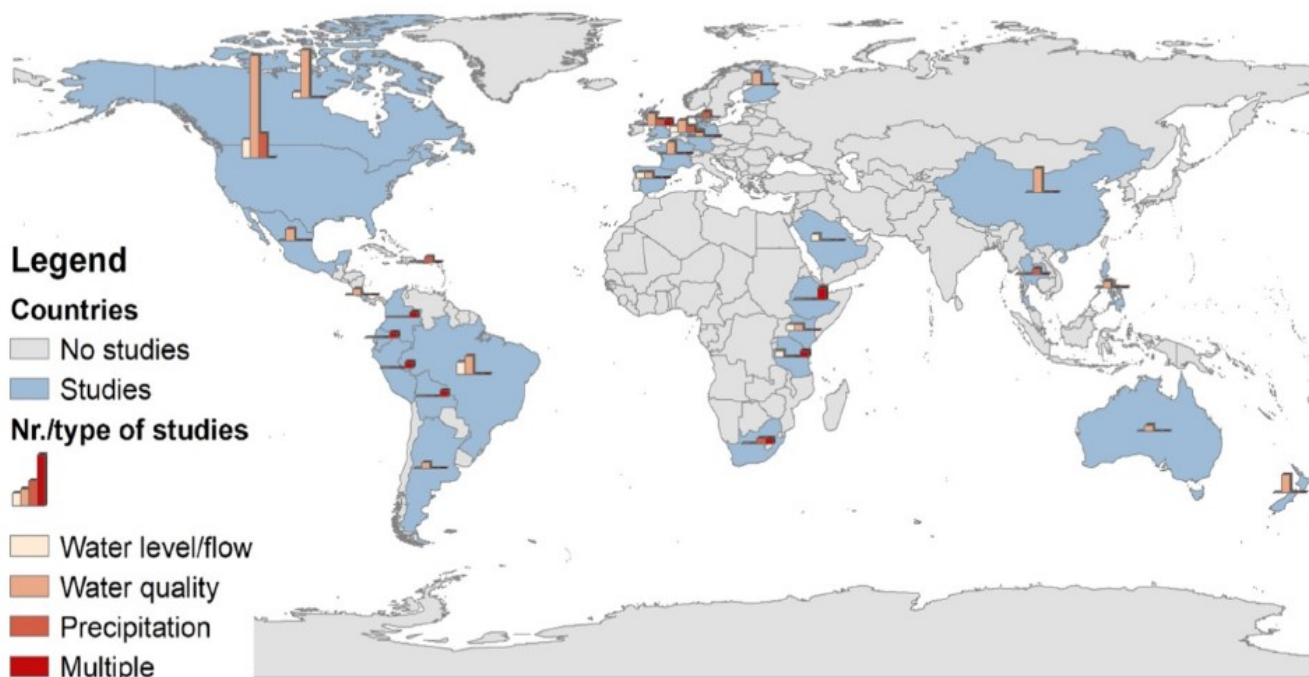


Figure 2.4 Distribution of studies and scope of hydrological monitoring per country.

2.5.3 Spatial and temporal extent

We grouped the spatial coverage and longevity of the programs into three and four categories, respectively (Figure 2.5). Spatial coverage varied widely across monitoring networks ranging from single sites spread across a city or country, to entire watersheds, provinces, or states. Of the studies for which the extent of spatial ($n=49$) and temporal data ($n=61$) could be assessed, most programs ($n=37$) monitored <100 sites and only 5 programs monitored >300 sites. One case has a platform that collects data at the global level (EarthEcho, 2015). The time scales for the monitoring period varied considerably ranging from a 1-day observation to >11 years of monitoring. Most studies ($n=32$) however, lasted 1-5 years (Figure 2.5). Moreover, programs ranged widely in the number of volunteers, with the largest group monitoring thousands of sites.

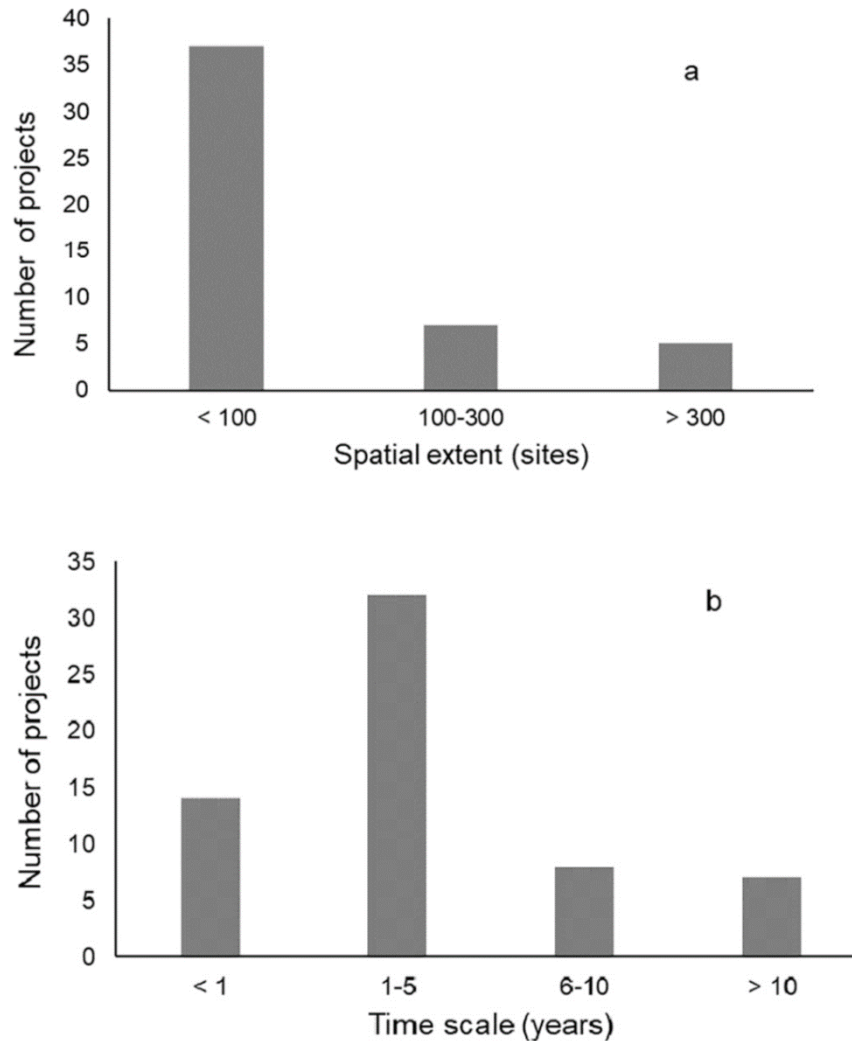


Figure 2.5 (a) Spatial and (b) temporal scales of citizen science projects.

2.5.4 Citizen involvement and training

Participation of citizens differed across programs. In some cases, citizen scientists played a central role in designing the research, protection and basic maintenance of monitoring equipment, data or sample collection, data analysis, interpretation and dissemination of results. We classified each study based on the degree of involvement of the participants as described by (Bonney et al., 2009; Shirk et al., 2012). Most of the studies included in our review (73%) were classified as contributory, i.e. the studies were designed by scientists with citizens primarily contributing to data collection or sample collection. Some studies also showed aspects of a collaborative model with citizens engaged also in analyses of the samples or dissemination of results (23%). Only 4% of the studies were classified as co-created projects, employing a deeper citizen involvement including study design,

data analysis and interpretation (García and Brown, 2009). Professionally executed (contractual model) and citizen-led approaches in scientific research (collegial model) were not employed in any of the studies. All studies involved citizens in data collection and most programs trained the citizens (82%) and followed various quality control measures (90%) to enhance credibility and quality of citizen science generated data. Burgess et al. (2017) note that best practices for scientific outcomes include attention to training, protocol and materials that prepare participants to effectively collect high quality data. The studies used quality control checks such as simplified data collection protocols, standardized training of participants, replication-based method, using time series analysis or comparing citizen science data with standard methods or expert data for validation and identification of outliers (Jollymore et al., 2017; McGoff et al., 2017; Moffett and Neale, 2015; Weeser et al., 2018; Zemadim et al., 2013). The ways in which the participants are approached and trained differ ranging from site visits with formal training in person (Cunha et al., 2017), to instructional online videos or slide shows (Good et al., 2014), and ad hoc instruction in the field by means of signage (Lowry and Fienen, 2013; Weeser et al., 2018).

2.5.5 Information flows and communication channels

The majority of the citizen science programs (n=55) had clear pathways to generate and transmit data. New technologies such as mobile applications, wireless sensor networks and online platforms show great promise for advancing citizen science. Within the reviewed studies, data collection and upload processes were either automated (i.e., data measured and uploaded via sensors or smart apps requiring some form of citizen intervention during installation), semi-automated (i.e., data collected using a sensor but uploaded manually), or manual (i.e., data manually collected, entered and uploaded by citizens). In other cases, data are submitted via paper forms and not available in real-time. In remote regions where internet connectivity is limited, data were crowdsourced using simple text messages (Weeser et al., 2018). A number of studies used a combination of several approaches to submit data such as manual recording of field data on sheets, emailing or using smartphone application (Little et al., 2016; Starkey et al., 2017). Our review reveals that use of smartphone applications is a well-established approach for data collection especially due to the ubiquity of smartphones with built-in options for positioning using global positioning systems (Dickinson et al., 2012). Some programs adopted communication strategies for retention of participants and sustainability of the projects. Continuous communication to provide feedback to

participants about the data submitted, data needs, scientific purpose and importance of data being collected is considered paramount for long term participation (Lowry et al., 2019). Forms of communications such as automated feedback, newsletters, leaflets or the mass media, emails, public meetings and making the data available to the public through online databases were some of the methods applied by programs reviewed (Kongo et al., 2010; Little et al., 2016; Weeser et al., 2018; Williams et al., 2016; Wilson et al., 2018).

2.5.6 Water level and discharge

Streamflow monitoring is complex in nature and mostly relies on indirect measurements of flow velocity, cross sectional area and water level to calculate the flow rate (Buytaert et al., 2014; Royem et al., 2012). In contrast, water level data are easy to collect using a citizen science approach as the measurements consist of observations comparing the level of the water with a clearly defined reference of a staff gauge (Assumpção et al., 2018; van Meerveld et al., 2017). With the expansion of the use of mobile phones in remote regions, there are projects that have successfully engaged citizen scientists in monitoring water levels and flows using text messages. Notable examples are CrowdHydrology in the US and a citizen science-based monitoring program in Kenya (Lowry and Fienen, 2013; Weeser et al., 2018). In these projects, water level gauges alongside signboards were installed at designated stream gauging stations. Citizen scientists, who visit or pass by the sites, sent a text message with the water level reading. Both studies showed that the accuracy of the crowdsourced water level data compared with data obtained from pressure transducer data (Lowry and Fienen, 2013) and automatic radar sensor (Weeser et al., 2018) was satisfactory. In the study of Turner and Richter (2011) citizen scientists successfully mapped the occurrence of stream flow in perennial streams in dryland regions in a 12 years project. Water levels, among other variables, are part of measurements collected by citizen scientists in the FreshWater Watch (<https://freshwaterwatch.thewaterhub.org>) and WeSenseIt programs (Shupe, 2017; Wehn et al., 2018). Other studies have reported the successful establishment of hydrological monitoring networks for river flow and rainfall through an integrated participatory approach involving the local community (Gomani et al., 2010; Kongo et al., 2010). Kongo et al. (2010) noted that the peak flows obtained by the local community was in close agreement with results obtained from a modelling exercise from the Potshini catchment in South Africa.

With the rise in robust sensing equipment and smartphones applications embedded in cameras, web-based mapping tools and global navigation satellite systems, new approaches are emerging that are easily integrated into a citizen science context (Buytaert et al., 2014). Little et al. (2016) involved citizen scientists in the monitoring of groundwater levels in private wells using water level sounders. Citizen scientists provided valuable data on groundwater levels across a large area in Alberta, Canada and measurements were accurate when compared with data from automatic pressure transducers (root mean square error of 3-11 cm). To characterize hydrological regime for ungauged catchments, (Gallart et al., 2017), developed and tested an open source software (TREHS) based on interviews to local people. In Tanzania, local communities were involved in the collection of water level data using a smart-stick technology and taking images for discharge measurements in rivers and furrows using smartphones (iMoMo, 2018). The CrowdWater and Stream Tracker projects crowdsource hydrologic measurements including water level, streamflow and flow condition of intermittent streams. The data are collected with a smartphone application, where the user takes a picture and use the app to add virtual staff gauge and no physical installations or sensors are needed for the measurements with this approach (Kampf et al., 2018).

2.5.7 Precipitation

Heterogeneous distribution of observational networks limit the spatial and temporal representation of precipitation measurements, especially in less populated regions (Kidd et al., 2017). The simple design, affordability, availability and the ease of installation and operation makes manual rain gauges suited for application in citizen science (Buytaert et al., 2014). Furthermore, observing precipitation requires no advanced education in meteorology and thus crowdsourcing for precipitation has a great potential to gather data (Elmore et al., 2014). The Community Collaborative Rain, Hail and Snow network (CoCoRaHS) initiated in 1998 is probably the largest and most effective example of a citizen science-based network that involves volunteers in recording daily precipitation using low-cost tools across the US and Canada (Cifelli et al., 2005; Reges et al., 2016). The UK Community Rain Network (UCRaiN) which was inspired by CoCoRaHS, also demonstrated the potential of community-based rainfall data collection. A correlation of 0.81 was observed between the citizen and an automatic rain gauge measurements (Illingworth et al., 2014). The Phenomenon Identification Near the Ground (PING) network in the US uses a mobile application (mPING) to crowdsource high quality, spatially and temporally dense precipitation

data. This data are used to improve the dual-polarization radar hydrometeor classification algorithm (Elmore et al., 2014), and to verify surface precipitation forecasts from operational numerical models (Apps et al., 2014). The Citizen Weather Observer Program is another initiative that demonstrates how a citizen science-based approach can increase the temporal and spatial resolution of monitoring real-time meteorological data supplementing traditional networks (Bell et al., 2013).

The Internet of Things (IoT) provides new opportunities for application of citizen science to acquire vast amounts of weather data, as many people are getting connected to the internet (Meier et al., 2015). As a result of these developments, there is a growing number of automated private weather stations (PWS) that link rainfall measurements to online platforms (Bell et al., 2015; Vos et al., 2017). For instance, the user-friendly and affordable NetAtmo personal weather stations are widely distributed around the world to monitor atmospheric conditions such as temperature, humidity, air pressure, CO₂, wind and rainfall. These smart devices are automatically linked with an online platform (<https://weathermap.netatmo.com/>) collecting and visualizing data from all operational stations (Vos et al., 2017). Studies have shown that crowdsourced atmospheric datasets obtained from NetAtmo weather stations can contribute to urban hydro-meteorological research (Meier et al., 2015), as urban areas are characterized by a high spatial heterogeneity of rainfall, not covered by the low-spatial coverage of institutional rainfall monitoring networks. Further, the NetAtmo rainfall time series resembled measurements from a conventional high-resolution electronic gauge (Vos et al., 2017). From the aforementioned works, it is evident that high-resolution precipitation data could improve hydrological applications even in data scarce regions. Such data can be obtained through citizen science monitoring, especially with the advent in technology and new innovative data collection techniques.


2.5.8 Water quality

Citizen science has been widely used to monitor water quality in lakes, streams, rivers, wells, ponds, and wetlands (Conrad and Hilchey, 2011). Currently, various organizations in several countries around the world are involved in collaborative efforts and support volunteer-based water quality monitoring programs (Deutsch and Ruiz-Córdova, 2015). Water quality data are essential to improve the management effectiveness of surface water systems (Zheng et al., 2018). The World Water Monitoring Day initiative (<http://www.worldwatermonitoringday.org/>) established by the America's Clean Water Foundation (ACWF) is a worldwide educational outreach program that

uses online means to recruit and engage citizens in protecting water resources and empowering them to conduct basic water quality monitoring of their local water bodies (EarthEcho, 2015). A similar scheme is coordinated by Community Science Institute in New York, to produce data that inform water resource management while simultaneously educating and empowering citizens to become stewards of their local environment (Community Science Institute, 2017). The Florida Lakewatch, and Alabama Water Watch (AWW) are successful examples of long-term volunteer water quality monitoring programs, working with thousands of citizen scientists for over ten years to study fresh water ecosystem dynamics and generating information on more than 1,500 water bodies (Deutsch and Ruiz-Córdova, 2015; Hoyer et al., 2014; Thornhill et al., 2018).

Although most citizen-science water quality programs collect data in the form of water samples (Breuer et al., 2015; Good et al., 2014), others involve *in situ* monitoring of parameters like turbidity and nutrient concentrations or ecosystem health indicators such as macroinvertebrates or *Escherichia coli* (Latimore and Steen, 2014; Scott and Frost, 2017; Thornhill et al., 2017). Various methods and techniques have been reported for different programs. They span from simple test kits to measure water quality parameters such as dissolved nitrate and orthophosphate, such as in the FreshWater Watch program (Shupe, 2017) or the World Water Monitoring Day initiative (EarthEcho, 2015). In other cases, citizens are involved in the visual assessment of water color, smell and surrounding conditions (Zheng et al., 2017). In the Sondu catchment of Kenya, a citizen science-based project engages citizen scientists in monitoring water levels and quality (Table 2.2). Nitrate levels are measured using simple colorimetric methods (Gräf, 2018). Secchi disks and turbidity tubes have been widely used in volunteer monitoring for water turbidity (Toivanen et al., 2013), and have been successfully applied in the Sondu catchment. Gräf (2018) tested the ‘tampon method’ using inexpensive passive samplers to detect optical brighteners in the surface waters of the Sondu catchment. Here, the community wash their clothes in the streams and it was hypothesized that optical brighteners from detergents could be detected downstream. In urban areas, optical brighteners are strong indicators of misconnected drainage in surface waters (Chandler and Lerner, 2015). However, application of this approach in streams could be influenced by high concentration of suspended sediments as demonstrated in the Sondu catchment (Gräf, 2018), and the method could be improved especially by protecting the tampons and sampler from sediments to improve accuracy.

Table 2.2 Citizen science-based water monitoring in Sondu Catchment, Kenya.

Parameter	Water levels	Optical brighteners	Nitrate	Turbidity
Method	Manual water level gauges at fixed locations. and a signage to provide instructions	A tampon fixed at a small metal bar. Presence of optical brighteners checked with a UV-torch light.	Dissolved nitrate measured from unfiltered samples using nitrate strips. Nitrate concentration estimated by comparing the resultant reaction to a reference chart with specific ranges.	Water turbidity determined through a calibrated turbidity tube, which is filled with water until the marking at the bottom is no longer visible when viewed from above. Turbidity is estimated against a turbidity unit scale.
Example				

Photos courtesy of Patrick Shepherd, Centre for International Forestry Research (CIFOR).

The increasing appeal in participatory research, advent of internet connectivity and low-cost sensing equipment improved monitoring capabilities for water quality. Projects are now increasingly adopting modern data collection and transmission technologies and making use of integrated sensing systems with multi-parameter monitoring (Kotovirta et al., 2014). Applications such as the automatic Secchi3000 (Toivanen et al., 2013), KDUINO ((Bardaji et al., 2016) and Hydrocolor (Leeuw and Boss, 2018) have been used and validated to measure water turbidity with citizens. Overall, the recently developed monitoring systems are cost-effective, portable, offer continuous real-time water quality monitoring and cloud data storage possibilities, and are easy to use with minimal training.

2.5.9 Social media

Researchers are increasingly mining volunteered geographic information such as images and videos shared via social media (e.g., Facebook, YouTube, Twitter and Flickr) to estimate water levels, flow velocities and discharges (Boursicaud et al., 2016; Fohringer et al., 2015; Le Coz et al., 2016; Michelsen et al., 2016). This sort of heterogeneous and complex information has, for instance been applied in hydrology for real-time mapping, to understand the dynamics of flood processes and to validate models for the prediction of flood events (Li et al., 2018; McDougall, 2011; Smith et al., 2017). Some of the studies reported (Table 2.3) did not actively involve or engage with the public directly like other deliberate citizen science approaches, hence the participants are probably unaware of their contribution and participation in a scientific study (Daume et al., 2014; Michelsen et al., 2016).

Table 2.3 Contribution of citizen science in hydrology through social media.

Reference	Location	Type of data	Application
Boursicaud et al., (2016)	France	Video of a flash flood event shared via social media (YouTube)	Estimation of water level, surface flow velocities and discharges
Le Coz et al., (2016)	Argentina, France and New Zealand	Video sent through the website	Estimation of water level/surface flow velocities and discharges
Michelsen et al., (2016)	Saudi Arabia	Videos and photographs shared on social media via YouTube	Analysis of water level time series
Li et al., (2018)	USA	Texts and pictures shared via Twitter	Flood mapping
McDougall, (2011)	Australia	Photographs and videos shared via Twitter and Facebook	Mapping of flood extent
Fohringer et al., (2015)	Germany	Photographs shared via Twitter and Flickr	Analysis of water level and flood inundation mapping.
Smith et al., (2017)	UK	Pictures and texts posted via Twitter	Modelling

2.5.10 Data credibility and application of citizen science data

Given the heterogeneity of citizen science based monitoring, most programs develop and adopt rigorous quality assurance/quality control measures for quality assessment to ensure the production of scientifically valid water data. The United States Environmental Protection Agency provides support to volunteer water quality monitoring programs by developing guidelines, manuals and toolboxes that are essential for communities (English et al., 2018). During the initiation phase of most projects, citizen scientists are provided with monitoring protocols, materials, equipment and training on water monitoring. Several recent studies have assessed the quality of the citizen science water quality data to account for data standards and reliability. Studies that compared volunteer *versus* professional datasets or with standard methods suggest that citizen scientists generate high quality data which is comparable to professional data (Aceves-Bueno et al., 2017; Canfield Jr et al., 2002; Hoyer et al., 2014; Loperfido et al., 2010; Nicholson et al., 2002; Storey et al., 2016). Fore et al. (2001) compared volunteer and professional monitoring of benthic macroinvertebrates as bio-indicators of water quality, reporting similar data quality. Water temperature and dissolved oxygen data in stream and rivers collected by scientists from the US Geological Survey and citizen scientists showed that both measurements are in the same range, although volunteer measurements underestimated dissolved oxygen levels (Safford and Peters, 2018). Aceves-Bueno et al. (2015) reviewed 83 citizen science studies and reported only one case of insufficient data quality associated with citizen science generated data.

Some organizations use and combine citizen scientists data as part of their research activity, which is an indication that scientists considered these datasets to be of sufficient quality for research (Follett and Strezov, 2015). In the US, the IOWATER volunteer water quality monitoring program supplements the information used by the government for regulatory purposes (Loperfido et al., 2010). Thornhill et al. (2018) used the FreshWater Watch datasets to explore the effect of increasing urbanization on the seasonal, chemical, and biological conditions of ponds and lakes. Elsewhere, Wang et al. (2018) used the data accrued by the Community Science Institute (CSI) to model stream *Escherichia* spp. concentrations and loadings. Koskelo et al. (2012) used rainfall data from the Weather Underground (WU) website (<https://www.wunderground.com/>) to quantify the spatial variability in rainfall and base flow separation for small watersheds. Lincoln et al. (2017) utilized > 200 rainfall reports obtained by citizen scientists in different programs to improve the

analysis of severity and scope of the North Central Gulf Coast historic rainfall event that occurred in April 2014. Organizations such as the US National Oceanic and Atmospheric Administration and the National Hydrologic Warning Council have integrated ground observations of precipitation obtained from CoCoRaHS monitoring network into their work to validate radar precipitation estimations and that obtained from automated rain gauge networks (Kluver et al., 2015; Simpson et al., 2017; Smith et al., 2015; Zhang et al., 2014). There are practical applications in the Netherlands, where 20 amateur stations were used to quantify the heat-island effect in urban areas (Wolters and Brandsma, 2012).

2.5.11 Data transmission

The growth in open science including the development of customizable mobile applications, scientific instrumentation and data storage technologies has increased the efficiency for direct and rapid data upload, validation and visualization of data on web-based databases (Little et al., 2016). Notably, these developments play a great role towards overcoming the potential for errors that come with manually recording and uploading data or loss of vast amounts of information produced (Curtis, 2018). Crowdwater (Kampf et al., 2018), Creekwatch (Kim et al., 2011), and Crowdmap (Ross and Potts, 2011) present mobile apps used to harness the power of citizen scientists to collect hydrologic data. Nowadays, citizen scientists can also collect data through images and videos with geo-located date and time-stamped information that can be used for further analyses. For instance in Creek Watch, a smartphone application allows to submit photos and qualitative stream data about water level, water flow rate and amount of litter along waterways (Kim et al., 2011). The applications are non-intrusive, cost-effective, portable and measurements are transmitted to a cloud database and automatically synchronized to be managed, analyzed and shared or exported. Additionally, the setup of the websites allows data validation, visualization, and real-time mapping of results (Bell et al., 2013) such as the Weather Underground (<https://www.wunderground.com/>), UK Met Office Weather Observation Website (<http://wow.metoffice.gov.uk/>). These websites provide an open platform for citizens to share weather data online with the wider community (Vos et al., 2017). Similarly, cloud-based storage has now become the standard means to store data, which facilitated the rapid growth in citizen science. Cloud server and storage solutions are low-cost, scalable allowing for platforms to be easily developed via application programming interfaces (APIs) to display large datasets in real time to end users (Chapman and Bell, 2018).

2.5.12 Future developments

Camera-based systems are increasingly used to collect environmental data because images and videos are more informative and intuitive than other crowdsourcing methods (Jiang et al., 2019). Large-Scale Particle Image Velocimetry (Tauro et al., 2017) and DischargeApp (iMoMo, 2018) methodologies have increased the ability to conduct streamflow measurements. However, camera based approaches are still limited in hydrology. Royem et al. (2012) developed a low-cost monitoring system based on a digital camera to measure water level, which showed good agreement with water levels measured traditional gauging stations. This method is simple enough to be applied in citizen science. Allamano et al. (2015) introduced a novel technique based on the quantitative detection and measuring of rainfall intensity from pictures of rainy scenes. Other studies demonstrated the use of *in situ* digital camera, wireless sensor network and other smartphone-based systems for real-time water quality monitoring (Goddijn-Murphy et al., 2009; Rasin and Abdullah, 2009; Srivastava et al., 2018). Sakai et al. (2018) developed and validated ECO-Heart, a simple tool for a community-based water quality assessment, which was used to monitor six parameters: pH, heavy metals, chemical oxygen demand, transparency, ammonia nitrogen and dissolved oxygen. Similarly, in remote regions such as mountain streams where physical installation of staff level gauges or sensors or camera-based systems to monitor water level is difficult, a virtual staff gauge approach could be used (Seibert et al., 2019).

2.6 Conclusions

This review shows that it is possible to successfully engage the public in hydrological monitoring. Hydrological citizen science monitoring programs can generate extensive datasets with broad spatial and temporal coverage. Most programs recruit and train participants and through validation and calibration, researchers have found that citizen scientists collect data comparable to professional data. Effective communication strategies have to be implemented to promote sustainability such as games for education, making data publically available (e.g. via websites, public meetings with scientists, newsletters and/or social media), developing interactive webpages, and providing automated feedback. In most projects, the role of citizen scientists is limited to information and data collection. Future citizen science in hydrology could benefit from more co-created types of projects to establish stronger ties between research and communities that lead to public engagement, thereby enhancing sustainability of monitoring networks.

An emerging area of research is the mining of volunteered geographic information from social media. Information shared through social media could provide highly valuable hydrological data that can offer direct insights in flow rate and help improve the understanding of extreme hydrological events. Moreover, the analysis of hydrological data from social media may support a better understanding of the interactions between humans and the environment for shaping future environmental management. Hence, future studies can benefit from crowdsourcing information of hydrological relevance from social media to improve the spatial coverage of the hydrological measurements. All these findings demonstrate the potential of citizen science networks to collect reliable, timely and long-term hydrological data, which is very important information for planning and management purposes. Possible developments are expected to draw large benefit from the rapid technological advancements in sensors and from the massive penetration of smartphone technologies, especially in low-income countries as well.

Acknowledgments

We thank the German Federal Ministry for Economic Cooperation and Development (Grants 81195001 “Low Cost methods for monitoring water quality to inform upscaling of sustainable water management in forested landscapes in Kenya” and Grant 81206682 “The Water Towers of East Africa: policies and practices for enhancing co-benefits from joint forest and water conservation”) for generously providing financial support, and the German Science Foundation DFG (BR2238/23-1) for co-funding this research. This work is a contribution to the CGIAR programme on Forest, Trees and Agroforestry led by the Centre for International Forestry Research (CIFOR).

We also thank the German Academic Exchange Service (DAAD), along with National Research Fund (NRF), Kenya for the scholarship award.

Appendix 2.1 Overview of citizen science application in hydrological monitoring.

Reference	Location	Number of sites/ participants/ measurements	Time scale	Monitoring Focus	Training	QA/ QC	Data transmission	Type of project	Program
Abbott et al. (2018)	France	13 sites	18 years	Water quality	n.s.	n.s.	n.s.	Contributory	Ecoflux
Bardaji et al. (2016)	Spain	2 sites	n.s.	Water quality	yes	yes	n.s.	Collaborative	
Breuer et al. (2015)	Germany	280 sites	1 day	Water quality	yes	yes	Grab water samples delivered to lab	Contributory	HydroCrowd
Brouwer et al. (2018)	Netherlands	85 sites/ 85 participants	n.s.	Water quality	yes	yes	Online survey - SurveyMonkey software	Contributory	Freshness of Water
Canfield Jr et al. (2002)	US	125 sites	>10 years	Water quality	yes	yes	Manual recording - data sheets	Contributory	Florida LAKEWATCH
Cifelli et al. (2005)	US	>1000 participants	7 years	Precipitation	yes	yes	CoCoRaHS webiste	Collaborative	CoCoRaHS
Cunha et al. (2017)	Brazil	64 sites	4 months	Water quality	yes	yes	Grab water samples	Contributory	Freshwater watch
Reutebuch et al. (2008)	US	>1950 sites/ >4,700 participants	>15 years	Water quality	yes	yes	Alabama Water Watch server	Collaborative	Alabama Water Watch
Deutsch et al. (2005)	Phillipines	n.s.	>5 years	Water quality	yes	yes	n.s.	Collaborative	
Edwards et. (2018)	US	n.s.	7 years	Water quality	yes	yes	n.s.	Collaborative	
Edwards, (2016)	US	3 sites	11 years	Water quality	yes	yes	n.s.	Contributory	
Elmore et al. (2014)	US	n.s.	4 months	Precipitation	yes	yes	Mobile application (MPING)	Contributory	
Farnham et al. (2017)	US	23 sites	>2 years	Water quality	n.s.	yes	Grab water samples delivered to lab	Contributory	
Flores-Díaz et al. (2018)	Mexico	30 sites	>5 years	Water quality	yes	yes	n.s.	Collaborative	Global Water Watch
Gomani et al. (2010)	Tanzania	39 sites	n.s.	Water level & flow, precipitation, and ground water level	n.s.	n.s.	n.s.	Collaborative	Resilient Agro-landscapes to Climate Change

Good et al. (2014)	US	>125 participants/ 685 measurements	1 day	Precipitation	yes	yes	Grab water samples delivered to the laboratory for analysis	Contributory	
Illingworth et al. (2014)	UK	13 sites	>1 month	Precipitation	yes	yes	Email or Twitter	Contributory	UCRaiN- the UK Citizen Rainfall Network
Jollymore et al. (2017)	Canada	n.s.	1 year	Water quality	n.s.	yes	Grab water samples delivered to the laboratory for analysis.	Contributory	Waterlogged citizen science campaign
Koch & Stisen (2017)	Denmark	n.s.	2 months	Precipitation	n.s.	n.s.	n.s.	Contributory	
Kongo et al. (2010)	South Africa	n.s.	2 years	Stream flows & precipitation.	yes	yes	Manual recording- data sheet	Collaborative	
Kosgei et al. (2007)	South Africa	3 sites	1 year	Precipitation	yes	yes	n.s.	Collaborative	
Kotovirta et al. (2014)	Finland	320 sites/ 872 participants	3 years	Water quality	yes	yes	Hydrocolor mobile application	Contributory	
Leeuw and Boss (2018)	USA	14 measurements	1 day	Water quality	yes	yes	Smartphone application	Contributory	
Lévesque et al. (2017)	Canada	28 sites/ 69 participants	>2 years	Water quality	yes	yes	Smartphone application	Contributory	Freshwater watch
Little et al. (2016)	Canada	40 sites	5 years	Water level	yes	yes	Telephone, fax or email and web portal	Contributory	
Loiselle et al. (2016)	Argentina, Brazil, Mexico and Canada	150 sites/ 1000 participants	2 years	Water quality	yes	yes	Online upload	Contributory	Freshwater watch
Lowry & Fienen (2013)	USA	9 sites/ 150 measurements	>6 months	Water level	none	yes	Simple text message	Contributory	Crowdhydrology
McGoff et al. (2017)	United Kingdom	76 sites	3 years	Water quality	yes	yes	Smartphone application	Contributory	Fresh water watch
Michelsen et al. (2016)	Saudi Arabia	16 videos	1 year	Water level	none	yes	Sharing of videos and photographs on YouTube.	Contributory	
Moffett & Neale (2015)	New Zealand	21 sites	11 years	Water quality	yes	yes	n.s.	Contributory	

Ochoa-Tocachi et al. (2018)	Peru, Ecuador and Bolivia	9 sites	n.s.	Precipitation and stream flow	n.s.	yes	n.s.	Contributory	Initiative for Hydrological Monitoring of Andean Ecosystems
Reges et al. (2016)	USA, Puerto Rico, US Virgin Islands, and Canada	>50 states/ >20,000 participants	>10 years	Precipitation	yes	yes	CoCoRaHS website	Collaborative	
Shahady & Boniface (2018)	Costa Rica	16 sites	2 years	Water quality	yes	yes	Manual recording - data sheet	Contributory	
Shupe (2017)	Canada	81 sites	4 years	Water quality	yes	yes	Manual recording and smartphone app in online database	Contributory	Freshwater watch
Starkey et al. (2017)	Britain	10 sites	>2 years	Water level, precipitation and water quality	yes	yes	Web forms, spreadsheets, email, meetings, and Android app	Contributory	
Storey and Wright-Stow (2017)	New Zealand	8 sites	>1 year	Water quality	yes	yes	n.s.	Contributory	
Storey et al. (2016)	New Zealand	11 sites/ 77 participants	>1 year	Water quality	yes	yes	n.s.	Contributory	
Thornhill et al. (2018)	UK, France, Netherlands, US, Canada & Australia	75 sites/120 participants	2 years	Water quality	yes	yes	n.s.	Contributory	Fresh water watch program
Toivanen et al. (2013)	Finland	100 participants/1146 measurements	1 year	Water quality	n.s.	yes	Smartphone application	Contributory	
Walker et al. (2016)	Ethiopia	8 sites	>1 year	Precipitation, stream water level & groundwater levels	yes	yes	Manual recording-data sheet	Collaborative	AMGRAF
Weeser et al. (2018)	Kenya	13 sites/ 125 participants/ 1175 measurements	1 year	Water level	yes	yes	Simple text message	Contributory	

Wendt et al. (2018)	USA	131 sites/ >50 participants	n.s.	Water quality	yes	yes	n.s.	Contributory	
Williams et al. (2016)	USA	424 sites/ 248 participants	10 years	Water quality	yes	yes	Direct online upload and grab samples delivered to lab	Contributory	Trout Unlimited
Wilson et al. (2018)	Canada	54 sites	8 years	Water quality	yes	yes	n.s.	Contributory	
Wiwatwattana et al. (2015)	Thailand	25 participants/ 301 measurements	140 days	Precipitation	yes	yes	Facebook application (SWUA)	Contributory	
Xu et al. (2017)	China	8 sites	>2 years	Water quality	yes	yes	Direct upload to online database	Contributory	Freshwater watch program
Zemadim et al. (2013)	Ethiopia	28 sites	n.s.	Precipitation, water level, groundwater level	yes	yes	Submitted monthly hard copies	Collaborative	
Zhang et al. (2017)	China	31 sites	4 years	Water quality	yes	yes	Smartphone app or by internet to online database	Contributory	
Zheng et al. (2017)	China	30 provinces/ 219 measurements	>1 year	Water quality	yes	yes	Smartphone application	Contributory	Freshwater watch program
Engel & Voshell, (2002)	USA	145 sites	2 years	Water quality	yes	yes	Manual recording-data sheets	Contributory	Virginia-Save-Our-Streams program
Nerbonne & Vondracek (2003)	USA	n.s.	2 years	Water quality	yes	yes	Manual recording-data sheets	Contributory	
Barrows et al. (2018)	USA	72 sites/ 117 participants	2 years	Water quality	yes	yes	Smartphone app, manual recording-datasheets & grab water samples delivered to lab	Collaborative	
Compas & Wade (2018)	USA	2 participants/ >30,000 measurements	11 days	Water quality	yes	yes	Smartphone application	Contributory	“Testing the Waters
Dorset Environmental Science Centre (2015)	Canada	>800 sites/ >600 participants	3 years	Water quality	yes	yes	n.s.	Contributory	Lake Partner Program

Fava et al. (2014)	Brazil	n.s.	n.s.	Water level	n.s.	n.s.	Mobile application	Contributory	
Alfonso et al. (2010)	Netherlands	4 sites/ 4 participants	1 month	Water level	n.s.	yes	Simple text message	Contributory	
Degrossi et al. (2014)	Brazil	10 participants/ 15 measurements	n.s.	Water level	yes	yes	Smartphone application	Contributory	
Turner & Richter (2011)	USA,	n.s.	12 years	Water level	yes	yes	Manual recording-data sheet	Contributory	
Kim et al. (2011)	USA	65 measurements	3 weeks	Water level, flow rate and trash	yes	n.s.	Mobile app	Contributory	
Muenich et al. (2016)	USA	206 sites/ 889 participants	5 years	Water quality	yes	yes	n.s.	Collaborative	
Vos et al. (2017)	Netherlands	63 sites	4 months	Precipitation	n.s.	yes	Direct upload through Wi-Fi connection	Collaborative	
Gallart et al. (2017)	Spain	119 sites	n.s.	Water flow	n.s.	n.s.	Questionnaire	Contributory	
García & Brown (2009)	Colombia	38 sites/ 30 participants	2 years	Water quality and water flows	yes	yes	n.s.	Co-created	
iMoMo (2018)	Tanzania	24 sites	6 years	Water flows	yes	yes	Simple text message and smartphone application	Co-created	iMoMo Global Initiative.
EarthEcho (2015)	Global	146 countries	>11 years	Water quality	yes	yes	Direct upload online to a central database.	Co-created	World Water Monitoring Challenge
Macknick & Enders (2012)	USA	19 sites/ 70 participants	> 1 year	Water quality	yes	n.s.	Grab samples	Contributory	
Castilla et al. (2015)	Brazil & China	13 cities	> 1 year	Water quality	yes	yes	Smartphone app	Contributory	Fresh Water Watch
Latimore & Steen (2014)	USA	> 500 sites	n.s.	Water quality	yes	yes	n.s.	Contributory	MiCorps
Scott & Frost (2017)	Canada	29 sites/111 participants	3 years	Water quality	yes	yes	Smartphone application	Contributory	Fresh Water Watch
Gräf (2018)	Kenya	6 sites	< 1 year	water quality	yes	yes	Simple text message	Contributory	
Stepenuck et al. (2011)	USA	6 states/ 150 participants	2 years	Water quality	yes	yes	Grab samples delivered to lab	collaborative	

*n.s.- not specified

3. Monitoring of suspended sediments in a tropical forested landscape with citizen science

This chapter is published in *Frontiers in Water* as:

Njue, N. K., Gräf, J., Weeser, B., Rufino, M. C., Breuer, L., & Jacobs, S., 2021. Monitoring of suspended sediments in a tropical forested landscape with citizen science. *Frontiers in Water*, 3, 56. <https://doi.org/10.3389/frwa.2021.656770>

3.1 Introduction

In the tropics, natural ecosystems and water resources are increasingly threatened by several factors including growing human population, climate change, deforestation, and increased cropping and grazing intensities (Berihun et al., 2019; Shupe, 2017; Smith et al., 2016). Consequently, many tropical forest ecosystems have been subject to disturbances, which vary through time and space. Previous studies have demonstrated the effect of land use change on soil erosion and sediment yield, with conversion of forest to agricultural or grazing land yielding the highest soil loss due to changes in soil properties such as reduced infiltration rates and water retention capacity (Owuor et al., 2018; Stenfert Kroese et al., 2020a). Increased surface runoff may lead to flooding and accelerates sediment transport processes, resulting in amplification of the sediment load in rivers (Owuor et al., 2018; Pacheco et al., 2014). Monitoring of sediment loads in catchments is important for the development of soil erosion management and control strategies, to inform policies for water resources management and for the validation of spatially distributed sediment delivery models (Walling et al., 2001; Kuhnle and Wren, 2005; Gao et al., 2007).

Much of the recent focus in hydrogeochemical research has been on the use of models, remote sensing and high resolution automated monitoring systems to further improve our understanding of ecological systems (Baldyga et al., 2008; Esteves et al., 2019; Jacobs et al., 2018). Although these approaches have been widely used to inform decision making for environmental management, they are expensive and their application within most developing countries is still hampered by poor infrastructure and technical capabilities (Nardi et al., 2020; Olang and Fürst, 2011). As a consequence, relatively few hydrogeochemical datasets exist (Zheng et al., 2017). As the acquisition of field data with high spatial and temporal resolution is very important for

sustainable water resource management and governance, this clearly raises the need to explore alternative cost-effective approaches for data collection (Malthus et al., 2020; Njue et al., 2019).

Advances in technology and the rise of robust simple and cheap sensing equipment provides unprecedented opportunities for data collection using citizen science in hydrological sciences and water resources management, especially in data scarce regions (Buytaert et al., 2014; Zheng et al., 2017). Citizen science refers to the involvement of the general public within the scientific research process for the generation of new scientific knowledge (Bonney et al., 2009b; Buytaert et al., 2014). Although citizen science is still uncommon practice in water research, we recognize that its uptake in low-income countries such as Kenya is gradually rising (Njue et al., 2019), especially in monitoring of precipitation, water levels and water quality (Gomani et al., 2010; Kongo et al., 2010; Walker et al., 2016; Weeser et al., 2018). As a scientific method, citizen science is acknowledged to play an important role in delivering valuable and robust environmental data from local to national scales, increasing knowledge of science and reducing monitoring costs (Bonney et al., 2009a; Haklay, 2015; Silvestro et al., 2012). Moreover, citizen observations can provide quality and detailed ground-based data for calibration and validation of satellite-based earth observation and high-resolution automated stations (Fritz et al., 2017; Nardi et al., 2020). Njue et al. (2019) present a comprehensive review on the successful implementation, contribution and significant growth in application of state-of-the-art citizen science approaches in hydrological monitoring in the past two decades. Looking ahead, citizen science could be used cost-effectively not only to fill data and information gaps, but also to work collaboratively with communities to generate relevant management-oriented knowledge.

This study aimed to evaluate the potential of using citizen science to explore spatiotemporal suspended sediment dynamics using turbidity as a proxy in the Sondu-Miriu river basin in Kenya. The Sondu river originates in the Mau Forest Complex, which is one of Kenya's remaining indigenous tropical montane forests. The Mau Forest Complex experienced a significant loss of 25% forest cover between 1973 to 2013 through illegal logging, forest excisions, charcoal burning and encroachment for settlement and subsistence farming by smallholder farmers (Brandt et al., 2018; Olang and Kundu, 2011; Otuoma et al., 2012; Swart, 2016). Previous studies have linked deforestation in the Mau Forest Complex, to changes in hydrological processes such as changes in flow regimes, soil and water quality deterioration in the catchment (Jacobs et al., 2017; Masese et

al., 2012; Otuoma et al., 2012; Owuor et al., 2018). Masese et al. (2012) highlight that due to the combined effects of human activities in the Sondu-Miriu river basin, turbidity has more than doubled in 30 years from a mean of 60 NTU in 1988 to 130 NTU in 2012. This could contribute to the accumulation of sediments in Lake Victoria at a rate of 2.3 mm yr⁻¹ and its effect on eutrophication (Verschuren et al., 2002; Zhou et al., 2014). Additionally, there has been a growing concern amongst the local officials in the water sector and water resource users on the significant increase in sediment transport in the Sondu river basin, which could be linked to high levels of encroachment (Kinyanjui, 2009).

Being the primary catchment area of the Sondu river, the Mau Forest Complex plays a critical role in the management of water resources, water quality and erosion. The Sondu river is not only important as a source of water for commercial (tea and forestry plantations) as well as smallholder agricultural and domestic use, but also for hydropower production. Improving the knowledge on water flows and suspended sediments dynamics in catchments with hydroelectric power plants is crucial (Esteves et al., 2019). Therefore, the collection of data to evaluate the spatial and temporal variability of sediment loads with the Sondu-Miriu river basin is needed to establish a proper baseline to assess alternative future management strategies. We hypothesized that citizen science is a cost-effective, and robust approach for data collection for sustainable water resource management, as it reduces the costs of suspended sediment monitoring and significantly improves data coverage. To our knowledge, this study presents the first analysis of community-based monitoring of sediment dynamics in a tropical forested catchment in East Africa.

3.2 Materials and Methods

3.2.1 Catchment description

The study was carried out in the Sondu-Miriu river basin (3,450 km²) which originates in the Mau Forest Complex and drains into Lake Victoria at an elevation range of 1,140 to 2,900 m a.s.l. (Figure 3.1A). The temporal rainfall distribution in the basin is driven by the intertropical convergence zone, generally exhibiting a bimodal rainfall pattern. A longer rainy season occurs from April to July, with rainfall peaks in April and May (>250 mm per month) in the upper part of the catchment, and a shorter rainy season between October and December. During the dry season in January and February the area receives the lowest amount of rainfall (<75 mm per month).

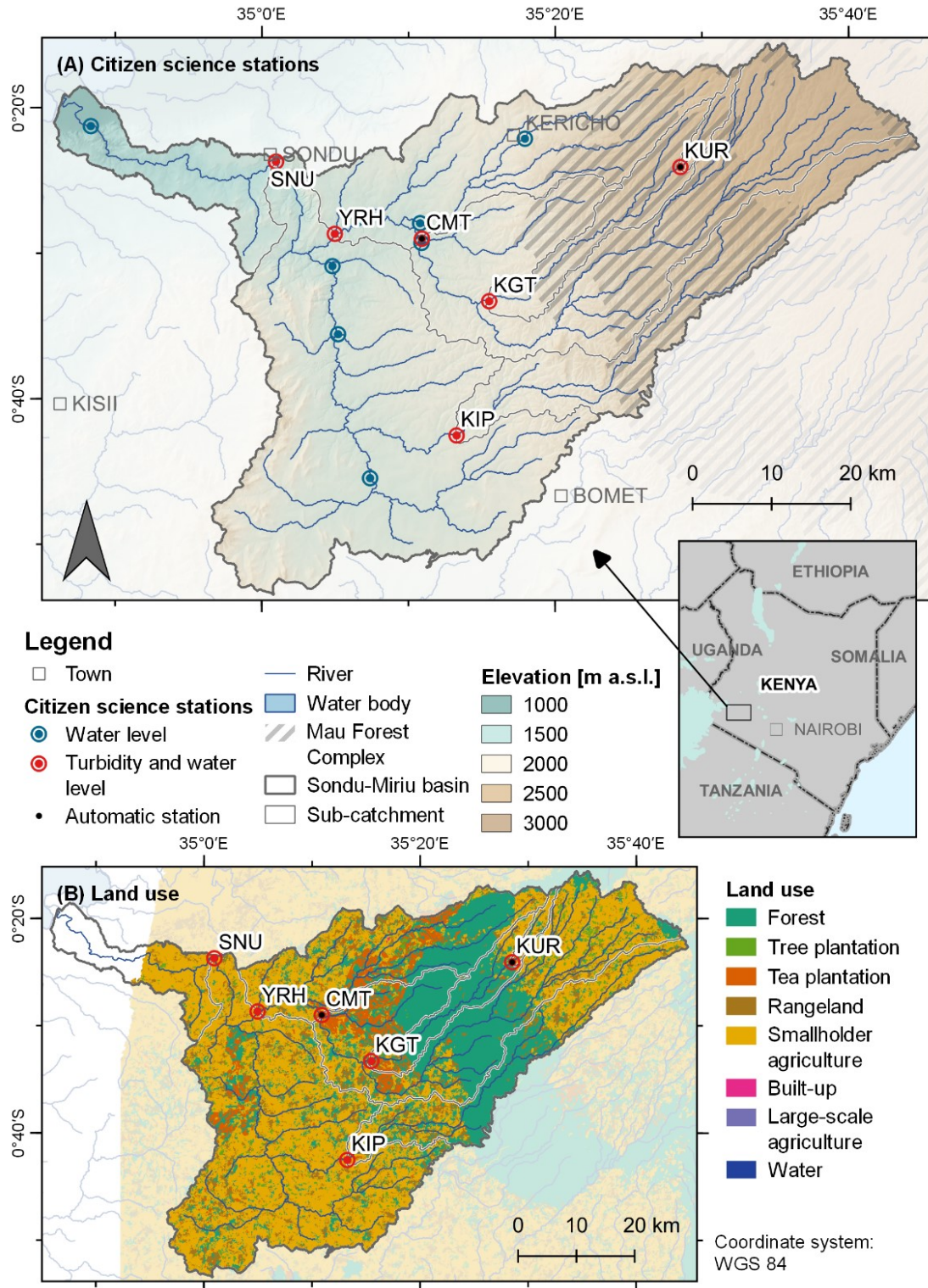


Figure 3.1 Map of the study area showing (A) elevation (SRTM digital elevation model 30 m resolution; USGS, 2000), citizen science stations and automatic water monitoring network and (B) land use within the Sondu-Miriu River Basin.

The annual average rainfall ranges from 1,300 mm yr⁻¹ in the lowland areas to 1,900 mm yr⁻¹ in the highlands. Mean annual temperatures range from 16°C to 22°C (Stephens et al., 1992; Vuai et al., 2012), with a potential evapotranspiration rate of 1,400 to 1,800 per annum at the uplands and lower altitudes, respectively (Krhoda, 1988).

The Sondu-Miriu river basin is characterized by diverse land use types. The upper highland zone is dominated by small-scale farming in the eastern part and indigenous forest and woodlands, which are part of the Mau Forest Complex, in the central part (Figure 3.1B). From the edge of the forest to the west, the land opens up to a rich upland agricultural area characterized by commercial tea and tree plantations. Moving downstream to the lower midland zone, a mixed land use pattern comprising of smallholder agriculture predominate with more settlements. In this area most of the natural vegetation has been replaced by exotic tree species interplanted with crops (Jaetzold and Schmidt, 1983; Masese et al., 2012). The lateral and longitudinal distribution of the riparian zones varies in terms of their structure, with severely degraded flood plains in some sites and those adjacent to agricultural land dominated by exotic tree species such as *Eucalyptus* spp. The riparian zones adjacent to the tea estates are well maintained with dense native vegetation forming a buffer up to 30 m distance (Njue et al., 2016). Farming of crops such as maize, beans and potatoes as well as livestock keeping by smallholder farmers plays an important role in the area for both subsistence and economic purposes.

Generally, the soils are well drained, deep (>1.8 m), fine textured with humic topsoil of high agricultural potential (Jaetzold and Schmidt, 1983). The predominant soils are humic Nitisols in the upper zones and Acrisols in the middle and Regosols in the lower zones. Mollic Andosols, Cambisols, Phaeozems, Planosols, Vertisols and Ferralsols are found in smaller proportions (Jaetzold and Schmidt, 1983; Ouma et al., 2011; Sombroek et al., 1982; Vuai et al., 2012) (Table 3.1).

3.2.2 Citizen science recruitment and training

The study was designed as a ‘contributory’ citizen science monitoring program, i.e. a scientist-directed program with citizen scientists primarily contributing to data collection (Bonney et al., 2009a). We selected six monitoring sites for turbidity monitoring out of the existing 13 sites for citizen science water level monitoring described in Weeser et al. (2018) (Figure 3.1A). During

selection, we considered the accessibility and proximity to potential citizen scientists. Physical characteristics for the sites and their corresponding subcatchments are provided in Table 3.1.

With the help of local administration and Water Resource Users Associations (WRUAs), sensitization meetings with the local community members were conducted at the selected sites. WRUAs were considered a good entry point to reach the community members as these are community groups formed out of local water users to promote sustainable and equitable water use through management and conservation of water resources (Richards and Syallow, 2018). The aim of the sensitization meetings was to promote the project and identify potential participants who would volunteer in the water quality monitoring program. To understand the local knowledge, level of awareness and perception of the local community on water quality and supply, sensitization meetings allowed interactive discussions between citizens and scientists. Besides, a conceptual model of a river system representation in a poster was used to help the participants understand the basic concepts of what a catchment is and how it generally works. Beyond contributing data for scientific purposes, the participants were sensitized on the importance of community-based monitoring in generating data to inform policy, conservation and land management at local level.

Following the sensitization meetings, 19 citizen scientists, ~ 3 participants per site (21% female and 79% male), were recruited from the local community based on their interest and willingness to participate and contribute to the monitoring program. Even though participation was open to all community members, several factors may have influenced the citizen's decision to participate in the project and this could explain why more men participated than women. The majority of the citizen scientists were between 25–34 years old (42.1%, n=8) with 21.1% (n=4) of the participants between 45-54 years. Respectively, 15.8% (n=3) and 10.5% (n=2) were above 55 years and below 24 years. 31.6% (n=6) of the participants had primary education, 52.6%, (n=10) had secondary level of education, and 15.8% (n=3) were college educated (e.g. vocational training and University) (Table 3.2).

Table 3.1 Catchment characteristics of the monitoring subcatchments in the Sondu-Miriu river basin, Kenya.

Station name	Chemosit 1JB03	Kipsonoi 1JF06	Kiptiget 1JA02	Kuresoi	Sondu 1JG05	Yurith 1JD03
Site-ID	CMT	KIP	KGT	KUR	SNU	YRH
Coordinates ^a	0°28'59.628"S 35°10'52.956"E	0°42'30.768"S 35°13'16.704"E	0°33'17.358"S 35°15'29.820"E	0°24'4.024"S 35°28'31.733"E	0°23'42.426"S 35°0'57.540"E	0° 45' 26.820" S 35° 7' 22.788" E
Area [km ²]	81,021	393	185	27	3,252	1569
Elevation range [m.a.s.l]	1,721-2,932	1,841-2,934	1,890-2,692	2,389-2,692	1,504-2,932	1,632-2,932
Mean slope [°]	7.4	8.5	7.6	6.6	6.7	6.9
Land uses ^b	Forest cover (51%), rangeland (8%), Smallholder agriculture (32%), tea plantation (7%), and tree plantation (2%)	Forest cover (47%), rangeland (14%), smallholder agriculture (37%), tea plantation (1%), and tree plantation (1.3%)	Forest cover (65%), rangeland (7%), smallholder agriculture (22%), tea plantation (4%), and tree plantation (1%)	Forest cover (16%), rangeland (15%), smallholder agriculture (64%), and tree plantation (4.4%)	Forest cover (36%), rangeland (13%), smallholder agriculture (45%), tea plantation (5%), and tree plantation (2%)	Forest cover (48%), rangeland (9%), smallholder agriculture (33%), tea plantation (8%), and tree plantation (2%)
Dominant soil types ^c	Humic Nitisols (68%) and Mollic Andosols (30%)	Humic Nitisols (47%) and Mollic Andosols (49%)	Humic Nitisols (100%)	Humic Nitisols (98%)	Humic Nitisols (46%), Eutric Planosols (12%), Rhodic Ferralsols (11%), and Vertic Luvisols (10%)	Humic Nitisols (99%)

^aWGS 1984^bSwart (2016)

KENSOTER Geology data from the Soil and Terrain database for Kenya (KENSOTER) version

At each site, a 1-day training session was conducted during which the participants were informed about the research design, and trained on sample collection and measurement procedures, data recording and submission. Following training, multiple test measurements were made by the team of participants and compared to those taken by instructors. Each citizen scientist was equipped with a turbidity tube, water-sampling device, and an instruction manual in simple language. To avoid communication barriers the trainings were carried out in Swahili. Moreover, the measurement process was explained in the manual using pictures and instructions written in English as well as Swahili. Citizen scientists were encouraged to send water level and turbidity data at least twice per week. To encourage sustained engagement, we implemented a reimbursement of cell phone credit worth US\$ 0.50 monthly (equivalent to 50 text messages) to the participants to compensate the costs incurred by sending the text message.

Table 3.2 Diversity in gender, age, education level and distance to the monitoring station of the 19 trained citizen scientists.

Variable	Category	% Citizen scientists
Gender	Male	78.9%
	Female	21.1%
Age	24 or younger	10.5%
	25-34	42.1%
	35-44	10.5%
	45-54	21.1%
	55 or older	15.8%
Education Level	Primary school	31.6%
	Secondary school	52.6%
	College education	15.8%
Distance to the station	<0.5km	42.1%
	0.5-1km	36.8%
	1-2km	5.3%
	>2km	15.8%

3.2.3 Field data acquisition and transmission

Citizens measured turbidity using a modified Wagtech turbidity tube (Total Ex-Works Wagtech Projects, Thatcham UK). The viewing disk of the turbidity tube was modified to a yellow

background colored with a black checker pattern to increase visibility. Turbidity was measured by filling the turbidity tube with river water, collected off the riverbank without disturbing the sediment, until the pattern on the disk fixed at the bottom of the tube was no longer visible when viewed from above. Turbidity was then estimated by reading the water level in the tube against the scale on the turbidity tube with values ranging from 5-500 TU (see details on calibration of turbidity tubes given below). In cases where the bottom was clearly visible when the turbidity was full, the turbidity reading was recorded as zero to indicate that the measurements were below the detection limit of the turbidity tube. Although Mitchell et al. (2007) advises to take the upper mark when the water level falls between two scale marks, this approach seems to underestimate suspended sediment concentrations. Instead, we used a second commonly used approach which is to estimate a fractional value between the two scale marks, assuming a linear scale. In addition to turbidity, citizen scientists took water level data by reading the value from a water level gauge installed at the site.

After taking the measurements, the citizen scientists sent a text message containing the records and a site-specific ID using their mobile phones to the central database. The submitted data was then parsed by a script (using open source programming languages – Python and JavaScript) and interpreted to associate measurements with the specific monitoring station and parameter. Further information on data transmission and processing is detailed in Weeser et al. (2018). Additionally, the participants recorded data onto a standard form in the field. The data collection started in September 2017 and is still ongoing. For the present study we compiled and processed the dataset collected up to September 2019, covering a representative range of hydrological variations coinciding with seasonal changes in the Sondu-Miriu river basin.

3.2.4 Analysis of level of engagement

To gain a deeper understanding of the citizen scientists' participation pattern over time we used several measures. These include counting the total valid data records of individual participants submitted over the monitoring period from September 2017 to September 2019, analyzing the participation of each participant per site over time, classification of activity of participants, and computing the corresponding Gini coefficient using the approach frequently used to determine inequality of income (Atkinson, 1970). The latter approach has been applied in other citizen science projects to evaluate participants' contributions (Sauermann and Franzoni, 2015; Scott and Frost,

2017). A Gini coefficient is based on the Lorenz curve, which indicates the cumulative data contribution (y-axis) that is made by a cumulative share of participants (x-axis). A 45° line corresponds to total equality, i.e., all participants contribute the same amount of data. The Gini coefficient was then calculated as the ratio of the area between the 45° line and the Lorenz curve over the total area under the 45° line. A Gini coefficient of 0 expresses perfect equality, i.e., equal sampling among participants during the entire monitoring period, whereas a coefficient of 1 expresses maximal unequal sampling effort among participants (Atkinson, 1970).

To provide insight into individual's micro-level participation pattern, we categorized the degree of participation into very active, active, moderate, and less active participation, based on the frequency of participation over time and total data contributions. The very active participants are defined as those that sampled more intensively over a longer period (at least 20 months over a minimum of 25 consecutive months), characterized by more monthly contribution (at least 8 measurements per month) and a dataset exceeding 100 records. Active participants are those that contributed data consistently on multiple days in a month (at least 4 measurements per month) during the first 10 months after inception and characterized by a dataset ranging from 50 to 100 records. Moderately active participants are those that contributed data occasionally with few very active months (contributed at least 2 to 4 measurements in active months) and characterized by a dataset ranging from 20 to 50 records. Less active participants are those whose participation was infrequent (had not contributed data for over 12 months continuously after their initial month of participation) and of low intensity (contributed 1 to 2 measurements in active months), with a dataset of < 20 records over the monitoring period.

3.2.5 Calibration

Calibration of the turbidity tubes was conducted and a relationship between turbidity and suspended sediments concentrations (SSC) was established from all the datasets obtained from the six citizen science monitoring stations and two automated monitoring stations, respectively. This was achieved by preparing suspensions covering a range of suspended sediment concentrations using fine sediments collected from different locations in the riverbed at each sampling site. We took the site-specific samples to account for potential differences in the physical and geochemical characteristics of the catchment and have a reasonable representation of the sediment transported in the catchment. The fine sediment material collected was first sieved to remove gravel and

particles larger than 0.5 mm. Then a suspension was prepared in a bucket using the fine sediment material and river water. Further separation was done after 100 s, corresponding to a theoretical grain size of $> 50 \mu\text{m}$ following Stoke's law (Equation 1) by decanting the suspension in another bucket. The decanted suspension was used for the calibration. The settling time was calculated using the equation

$$t = \frac{18\eta h}{(\rho_s - \rho_l)X^2 g} \quad (1)$$

Where t is the settling time, η is the fluid viscosity [kg/ms], h is the settling depth [m], ρ_l is the liquid density [kg/m³], ρ_s is the particle density [kg/m³], g is the acceleration due to gravity [m/s²], and X is the particle diameter [m].

To obtain the required range of turbidity and suspended sediment concentrations, dilutions were made from the main suspension using clear water. The unit scale of the turbidity tube ranging from 5 to 500 TU was used to guide the calibration process. For each stepwise dilution, the suspension was homogenized by stirring the suspension continuously to prevent settling of sediments, filled in the tubes and the tubes' turbidity was recorded. We then calibrated the suspension in two ways. In the first one, 250 mL of the suspension was taken for the analysis of the suspended sediment concentration (mg L⁻¹), which was determined gravimetrically, to determine the relationship between turbidity and SSC (Anderson and Davie, 2004; Gray et al., 2000). In a second approach, we measured the turbidity using the spectro::lyser installed at the two monitoring sites at KUR and CMT. The turbidity values recorded with the turbidity tube and spectro::lyser were calibrated against suspended sediment concentrations for each site using empirically derived linear regression models to allow for statistical prediction of these parameters.

3.2.6 Data validation

Two sites (KUR and CMT) were located next to automatic monitoring stations measuring turbidity in FTU (formazin turbidity unit) using a UV-Vis based sensor (spectro::lyser, SCAN Messtechnik, Vienna, Austria) and water level with a radar-based sensor (VEGAPULS WL61, VEGA Grieshaber KG, Schiltach, Germany) at 10-minute interval. Stenfert Kroese et al. (2020b) provide a detailed description of the stations. Turbidity data from the sensors were calibrated following the same approach as described in Section 3.2.5. These data were used to evaluate the accuracy of the citizen-

science data using a linear regression model. For each data point in the citizen science dataset, the corresponding measurement at the same day and time (± 10 minutes) was obtained from the automated stations. Following the assumption that citizen scientists would not measure after sunset, measurements received by the SMS server past 6 pm were omitted to control sources of variability between the actual time the measurement was taken and when it was submitted, as this may account for differences when comparing the two datasets. Additionally, measurements which were taken at the same time by different participants but did not match or those that did not have a valid measurement from the automated station were excluded.

3.2.7 Quality control and assurance

Our study adopted multiple quality control measures to ensure the production of valid data that can yield both scientific and educational outcomes as proposed by Wiggins et al. (2011). This involved developing simple and standardized data collection protocols and monitoring tools (manual containing instructions and water sampling equipment) that were essential for the process. Further, we trained the participants before embarking on the monitoring program and tracked their performance through follow-up meetings once per month. Additional quality control measures include replication through multiple measurements by the same participant and by having 3 or 4 participants per site to reduce sampling error and bias, submission of data to the central database along with field data sheets for verification, as well as manual screening and identification of outliers in the dataset. Furthermore, the citizen science generated data was compared and validated with the data recorded by the spectro::lyser sensor of the automated stations.

Due to the low number of cases of data replication, we filtered outliers by visually inspecting of the time series data and removed spurious data points. From over 1300 dataset, 80 (6%) measurements contained invalid data and were not included for further analysis. The invalid data were due to errors associated with typing, omitting of site-ID or sending the measurement to a wrong code e.g. submitting water level data using the code for turbidity.

3.2.8 Statistical analyses

The suspended sediment concentrations were tested for normality using Q-Q plots and the Shapiro-Wilk test ($p < 0.05$) which revealed non-normal distribution of data. Therefore, all tests used in this study are non-parametric. To test for significant differences in the suspended sediment

concentrations among different sites, the Mann-Whitney U test was used at $p < 0.05$. Spearman's correlation coefficients were calculated to identify the strength and direction of significant relationships ($p < 0.05$) between SSC concentrations and explanatory variables.

3.3 Results and Discussion

3.3.1 Relationship between turbidity and suspended sediment concentration

To visualize the relationship between suspended sediment concentrations and the measured turbidity values from both turbidity tubes and automated stations measurements, the calibration dataset was pooled to obtain one rating curve for the turbidity tube and one for the automated stations. In the view of the potential loss of information through pooling of the data from the six subcatchments, we further compared the resulting regression statistics and found no significant difference between the slopes for each site-specific calibration ($P > 0.1$). Pooling data allows to establish one common calibration which can be used in case turbidity tubes are used in additional so far not measured subcatchments. The relationship between turbidity and suspended sediment concentrations showed a strong linearity (Figure 3.2). The strong relationship indicates a high predictability of SSC from turbidity tube readings and automated stations. Studies conducted to evaluate the use of turbidity tubes to predict total suspended solids concentrations in streams in northeast Ohio revealed also a highly predictive correlation ($R^2=0.896$) (Anderson and Davie, 2004). Similarly, Stenfert Kroese et al., (2020b) reported a strong correlation between turbidity readings (FTU) and suspended sediment concentrations for the automated stations used in this study ($R^2=0.98$).

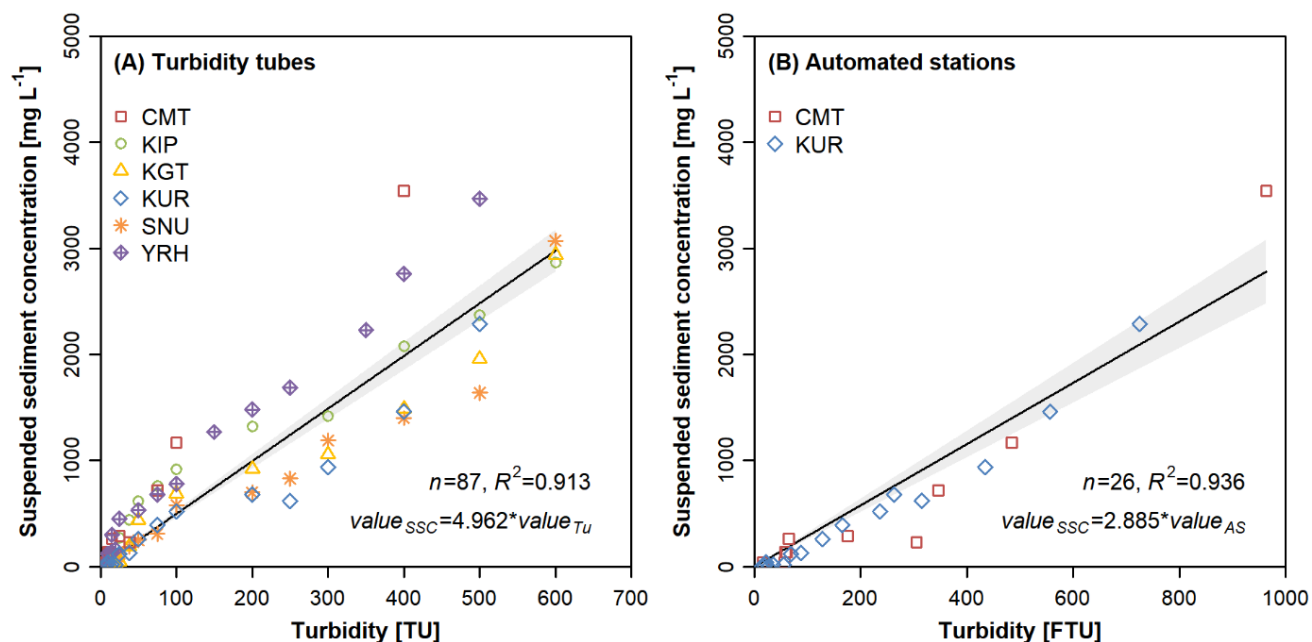


Figure 3.2 Relationship between suspended sediment concentrations (SSC) (mg L^{-1}) and turbidity measurements using (A) turbidity tubes (Tu) at the six monitoring sites and (B) automated station (AS) at two monitoring sites (KUR and CMT) in the Sondu-Miriu river basin, Kenya.

3.3.2 Validation of citizen science data

A comparison between citizen scientist collected data and measurements obtained with automated stations at KUR and CMT showed high correlation of 0.95 and 0.94, with a root mean square error (RMSE) of 40.2 mg L^{-1} and 33.1 mg L^{-1} , respectively (Figure 3.3). However, citizen scientists measurements at KUR tended to deviate from the 1:1 slope to a great extent and the suspended sediment concentration was found to be more likely to be underestimated at higher concentrations ($>50 \text{ mg L}^{-1}$, $P < 0.05$), a bias observed in other citizen science datasets as well (Ho et al., 2020). For data comparability and quality between participants, the relative difference between suspended sediment data collected with the turbidity tubes by the two most active participants per site and the data measured by the automated station was calculated (Figure 3.4). The results show that the citizen scientists at KUR underestimated SSC by $\sim 30\%$ and generally overestimated low SSC values at CMT, but there was no significant difference in measurements between the participants ($p > 0.05$). Other studies suggest that turbidity tube readings can over- or underestimate actual turbidity values for particular locations due to site-specific characteristics such as particle size, composition of particulate matter, lighting conditions and error between different observers (Dorea

and Simpson, 2011; Rügner et al., 2013; Scott and Frost, 2017). We found no significant difference between the citizen scientists' data and automated stations data at CMT ($p > 0.05$), indicating consistency in suspended sediment concentrations between the two methods. Scott and Frost (2017) reported a good relationship between turbidity measurements taken by volunteers using turbidity tubes and lab measurements of total suspended solids ($R^2 = 0.68$). This is an indication that measurements taken by citizen scientists using turbidity tubes can provide useful information on the concentration of suspended sediments in rivers in the Sondu-Miriu catchment, as found elsewhere (Anderson and Davie, 2004).

Our results indicate that the lower detection limit for SSC under field conditions for our turbidity tubes is about 25 mg L^{-1} . Anderson and Davie (2004) reported that an accurate estimation of SSC in the lower ranges ($10\text{-}20 \text{ mg L}^{-1}$) is more difficult due to low repeatability owing to the detection limits of the turbidity tubes. Also, the scale on the turbidity tube, especially for larger values, is so rough that some detail is lost at this range. A similar observation was reported by the Forest Water Watch project in Toronto, Canada (Scott and Frost, 2017). Additionally, only very few SSC values $>200 \text{ mg L}^{-1}$ were recorded by the citizen scientists, thus failing to capture major sediment export events, a sampling bias frequently reported with citizen science approaches (Miguel-Chinchilla et al., 2019; Thornhill et al., 2016). We attribute this to individual preferences of citizen scientist as high SSCs are likely correlated with increased water levels, rainfall and 'bad weather'. It is very likely that citizens simply avoid sampling under these conditions. This could have resulted in the underestimation of SSC from each of the monitored subcatchment by an unknown proportion (Dutton et al., 2018; Ziegler et al., 2014).

Rapid developments in technology and rise of low-cost robust sensors with improved detection limits and resolution could be suitable for citizen science studies to complement already existing crowdsourcing efforts (Buytaert et al., 2014; Scott and Frost, 2017). Recently, an improved quantification of both turbidity and concentration of suspended particular matter by use of smartphone applications such as HydroColor has been successfully tested in Australia and USA to monitor inland waters (Leeuw and Boss, 2018; Malthus et al., 2020) and in Myanmar to monitor Ayeyarwady river (Thatoe Nwe Win et al., 2019). Other studies have demonstrated working methods using digital cameras in Wisconsin for water quality mapping (Compas and Wade, 2018).

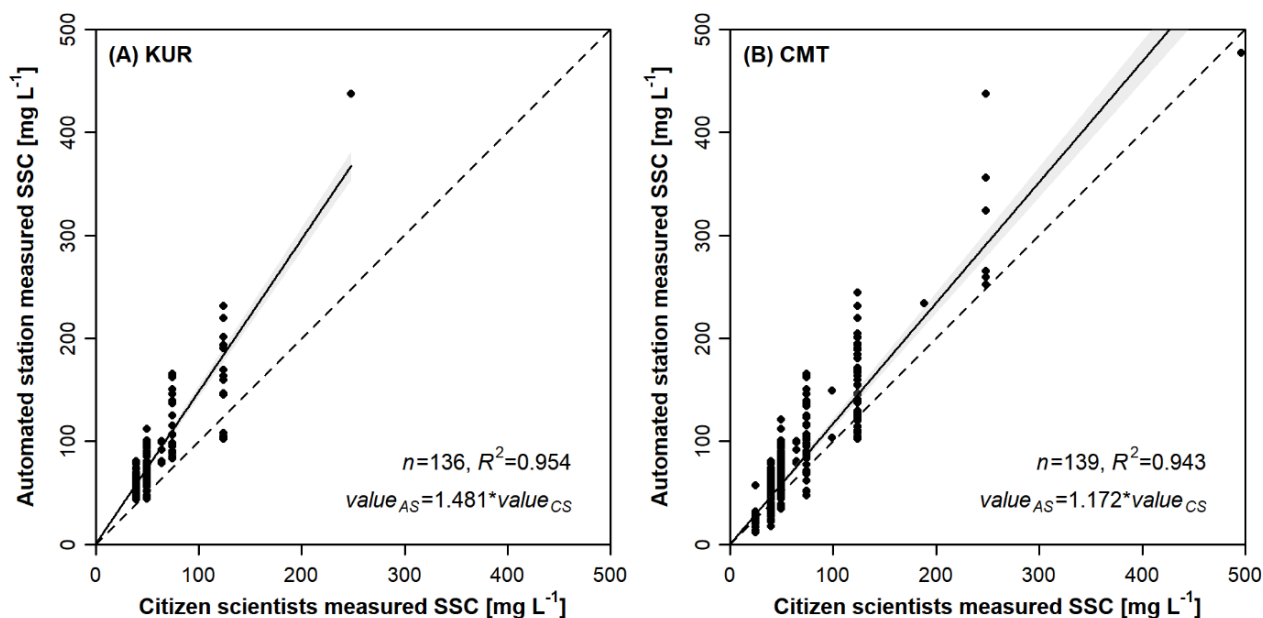


Figure 3.3 Comparison of the suspended sediment concentration (mg L^{-1}) calculated based on calibrated turbidity measurements collected by citizen scientist and automated stations between September 2017 and September 2019 for (A) KUR and (B) CMT in the Sondu-Miriu river basin, Kenya. The dashed line represents the 1:1 relationship.

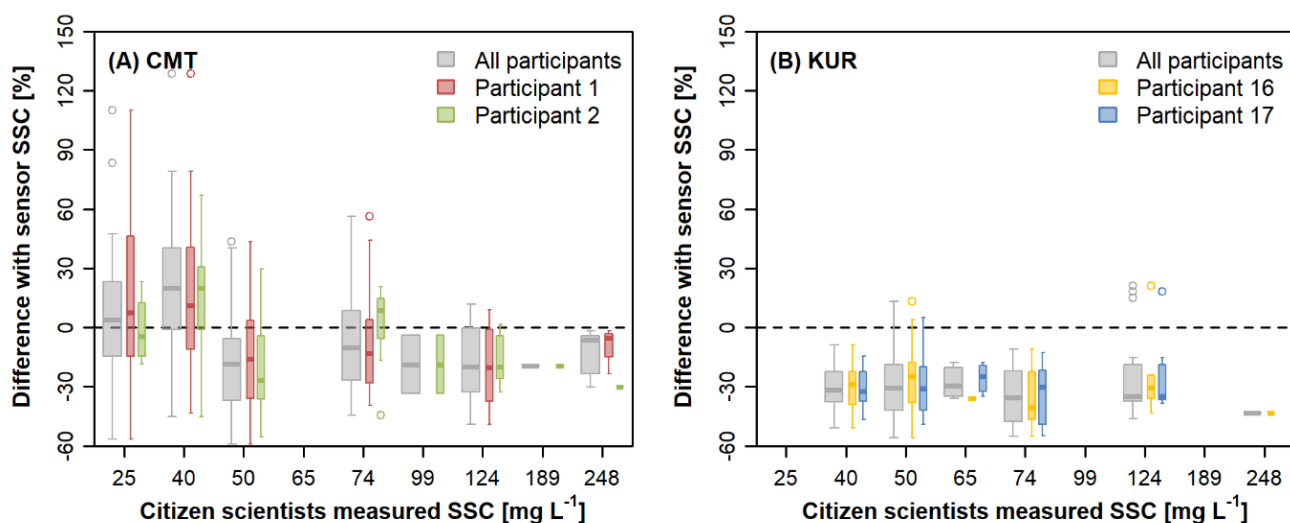


Figure 3.4 Relative difference between citizen scientists measured SSC (mg L^{-1}) using turbidity tubes and the SSC (mg L^{-1}) obtained from turbidity data recorded by an *in situ* UV-Vis sensor at the corresponding automated station for (A) KUR and (B) CMT. The grey boxplots show the relative difference for all participants at a given site. Participant number corresponds to the participant ID shown in **Figure 3.6**.

3.3.3 Participation rate

Sustained engagement and generating the required participation levels in citizen science are of primary importance in contributing to data quality and should therefore be carefully considered (Moor et al., 2019; Scott and Frost, 2017; Serret et al., 2019). To evaluate this, we used data on the participation of the citizen scientists from the six monitoring sites. We noticed that the number of participants, of which 19 participated in one-day training meetings held at the monitoring sites, increased to 37 during the project. Unlike the original 19 participants, these 18 ‘new’ citizen scientists were not followed up intensively during the project. We assume that some of the 18 ‘new’ participants borrowed the tubes and received training from the original participants during their weekly sampling and contributed to the dataset out of intrinsic motivation. This is consistent with other research that reported on citizen science behaviors as a potential avenue for recruiting new members to the program and diffusion of knowledge, for example the Wabash Blitz volunteer experience (Church et al., 2019). Alternatively, the original participants changed their cellphone numbers during the monitoring period and were consequently considered as ‘new’ participants. However, since none of the ‘new’ participants showed a sudden and strong activity in the middle or towards the end of the study period, it is unlikely that such cases occurred as the trained participants consistently contributed most of the data each month. Additionally, there are those participants who contributed data occasionally during the training, and/or monthly sensitization meetings.

The sampling effort and data contribution varied over time with noticeable spikes. Figure 3.5A reveals that the highest level of participation was recorded during early stages of the project with October 2017 having the highest number of measurements ($n = 101$) followed by a decline in the subsequent months. This could be attributed to the initial novelty when the project activity started and the motivation of the community to learn a new skill (Raddick et al., 2009; Rotman et al., 2012). The monthly spikes can be explained by subsequent growing interest among participants as they became more experienced in the monitoring, new participants who joined later in the project phase or by monthly sensitization meetings undertaken by the project to encourage engagement.

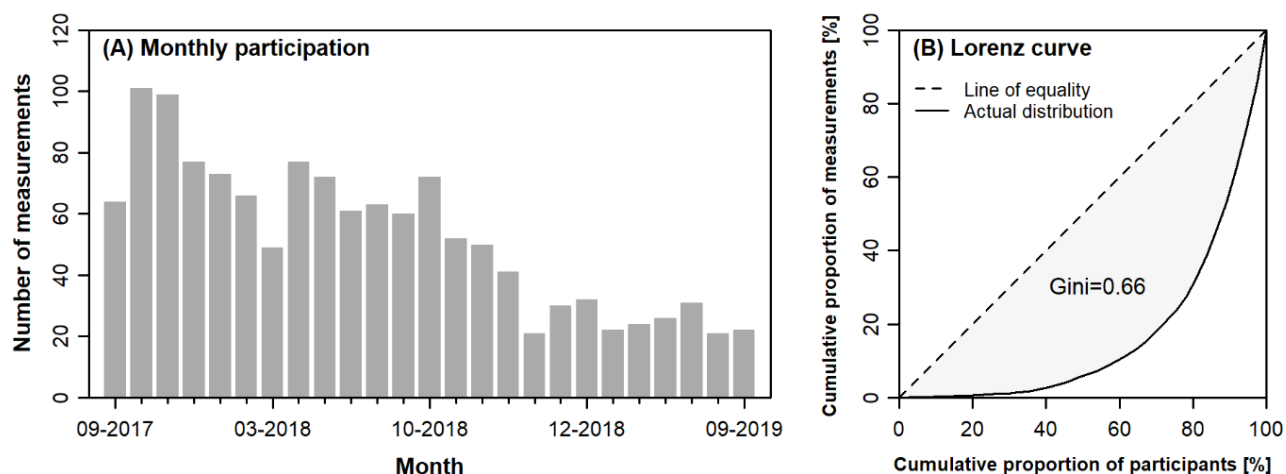


Figure 3.5 Participation of citizen scientists in data collection and cumulative for the monitoring period from September 2017 to September 2019 in the Sondu basin, Kenya: (A) total number of measurements per month B) Lorenz curve representing inequality in data collection by all participants.

All of the participants at sites KUR, CMT and KIP that contributed large numbers of readings lived within 1 km distance from the monitoring station and visited the river more often as they depend on river water for domestic use (Table 3.3). In contrast, reduced motivation over time due to limited ease of access and proximity to monitoring stations could be associated to the low participation rate thus a smaller amount of data at sites SNU, and YRH where 4 out of 6 of the participants lived more than 2 km away. Besides, one of the participants at SNU mentioned that monitoring water level was easy as the staff gauges alongside signboards were installed at designated gauging station, whereas the water quality measurements required bringing own equipment to the site. A reducing interest in long-term citizen science based research is a typical pattern found in other projects as well. Volunteer Lake Monitors in Minnesota and Alabama Water Watch programs reported an overall increase in number of dropouts after the 1-3 years of the monitoring program (Deutsch and Ruiz-Córdova, 2015; Klang and Heiskary, 2000). Notwithstanding, the last phase of the project was characterized by a more stable monitoring effort as compared to other phases with an average rate data contribution of 25 measurements per month over all the sites.

As noted by Wilkinson (2008), participation follows a power law of distribution in which a small number of very active participants account for most of the activity. This is reflected in the Gini coefficient of 0.66 (Figure 3.5B). While still being relatively high and indicating the dominance of

a few participants providing most of the data, our Gini coefficient is somewhat lower than those reported for other projects such as the Toronto Forest Water Watch project and Zooniverse with Gini coefficients of 0.84 and 0.85, respectively (Sauermann and Franzoni, 2015; Scott and Frost, 2017). Analyzing individual-level total data contribution, we find that the very active participants (11%, $n = 4$) and active participants (11%, $n = 4$) contributed 72% of the data. The remaining data were collected by moderately active members (19%, $n = 7$), and less active participants (59%, $n = 22$), most of whom we presume belong to the group of new participants.

Table 3.3 Demographics of the 19 trained citizen scientists in relation to the level of engagement based on the total number of valid measurements contributed over the entire monitoring period between September 2017 to September 2019 (Very active: >100, active: 50–100, moderately active: 20–50, less active: < 20).

Variable	Category	Level of engagement			
		Very active	Active	Moderately active	Less active
Gender	Male	10.5 % (n=2)	21.1% (n=4)	26.3% (n=5)	21.1% (n=4)
	Female	10.5% (n=2)		5.2% (n=1)	5.2% (n=1)
Age	24 or younger			10.5% (n=2)	
	25-34	15.8% (n=3)	10.5% (n=2)	5.2% (n=1)	10.5% (n=2)
	35-44			5.2% (n=1)	5.2% (n=1)
	45-54		5.2% (n=1)	10.5% (n=2)	5.2% (n=1)
	55 or older	5.2% (n=1)	5.2% (n=1)		5.2% (n=1)
Education Level	Primary school	15.8% (n=3)	5.2% (n=1)	5.2% (n=1)	5.2% (n=1)
	Secondary school	5.2% (n=1)	10.5% (n=2)	26.3% (n=5)	10.5% (n=2)
	College education		5.2% (n=1)		10.5 % (n=2)
Distance to station	<0.5km	10.5% (n=2)	10.5% (n=2)	10.5%(n=2)	10.5% (n =2)
	0.5-1km	10.5% (n=2)	5.2% (n=1)	10.5% (n=2)	10.5% (n =2)
	1-2km			5.2% (n=1)	
	>2km		5.2% (n=1)	5.2% (n=1)	5.2% (n=1)

Of all the participants, four (11%) contributed data consistently for the entire monitoring period (25 months), indicating a long term-commitment from participants residing near to the monitoring locations. 35% ($n = 13$) of the participants dropped out of the program after 1-2 months of monitoring, while 30% of the participants monitored for a period of 11-25 months (Figure 3.6).

The greatest proportion of participants with the highest level of engagement were between 25 and 34 years with primary education, even though most of the citizen scientists had secondary school education (Table 3.3). The findings resonates with other studies that observed a similar pattern in which younger (<35 years) and lower educated people showed active participation and long-term commitment in citizen science projects (Brouwer and Hessels, 2019; Weeser et al., 2021). Nevertheless, even occasional participants can successfully contribute to the monitoring program as most contributions in citizen science are attained by returning participation (Sauermann and Franzoni, 2015).

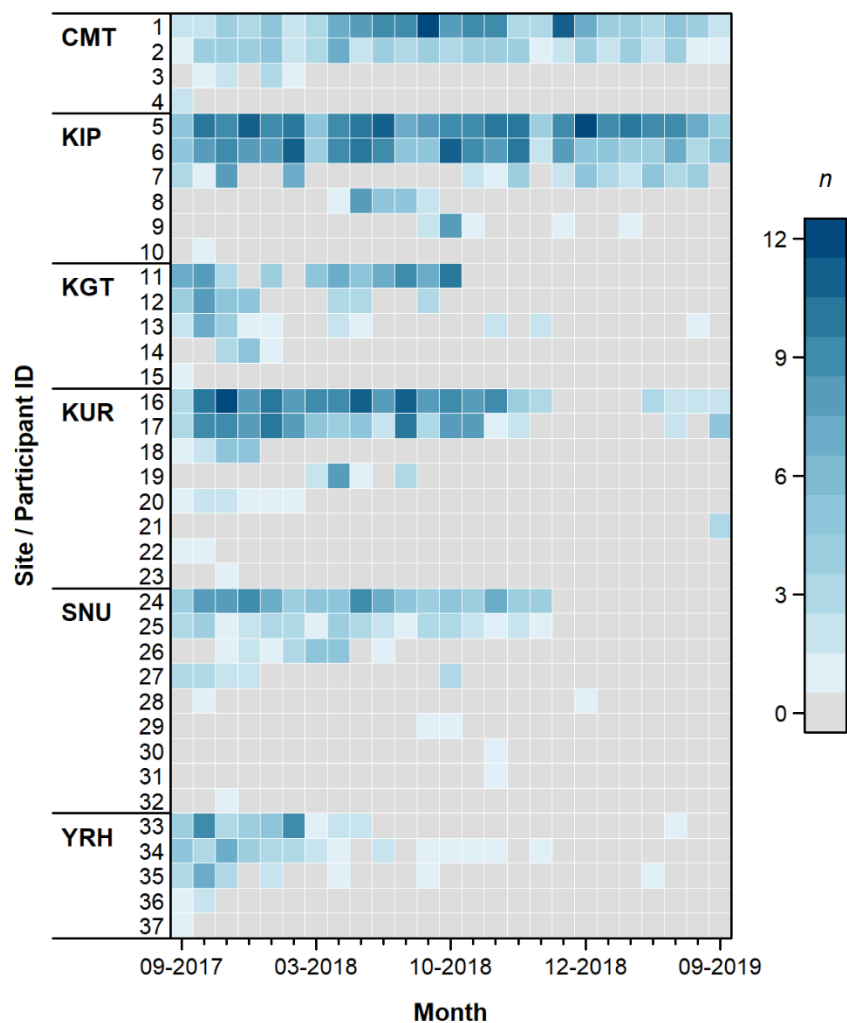


Figure 3.6 Temporal distribution of data collected by all participants at all the monitoring sites for the monitoring period from September 2017 to September 2019. Level of engagement is based on the number of measurements (n) contributed per month.

3.3.4 Method of engagement

In addition to generating relevant research data and increasing scientific knowledge, designing, and building a citizen science project requires the consideration of social aspects to sustain user motivation and achieve project goals (Domroese and Johnson, 2017; Shirk et al., 2012). The decline in participation rate and drop out of citizen scientists in the study could have been contributed by the cost of 0.01 USD involved in the transmission of data (Weeser et al., 2021). Additionally, a delay in the reimbursement of credit after submission of data, as this was done at the end of the month, could have demotivated participants thus resulting in declining participation (Wald et al., 2016). Other studies have identified financial incentives as a significant barrier for participation in developing countries where citizen scientists expect to derive income from their engagement (Buytaert et al., 2014; Hobbs and White, 2012). Another challenge in engaging long-term participation could be attributed to the disconnect between the projects objectives and needs of the community as well as interests of the participating group (Church et al., 2019; Wald et al., 2016). According to Golumbic et al. (2020), identifying and addressing a community need can ease the challenging process of participant retention and support sustained engagement.

To minimize barriers for participation we kept the method of sending data as simple as possible. As mobile phone coverage and usage become a more established method of communication in East Africa (Krell et al., 2020), we chose the text message service since it is easy to use, user-friendly, stable, and inexpensive (Weeser et al., 2018). Delivery of feedback is a fundamental element of a successful citizen science program (Brouwer et al., 2018). In this study we incorporated an automated feedback built into the central server to provide an immediate feedback to the citizen scientists and appreciation message of ‘Thank you’ based on the participant’s measurements. Such an engagement strategy has a positive influence that could keep the citizen scientists motivated as it acknowledges their contribution and indicates the level of activity (Lowry and Fienen, 2013; Weeser et al., 2018). Additionally, two meetings at two sites (KUR and SNU) were organized to communicate preliminary results to the citizen scientists and to other local community members. This provided a platform for interactive feedback between the researchers, citizen scientists and community members after which some participants would be motivated and encouraged to continue sending data. Majority of the volunteers who participated in the water level monitoring program in the same catchment reported that such meetings were powerful means to reach out to the

community and engage motivated volunteers (Weeser et al., 2021). Furthermore, visualization and communication of results through meetings or other virtual platforms such as web-based technologies could incentivise citizen scientists for further engagement as they can directly gain from participation (Buytaert et al., 2014; Golumbic et al., 2020).

3.3.5 Spatial and temporal trends of suspended sediment concentrations

Suspended sediment concentrations in the Sondu-Miriu river basin ranged from 25 to 496 mg L⁻¹ with an average of 75 ± 56 mg L⁻¹. The data revealed significant differences among sites ($p < 0.05$). The suspended sediment concentrations were significantly higher at SNU than at all other sites (109 ± 94 mg L⁻¹) while KGT had the lowest SSC (50 ± 25 mg L⁻¹), ($p < 0.05$) (Figure 3.7). The proportion of smallholder agriculture ($r = 0.11$) and catchment area ($r = 0.17$) were positively but weakly correlated with SSC concentrations ($p < 0.05$). There is a large body of literature that shows a tight relation of land use and erosion rates. Particularly, agriculture is associated with increased erosion rate due to arable practices, loss of soil structure and reduced forest cover (Ou et al., 2016; Poudel, 2016; Tanaka et al., 2016), that limit infiltration rates and soil hydraulic conductivity properties in the catchment (Nadal-Romero et al., 2018; Owuor et al., 2018). Earlier studies in the neighboring Mara river basin found that unregulated livestock grazing and agricultural land conversion may have increased erosion and contributed to the higher than expected sediment yields from the catchment (Dutton et al., 2018). Stenfert Kroese et al. (2020b) observed that agriculture and unpaved tracks, which are pathways for people and livestock to the streams, in a smallholder catchment in the Sondu-Miriu river basin could be another driving force for the total sediment load into rivers, due to more overland flow. The presence of intact riparian zones, characterized by mixed dense indigenous vegetation, and commercial tea plantation and forest plantation practices around KGT may explain the low suspended sediment concentrations. In contrast, the longitudinal quality of the riparian zone at SNU is degraded with limited ground cover and disturbed banks due to cultivation of crops and plantation of woodlots with exotic tree species. Forests and riparian buffer zones can act as a filter, controlling and decreasing the sediment load by surface runoff (Mello et al., 2018). Similar effects were reported in previous studies that found forested watersheds to have lower suspended sediment concentrations as compared to agricultural landscapes (Mello et al., 2018; Stenfert Kroese et al., 2020b; Tu, 2013; Zhang et al., 2017). Contrasting the effect of land use, we have no clear explanation for the positive correlation with

catchment size, as we would have expected higher SSC with smaller catchment size, due to higher stream velocities, as well as larger variability and extremes of discharge.

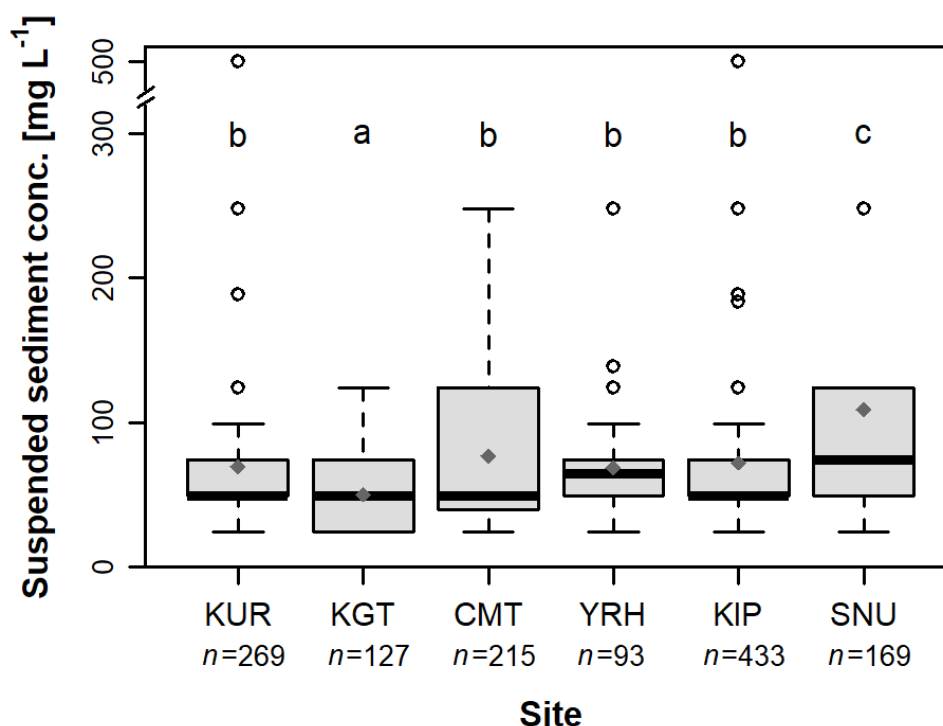


Figure 3.7 Variation in suspended sediment concentrations across the monitoring sites for the sampling period September 2017 to September 2019. The lower and upper lines of the boxplots correspond to the 1st and 3rd quantile (Q_1 and Q_3), respectively, while the solid horizontal line inside the box represents the median value (Q_2). The lower and upper whiskers show the minimum and maximum values within 1.5 times the interquartile range, while the circle markers represent extreme values outside of that range. Significant differences among sites are indicated with different letters ($P < 0.05$).

Visual assessment of the hydrological time series data shows seasonal variability in both suspended sediment concentration and water level (Figure 3.8). YRH was omitted from the analysis as it had a short time series because the installation of water level gauge and monitoring of the water level started later in March 2018. The time series of citizen science generated water level and SSC data at sites KUR and CMT show similar trends with the data from the automated station in relation to high and low flow conditions (Figure 3.8A, C). Nevertheless, the citizen scientists did not manage to capture the same degree of variability in SSC concentrations, especially during the rainy season. Peak SSC concentrations were reached in early to mid-rainy season (in the months of April-July

for long rains and September to October for short rains), in some instances prior to peak flow, and decreased in the transition from rainy to dry season (in the months of December-March). The higher concentrations of suspended sediments during the rainy season and the lower concentrations in the dry season in this study are consistent with other rivers studied in the Mau Forest Complex (Dutton et al., 2018; Stenfert Kroese et al., 2020b). Also notable are the considerable high SSC even in times when flows were consistently lower in March and May 2019 at site CMT and KIP. This could be due to the time lapse between the rains and their respective effect on the concentration and water level (Göransson et al., 2013). Other studies have reported similar results showing that the SSC did not necessarily change with discharge values which is an indication that other factors besides rainfall such as natural and anthropogenic disturbances control the SSC in small catchments (Ouellet-Proulx et al., 2016; Rodríguez-Blanco et al., 2018). Stenfert Kroese et al. (2020b), in a study in the same catchment, reported that the impulse response between the peaks of discharge and sediment concentration was in general longer compared to the rainfall peak.

Overall, citizen science project in Kenya indicate a promising new approach for recording water quality data in a remote tropical environment. The study also reveals that, when appropriately used, turbidity tubes can be an effective and inexpensive monitoring tool to estimate relative sediment concentrations from different catchments. The total cost for setting up and operating the entire citizen science based network for one year cost ~ \$10,000 (including cost for the purchasing of sampling materials, meetings and on-site visits, and maintenance of the data server). In contrast, setting up an automated station at one site cost ~ \$50,000, which is much more expensive as compared to operating a citizen-science approach. Furthermore, extra costs incur annually for security and regular maintenance of automated stations, despite of malfunctioning of sophisticated analytical instruments due to harsh environmental conditions in tropical ecosystems.

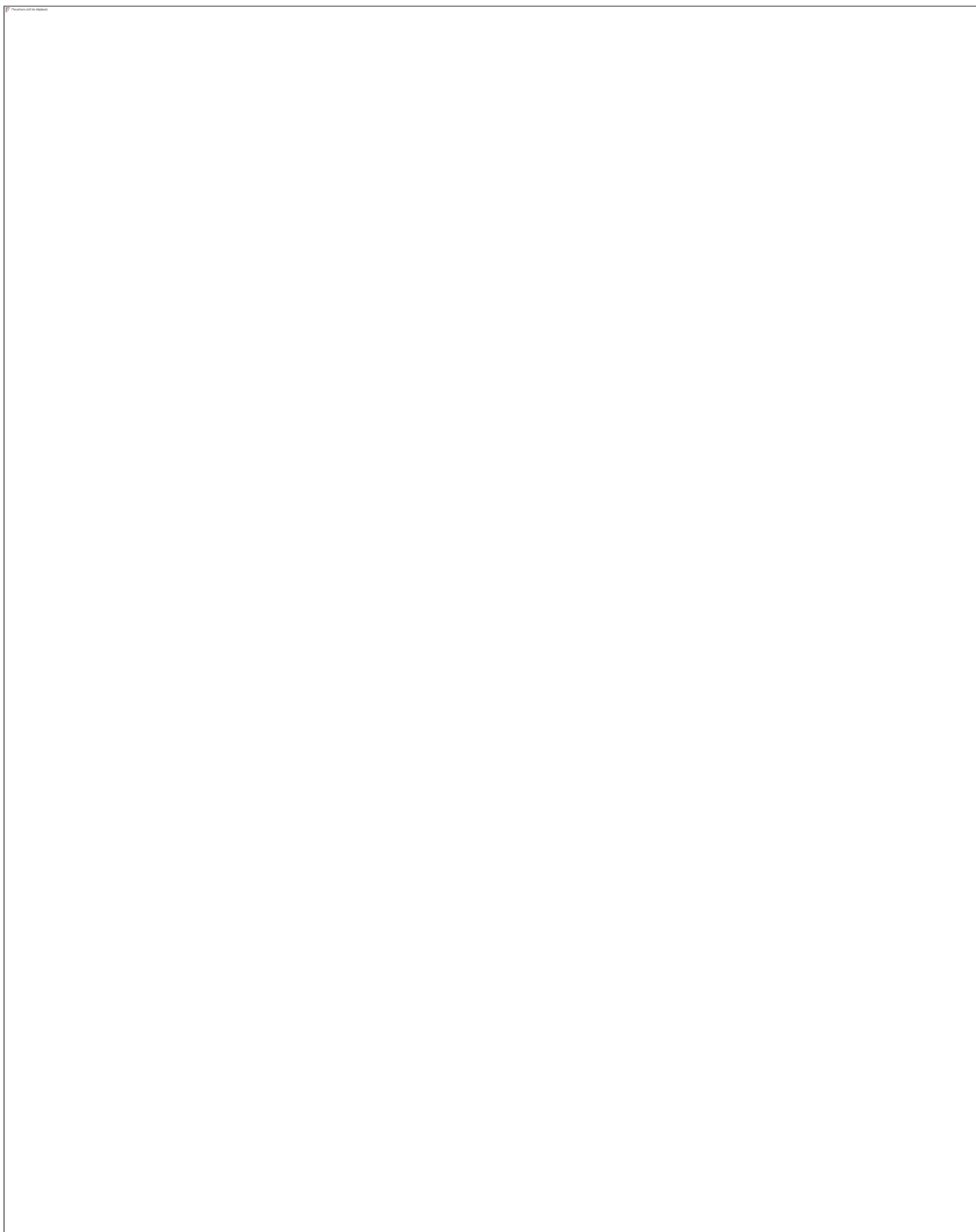


Figure 3.8 Time series of suspended sediment concentration and observed water level transmitted by citizen scientists at five sites and measured by automated stations at sites KUR and CMT in the Sondu-Miriu river basin over the monitoring period between September 2017 to September 2019.

3.4 Conclusion

This study evaluated the potential of citizen science to monitor suspended sediment concentrations in a remote tropical river basin using turbidity measured with turbidity tubes as a proxy. The citizen science generated data showed a good relationship with the automated measurements of suspended sediment concentrations, which reveals that turbidity tubes can be an effective and inexpensive tool to estimate relative differences in suspended sediment concentrations between catchments with contrasting conditions. This is at least the case under low to moderate water levels. Limitations such as sampling biases attributed to underestimation and the precision of measurements due to low repeatability owing to the detection limits of the turbidity tubes were observed. Notwithstanding, understanding the error and bias associated with citizen science generated data in estimating suspended sediments, the data can be used to provide baseline information on concentrations and support implementation of catchment and land use best management practices. Where the purpose of the data is to calculate sediment yields, further investigation through extensive sampling and increased spatial and temporal resolution is recommended. The possibilities of sampling even extreme events might be even more difficult. On the one hand, because it is difficult to take representative water samples from the middle of stream where sediment loads are likely highest and, on the other hand, because the willingness of the citizens to voluntarily work outside under extreme weather conditions is low.

Despite the limitations of the data collected with the turbidity tubes, the data provide good insights of the spatial and temporal dynamics of sediment concentrations in the Sondu-Miriu river basin. Our findings highlight the forest cover as a key landscape feature as low levels of suspended sediment concentrations were recorded in areas with high forest cover. In contrast, suspended sediment concentrations in the downstream subcatchment dominated with agriculture and rangeland was significantly higher as compared to other subcatchments upstream, indicative of the impacted state of the river ecosystems in the Sondu-Miriu river basin.

Prospective future works should consider employing smartphone applications and robust sensors with improved detection limits and resolution that are suitable for citizen science studies in order to increase the precision of concentration measurements, allow for higher sampling rates and less subjective readings. We particularly see an advantage of those systems that will allow contact-free, remote measurements of the river through taking pictures or video-taping from remote places such

as a bridge.

Finally, long-term participation of citizen scientist remains a challenge. While the participation and sampling equality rates were comparable to other citizen science projects, only 11% of the participants remained engaged for the full monitoring period, an indication of a high dropout rate. However, both long-term and short-term monitoring efforts from the participants can increase the spatial and temporal coverage of the overall dataset. Increased collaboration between researchers and the citizen scientists through interactive feedback and communication strategies could be an incentive to promote sustained participation. This study emphasizes the need for further empirical research on the social processes within the context of citizen science in low-income regions to understand in depth the motivations and engagement dynamics to minimize barriers and improve overall participation.

Overall, the results indicate that citizen science is no panacea but is a promising new cost effective approach that affords a unique opportunity for monitoring hydrological and water quality data in a remote tropical montane rainforest environment.

Acknowledgements

We thank the German Federal Ministry for Economic Cooperation and Development (Grants 81195001 “Low Cost methods for monitoring water quality to inform upscaling of sustainable water management in forested landscapes in Kenya” and Grant 81206682 “The Water Towers of East Africa: policies and practices for enhancing co-benefits from joint forest and water conservation”) for generously providing financial support, and the German Science Foundation DFG (BR2238/23-1) for co-funding this research. This work is a contribution to the CGIAR programme on Forest, Trees and Agroforestry led by the Centre for International Forestry Research (CIFOR). We also thank the German Academic Exchange Service (DAAD) in collaboration with National Research Fund (NRF), Kenya for the scholarship award. The participation of citizen scientists and Water Resource Users Associations (WRUAs) of the Sondu-Miriu river basin was very crucial for the success of this research and is greatly appreciated. We would also like to thank Zacchaeus Kemboi (GIZ) as well as the officers of the Water Resources Authority (WRA) for their support in the implementation of the program.

Supplementary material

The Supplementary Material for this article can be found online at:
<https://www.frontiersin.org/journals/water/articles/10.3389/frwa.2021.656770/full#supplementary-material>

4. Valuation of water-related ecosystem services: Implications for sustainable management of tropical montane forests

This chapter has been submitted to *Ecosystems and People* as:

Njue, N. K., Rufino, M. C., Breuer, L., and Jacobs, S. Valuation of water-related ecosystem services: Implications for sustainable management of tropical montane forests. Under review for *Ecosystems and People*.

4.1 Introduction

Forested watersheds provide ecosystem services in the form of provisioning, regulating, supporting and cultural services which are significant not just locally but also globally (MEA, 2005). Of these, the provisioning of water-related (hydrological) ecosystem services (WES) are of vital importance to society and human well-being (Brauman et al., 2007). Paired catchment studies have shown that forests influence the quantity, quality and timing of water supply while also performing protective functions like preventing erosion, reducing flood risk, storage of carbon, regulating micro-climate, and providing cultural services like recreation among many others (Bruijnzeel, 2004; Calder, 2002; Ellison et al., 2017). The capacity of the forest to provide WES is, however, dependent on ecosystem health and their sustainable management (Báliková et al., 2020). In spite of this, most world's forest management programs seem to focus on biodiversity conservation and only 12% are managed with provisioning of WES as the primary objective (Báliková et al., 2020; Springgay et al., 2021). This fact could reflect the lack of full recognition or undervaluation of the relevance of WES within decision-making processes (Hohenthal et al., 2015; Springgay et al., 2019). In the light of the growing proportion of the population depending on natural forest resources for their livelihoods, amidst the effects of climate change and water scarcity estimated to affect two-thirds of the world's population by 2025, maintaining healthy forested landscapes is becoming increasingly critical (FAO, 2013). However, reducing the trade-offs between maintaining healthy forested ecosystems and other land-use decisions that favour other provisioning services (such as food, energy and timber) presents a significant challenge (Grizzetti et al., 2016).

This tension between objectives also applies to Kenya's water towers, such as Mau Forest Complex, which are constantly threatened by conversion to other land-use types (Jebiwott et al.,

2021). The Mau Forest Complex is the largest remaining closed-canopy indigenous tropical montane forest in East Africa. It is an important area that feeds major rivers and lakes in the country which support major economic sectors and serve as a vital source of water to over 5 million people living downstream (UNEP, 2008). However, despite its importance, the forest has been under enormous pressure for the past few decades due to anthropogenic activities coupled with climatic variations (Jebiwott et al., 2021; Swart, 2016). Conversion of the Mau forest to smallholder agriculture and pasture has been the main driver of deforestation linked to a significant loss of > 25 % forest cover between 1973 and 2013 (Brandt et al., 2018; Swart, 2016), with a net loss in forest area estimated at 699 km² during the period 1984-2020 (Jebiwott et al., 2021). As a result, the hydrological functioning of the forest, which is necessary for providing essential WES, has declined (Masese et al., 2012). This is coupled with ecosystem degradation, which has cascading effects on food security, water availability, human health, security, and social safety, which in turn undermine the resilience of the local community (Mwangi et al., 2020).

The adverse impacts caused by changes relating to forest, water and associated ecosystem services are felt most at the local level, where people are highly dependent on these resources and services for their livelihood and wellbeing (Acharya et al., 2019; Dorji et al., 2019; Gebrehiwot et al., 2014). Nevertheless, local peoples' perspectives and ecosystem service values are not always adequately incorporated in management decisions and conservation policies (Langat et al., 2021). This is despite the empirical evidence showing that successful participatory forest conservation outcomes are often dependent on local support (Mbeche et al., 2021; Njue et al., 2019) and the growing interest towards increased involvement of local communities in the conservation of the Mau forest (Ombogoh et al., 2022). Although previous studies conducted biophysical assessments (Jacobs et al., 2017), economic valuations (Langat et al., 2021) and participatory mapping (Miller et al., 2021) to quantify the ecological values of the Mau forest, little is known about the socio-cultural values attached to WES provided by the forest. Incorporating social-cultural valuation and their underlying factors alongside economic and biophysical quantification of ecosystem services, especially in regions undergoing rapid land use change and water scarcity, is, however, imperative. This can help unravel the complexities of socio-ecological interactions and uncover the potential trade-offs and synergies between different services in a spatially-explicit form (Martín-López et al., 2014; Stosch et al., 2017). Furthermore, this would facilitate development of effective conservation policies and designing of more adaptable locally-based interventions that promote

sustainable livelihoods and environmental sustainability (Hohenthal et al., 2015; Springgay et al., 2019).

Given this context, this study explored the socio-cultural values of WES provided by a tropical montane forest and their implications for local ecological management using a modified conceptual framework. Adapted from Haines-Young & Potschin (2010) and Maes et al. (2016), the framework links forest ecosystems to the livelihood and well-being of the society via the flow of WES (Figure 4.1). The framework depicts that forest ecosystems provide the necessary structures and processes that underpin the capacity of the forest (ecosystem function) to provide WES (de Groot et al., 2010). WES contribute to livelihoods and well-being of the society through the benefits they provide, and whose importance can be valued in different terms (Haines-Young & Potschin, 2010). For example, forest ecosystems have the capacity to trap sediments and break down pollutants, which results in water purification and subsequent provisioning of clean water for domestic purposes. This benefit can be valued based on socio-cultural values or by evaluating people's willingness to pay for conservation purposes to ensure clean water.

The objectives of this study were to: 1) assess the perceived role and contribution of forests to the provisioning of WES; 2) assess the perceived importance and trends in WES provided by the forest; 3) examine the relationship between WES prioritisation and underlying socio-demographic and environmental factors; and 4) evaluate the community's willingness to pay for management interventions that improve the supply of WES from forests. The findings of this study will be useful in supporting the ongoing conservation efforts and developing suitable management strategies based on the needs and priorities of local communities. They also provide complementary information necessary for designing incentive-based schemes such as payment for ecosystem services.

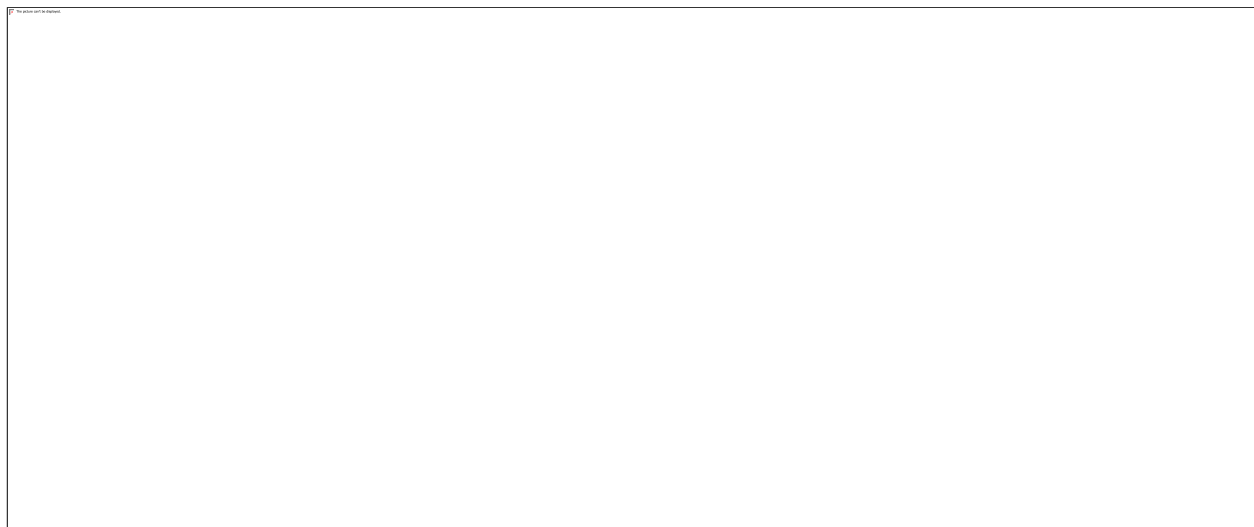


Figure 4.1 Conceptual framework linking forest ecosystems with livelihood and well-being through the flow of water-related ecosystem services.

4.2 Materials and methods

4.2.1 Study area

The study was carried out in the South-West Mau block (84,000 ha) of the Mau Forest Complex, located between 35°15'–35°40'E and 0°20'–0°45'S. The South West Mau is an important catchment area of the Sondu river that drains into Lake Victoria (Figure 4.2). Rainfall in the area exhibits a bimodal distribution, with total annual precipitation ranging between 1,000 mm yr⁻¹ in the lowlands and 2,000 mm yr⁻¹ in the highlands (Obati, 2007). The long rains start from April to July with at peak in April, and short rains occur from October to December, while January to March are the driest months (<75 mm per month) (Jacobs et al., 2017). The mean monthly temperatures range from 16°C to 22°C, with July having the lowest temperature and February and March having the highest maximum temperatures (Stephens et al., 1992). Potential evapotranspiration rates vary between 1,400 mm to 1,800 mm yr⁻¹ in the uplands and lower altitudes, respectively (Krhoda, 1988). The area has well-drained, fertile and deep humic Nitisols soils (>1.8 m) that are generally suitable for agriculture (Jacobs et al., 2017; Sombroek et al., 1982).



Figure 4.2 Map of the study area showing locations of the sampled households in the South-West Mau, Kenya.

The area is characterized by diverse land use types constituting forest (40%), cropland (31%) and grassland (28%) as the dominant land cover (Kenya Water Towers Agency, 2020). The north eastern upper part of the area located above 2,400 m a.s.l. is dominated by small scale subsistence farming. This majorly involves the cultivation of food crops including maize, potatoes, beans, peas, cabbages, kales on farm holdings averaging 2 ha, supplemented by cash crops such as tea and livestock keeping. The farms are interspersed by grazing fields and small woodlots of *Eucalyptus*, or *Cupressus* spp majorly for timber production (Jacobs et al., 2017). The local communities in this area rely more heavily on the natural forest especially for grazing and fuelwood, timber, poles and medicinal plants owing to their close proximity. The natural forest occupies the central part of the catchment occurring at 1,900 m and 2400 m a.s.l. The forest has a moist vegetation type exhibiting a broad altitudinal zonation from West to East; with tree species primarily consisting of *Aningeria adolfi-friedericii*, *Strombosia scheffleri*, *Tabernaemontana stapfiana*, *Syzygium guineense*, *Neoboutonia macrocalyx*, and *Olea capensis* (Kinyanjui et al., 2020). Below 2,100 m a.s.l., the

land opens up to an area dominated by commercial tea plantations, covering approximately 20,000 ha, and tree plantations of *Eucalyptus* and *Cypress* mainly used for tea processing. Neighbouring the commercial tea plantations at elevations below 1,800 m a.s.l., are smallholder farms consisting of a mosaic of tea farming on plots less than 1 ha, annual food crops, dairy farming, *Eucalyptus* woodlots, and conservation areas along riparian zones (Jacobs et al., 2017).

The South-West Mau is one of the largely affected blocks of the Mau Forest Complex and has been increasingly threatened by, among other things, forest excisions, encroachment, overgrazing, illegal logging, charcoal production poaching, infrastructural development and forest fires (Kenya Water Towers Agency, 2020). Between 1990 and 2019, the forest cover loss was estimated at 3% yr⁻¹, largely attributed to forest excisions in the year 2001, where 27.3% (22,797 ha) of the forest area were excised for settlement and farmland (UNEP, 2008).

4.3 Household survey

4.3.1 Survey design

A semi-structured questionnaire was developed in LimeSurvey (<https://www.limesurvey.org/>) and adapted in the Offline Survey application for Android smartphones (<https://www.offlinesurveys.com/>). The survey questions addressed 15 WES based on a review of previous literature and organized around the cascade model (Grizzetti et al., 2016; Haines-Young and Potschin, 2010; Paletto et al., 2021; Springgay et al., 2019). Following the typology of ecosystem services classification by the Millennium Ecosystem Assessment (MEA, 2005), the WES were grouped into three categories including provisioning, regulating, and cultural ecosystem services (Appendix 4.1). Supporting services were excluded from the categories of services because they are considered as underlying functions that sustain the supply of services (Stosch et al., 2017). The term ‘water-related benefits’ was used instead of WES while conducting the survey to facilitate understanding of the participants and avoid education-level bias (Martín-López et al., 2012).

The questionnaire included three main sections. The first section elicited information on socio-demographic attributes including participants’ gender, age, education level, years of residence, household size, source of income, annual income, and land size. The second section explored perceptions of the role of forest in providing WES, as well as the perceived importance and trends of these services in the last 10 years. To get a general overview of the importance of forest in the

study area to the community, the participants were asked to indicate to what extent (to a great extent, somewhat, very little extent, not at all) they felt that the forest provides water-related benefits that contribute to livelihoods and well-being of society. Subsequently, we investigated the perceived role of forest in providing specific WES using statements that were developed from hypothesized relationships between forest and hydrological services based on previous studies on forest hydrology and local perceptions (Calder, 2002; Dave et al., 2017; Gebrehiwot et al., 2014; Wilk, 2000). The participants were asked to indicate their level of agreement with each statements measured on a five-point bi-polar response scale ranging from 1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, 5 = strongly agree. They could also choose 'I don't know' as an answer.

Moreover, the perceptions regarding the importance of WES provided by the forest were examined using a 5-point Likert scale and ranking technique, respectively (Alba-Patino et al., 2021). The participants were asked to rate the importance of each WES for societal well-being on a scale of 1 (not important) to 5 (very important), and also rank the top five services they considered as most important for their individual well-being. For the perceived trend, they were asked to indicate how each WES supply had changed over the past 10 years (declining, no change, increasing, or I don't know). We used observable indicators of change for each WES. Because perceived trends reflect the degree of vulnerability people associate with different ecosystem services, a period of 10 years was considered robust enough to capture meaningful environmental change (Alba-Patino et al., 2021; Castro et al., 2016).

In the third section, participant's environmental behaviour was evaluated using a set of questions regarding their membership to an environmental conservation organization or social group, previous training on forest and water conservation, whether they voluntarily undertook conservation activities on their farms, and their willingness to pay for ecosystem for conservation purposes to ensure clean water. We evaluated the maximum amount of money participants' would be willing to pay ranging from < 1,000; 1,000-5,000, 5,000-10,000, and >10,000 KES/month, (equivalent to < 10, 10-50, 50-100, and > 100 \$USD/ month, respectively). Those who were not willing to pay were asked to state the reasons for their decision. The questionnaire's content and structure are presented in Appendix 4.3.

4.3.2 Household selection

A multi-stage sampling technique was used to select sample households, which were the primary sampling units for the study. First, the study area was stratified into three zones to capture spatial and context-specific information that was representative of the local environmental and socio-economic conditions from across the study area. The zones were classified into an upper (situated above 2,400 m a.s.l.), middle (at 2,100 m a.s.l.), and lower part (at 1,800m a.s.l.) using geographical location as criteria for stratification. From each zone, one sub-location (the lowest administrative unit at local level) was selected on the basis of their relative proximity to the forest. In each of the selected sub-locations, 3-4 study villages were randomly selected in consultation with the local administrative officials. Finally, about 18 to 24 households were randomly selected from each village based on estimated total number of households provided by village elders that constituted the sampling frame. A sampling intensity of 15-20% was adopted to obtain a representative sample of households per zone, given the relative homogeneity of households (Ketema et al., 2021). Overall, 217 households were sampled in 11 villages out of which 73 households were from the upper zone, 72 from middle zone, and 72 in the lower zone, respectively (Table 4.1). This sample size results in a 6% error margin with a 95% confidence level following Cochran (1977).

Table 4.1 Characteristics of the sampled households across the three zones under study, in the South-West Mau.

Zone	Average elevation (m)	Sub-location	Population Density (persons km ⁻²) ^a	N ^o . of villages sampled	Distance from the forest edge (km)	Total N ^o . of households	Sample size
Upper	2,400	Chemare	300	3	0-7 km	381	73
Middle	2,100	Sotit	422	4	0-3 km	348	72
Lower	1,800	Kipkirieny	732	4	13-15 km	464	72
Total				11		1,193	217

^a Population density data was sourced from KNBS (2019).

4.3.3 Implementation

The survey was conducted in April 2022 through face-to-face interviews. The questionnaire was pre-tested with 12 randomly selected households outside the sample frame to test the relevance, consistency and validity of the survey instrument (Babbie and Mouton, 2001). Before the survey, the participants were informed about the purpose of the survey and the research in general, that participation was voluntary and that they could withdraw participation at any time, that they did not have to answer questions they did not want to answer and that all data would be stored and analysed anonymously. The survey was only conducted when explicit informed consent was obtained from the participant. The interviews lasted 45 to 60 minutes and were conducted in Kiswahili and, if required, questions were translated to the local language by the enumerators.

4.4 Data analysis

Descriptive statistics (frequency distribution, mean and standard deviation) was used to analyse the data. Kruskal Wallis test in combination with the Dunn multiple comparison test was used to analyse differences in perceptions between the ecosystem service categories and zones. A prioritization matrix was used to assess the vulnerability of ecosystem services by taking into account the perceived importance and trends values. In doing so, we categorized WES into four types: very important with decreasing trend (*critical*), very important with increasing trend (*important but not vulnerable*), not important with decreasing trend (*vulnerable but not important*), and not important with increasing trend (*less relevant*) (Alba-Patino et al., 2021; Iniesta-Arandia et al., 2014). A binomial logit regression model was used to identify how perceptions regarding the importance of each WES were influenced by explanatory variables including socio-demographic characteristics and environmental behaviours (Appendix 4.2). The dependent variable was coded '1' if the perceived importance was > 4 and otherwise '0'. To build the models we considered 9 explanatory (independent variables). The best predictive model was selected using Akaike's Information Criteria (AIC), whereby the model with smallest AIC value and the smallest factor number was selected (Burnham and Anderson, 2004). We performed all statistical analyses using R software version 4.2.1.

4.5 Results

4.5.1 Socio-demographic characteristics

Overall, 55.8% (n=121) of the participants were female and 44.2% (n=96) were male with a mean age of 42.5 ± 14.6 years. Highest education level was observed in the lower zone with 37.5% having completed either college or university, whereas this was 29% and 14% in the middle and upper zones, respectively. Participants in the upper zone have lived fewer years in the area (16.9 ± 10.1) than those in the lower (30.5 ± 17.4) and middle (31.9 ± 18.0) zone. Land sizes were largest in the middle zone with an average of 4.2 ± 6.9 ha. About 86.3% of the participants in the upper zone have a low income (< \$1,000) compared to 50.7% and 51.4% in the middle and upper zone, respectively. Overall, 88.0% (n=191) of the participants derived their main source of income from on-farm activities, primarily crop production and livestock keeping. Although most of the households (77.0%; n=167) were voluntarily undertaking management activities on their farms and 54.4% (n=118) had received training/information on forest and water resources management, only 17.8% (n=34) were members of an environmental conservation organisation or social group (Table 4.2).

Table 4.2 Socio-demographic and environmental characteristics of the households. For continuous variables mean \pm standard deviation are provided, for categorical values the number of respondents in each category and the corresponding percentage relative to the total number of participants in each zone. NA values have been excluded and as a consequence, percentages do not always sum to 100%. The significance level is indicated as follows: * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

Variable	Lower (n=72)	Middle (n=72)	Upper (n=73)	Pooled (n=217)	χ^2	
<i>Demographic</i>						
Age (years)	42.0 \pm 14.3	44.8 \pm 16.4	41.1 \pm 12.8	42.5 \pm 14.6	1.28	
Gender	- Female	41 (57.0)	37 (51.4)	43 (58.9)	121 (55.8)	0.89
	- Male	31 (43.1)	35 (48.6)	30 (41.1)		
Education level	- No formal education	1 (1.4)	6 (8.3)	5 (6.9)	12 (5.5)	17.9*
	- Primary school	20 (27.8)	24 (33.3)	34 (46.6)	78 (35.9)	
	- Secondary school	24 (33.3)	21 (29.2)	24 (32.9)	69 (31.8)	
	- College/Polytechnic	17 (23.6)	10 (13.9)	8 (11.0)	35 (16.1)	
	- University	10 (13.9)	11 (15.3)	2 (2.7)	23 (10.6)	

Variable	Lower (n=72)	Middle (n=72)	Upper (n=73)	Pooled (n=217)	χ^2
Source of income					
- On-farm activities	56 (77.8)	64 (88.9)	71 (97.3)	191 (88.0)	13.12**
- Off-farm activities	16 (22.2)	8 (11.1)	2 (2.7)	26 (12.0)	
Annual income (KES)					
- <100,000	36 (51.4)	36 (50.7)	63 (86.3)	135 (63.1)	26.6***
- 100,000-300,000	26 (37.1)	29 (40.9)	9 (12.3)	64 (29.9)	
- > 300,000	8 (11.4)	6 (8.5)	1 (1.4)	15 (7.0)	
Years of residence	30.5±17.4	31.9±18.0	16.9±10.1	26.4±16.9	37.50***
Household size	5.9±2.0	6.6±3.6	6.2± 2.5	6.2±2.8	1.41
Land size (ha)	3.4±4.0	4.2±6.9	3.2±2.2	3.6±4.8	1.27
<i>Environmental behaviour</i>					
Voluntarily undertaking conservation activities	58 (80.1)	57 (79.2)	52 (71.2)	167 (77.0)	2.07
Member of environmental conservation organization or social group	11 (15.3)	7 (9.7)	16 (21.9)	34 (17.7)	4.01
Training on forest and water resources	41 (56.9)	40 (55.7)	37 (50.7)	118 (54.4)	0.63

4.6 Socio-cultural valuation of WES

4.6.1 Perceived roles of forests in provisioning of WES

This study shows that 87% of the participants acknowledged that the forest in the study area provides WES that are contributing to the society's livelihood and general well-being to a great extent. Notably, forests were highly appreciated for the role they provide regulating services, followed by cultural services and then provisioning services. The lower zone had a higher rating for the role and contribution of forest to providing WES, followed by the middle and upper zones.

However, in all three zones, the participants reported strong agreement with statements about the forests' capacity to provide services like climate regulation (4.69±0.61), water provision (4.61±0.74), water purification (4.58±0.63), water regulation (4.54±0.66), erosion prevention (4.37±0.67), groundwater recharge (4.34±0.76), and religious and spiritual values (4.28±0.74), while food provisioning had the lowest score (2.74±1.23) (Figure 4.3). Nonetheless, there were only a few significant differences regarding the participants' perceived role of forest in providing individual WES among the three zones. One such difference was that the participants in the lower zone highly attached a more important role of forest to food provisioning ($p<0.001$), soil fertility

maintenance ($p=0.012$), and flood protection ($p=0.05$) compared to other zones. This could indicate a higher reliance on rivers to provide food (fish), exposure to frequent flooding, and declining soil fertility associated with ecological factors and land use changes, making participants in the lower zone more aware of their vulnerability.

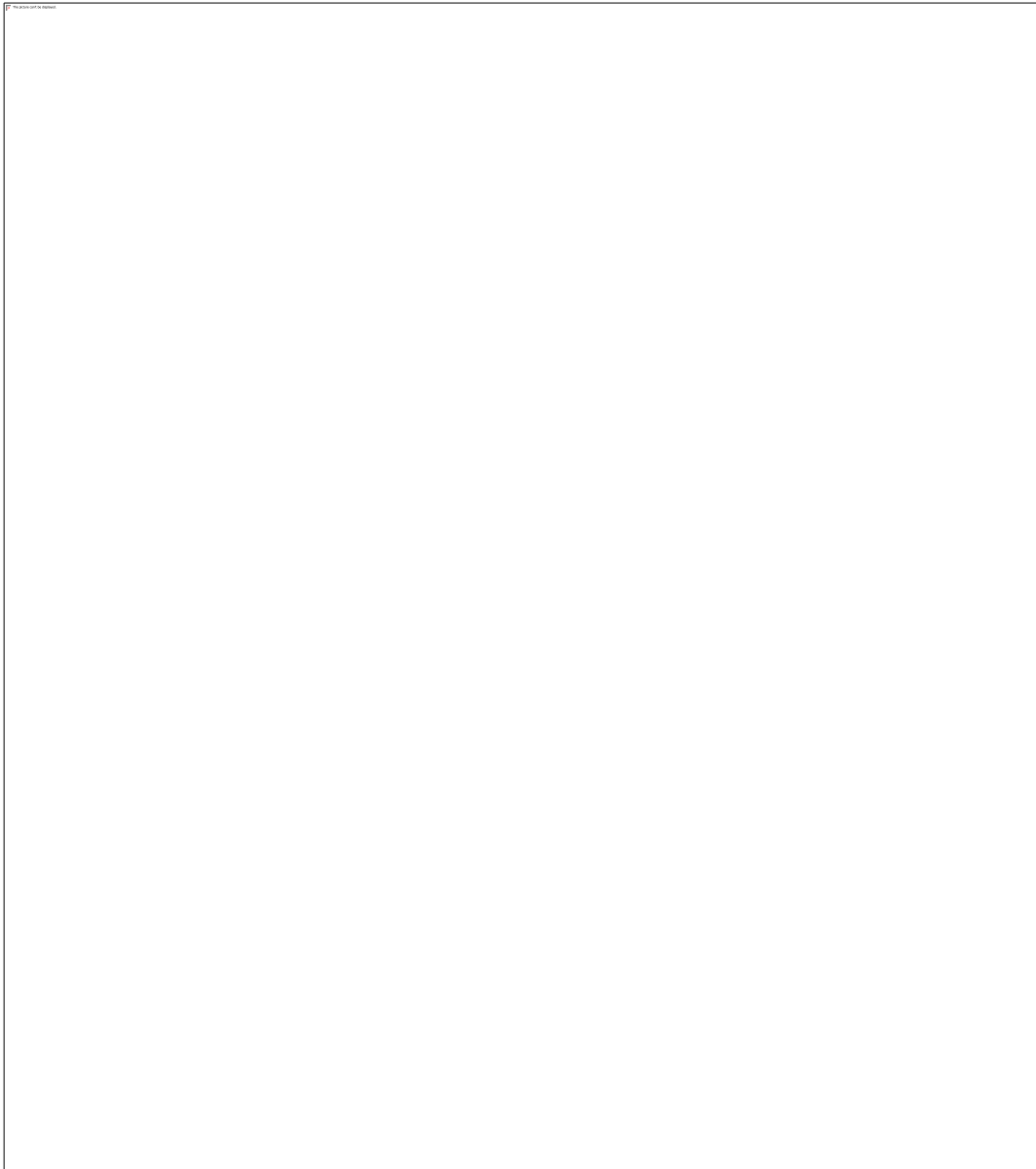


Figure 4.3 Perception of the role of forests in providing various WES (left) and the mean score for each WES (right) in the South-West Mau (n=217). The Y-axis presents individual WES per zone (L=lower, M=middle, and U=upper zone) and X-axis denotes the proportion of participants.

4.6.2 Perceived importance of WES

The perceived importance of WES varied significantly among the zones (Table 4.3). The highest importance was attributed to the category of regulating services with a mean value of 4.22 ± 0.56 , followed by provisioning services at 3.57 ± 0.56 and then cultural services at 3.09 ± 0.93 . Furthermore, we noted that on overall the participants in the lower zone assigned higher importance values to WES (3.84 ± 0.86), as compared to middle (3.65 ± 0.86) and upper zone (3.39 ± 0.87).

Table 4.3 Perceived importance of provisioning, regulating and cultural ecosystems services across the zones (Mean \pm SD; the different letters indicate significant differences among the zones).

Category of WES	Lower (n=72)	Middle (n=72)	Upper (n=73)	All (n= 217)
Provisioning	$3.77 \pm 0.71a$	$3.63 \pm 0.75a$	$3.32 \pm 0.61b$	3.57 ± 0.56
Regulating	$4.42 \pm 0.51a$	$4.21 \pm 0.52ab$	$4.03 \pm 0.58b$	4.22 ± 0.56
Cultural	$3.34 \pm 0.92a$	$3.11 \pm 0.86ab$	$2.82 \pm 0.91b$	3.09 ± 0.93
Overall per zone	$3.84 \pm 0.86a$	$3.65 \pm 0.86a$	$3.39 \pm 0.87b$	

Regarding the perceived importance of WES for societal well-being, water provisioning was perceived as the most important, followed by climate regulation, water purification, water regulation, groundwater recharge and religious and spiritual values, respectively (Figure 4.4). In contrast, food provisioning was assigned lowest importance. The Kruskal-Wallis test revealed that the importance attributed to food provisioning ($p < 0.001$), soil fertility maintenance ($p = 0.005$), flood protection ($p = 0.001$), groundwater recharge ($p = 0.02$), recreation ($p = 0.001$), aesthetics ($p < 0.001$), and religious and spiritual values ($p = 0.02$) differed significantly among the three zones, whereby participants from the lower zone generally perceived the WES as more important (Figure 4.4).

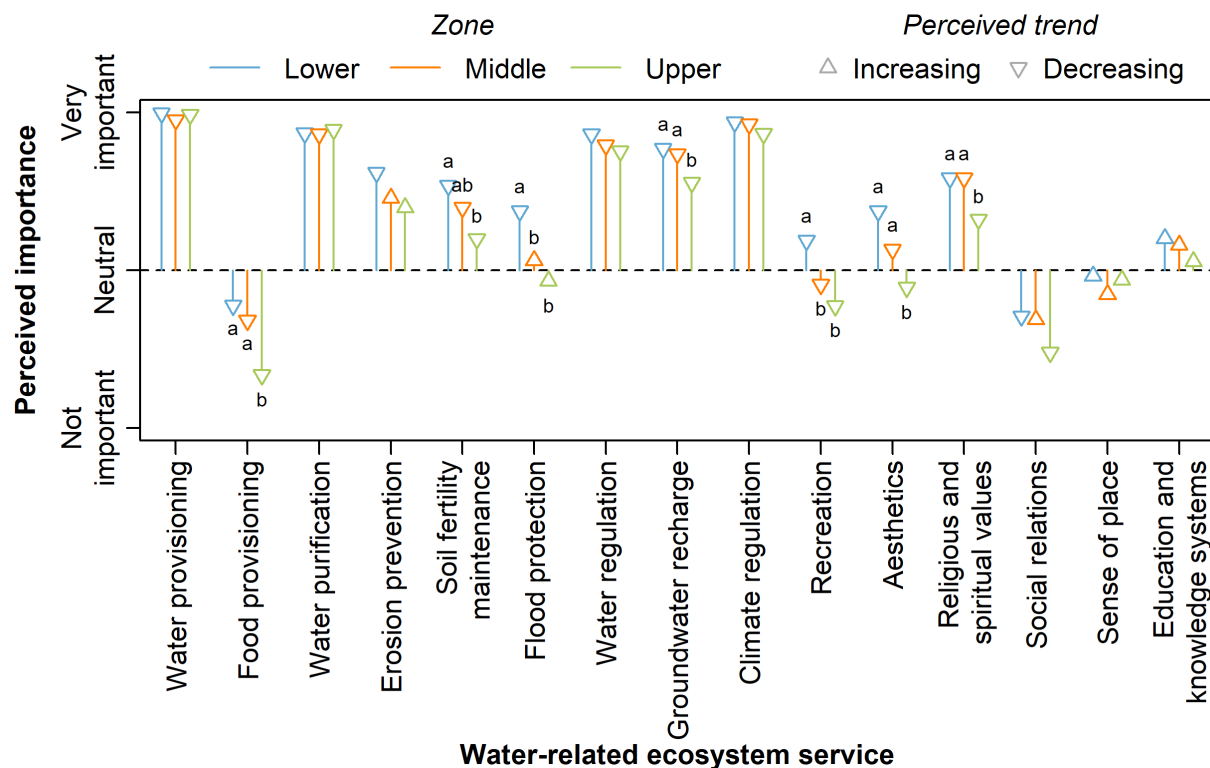


Figure 4.4 Comparison of perceived importance of WES and trends between the three zones (n=217). Significant differences in perceptions of importance among zones are identified with different letters. If no letters are provided, there were no significant differences among zones. The symbols indicate whether participants in each zone perceived a generally increasing or declining trend for the WES, respectively.

4.6.3 Prioritized WES

When participants were asked to rank the top five most important services for their individual well-being, most participants prioritised water regulation (n=202), followed by water provisioning (n=201), water purification (n=188), climate regulation (n=169) and ground water recharge (n=105). These services were also among the highly rated for societal well-being, although in a slightly different order of priority. This suggests that the demand for these services is consistently high across the three zones (Figure 4.5).

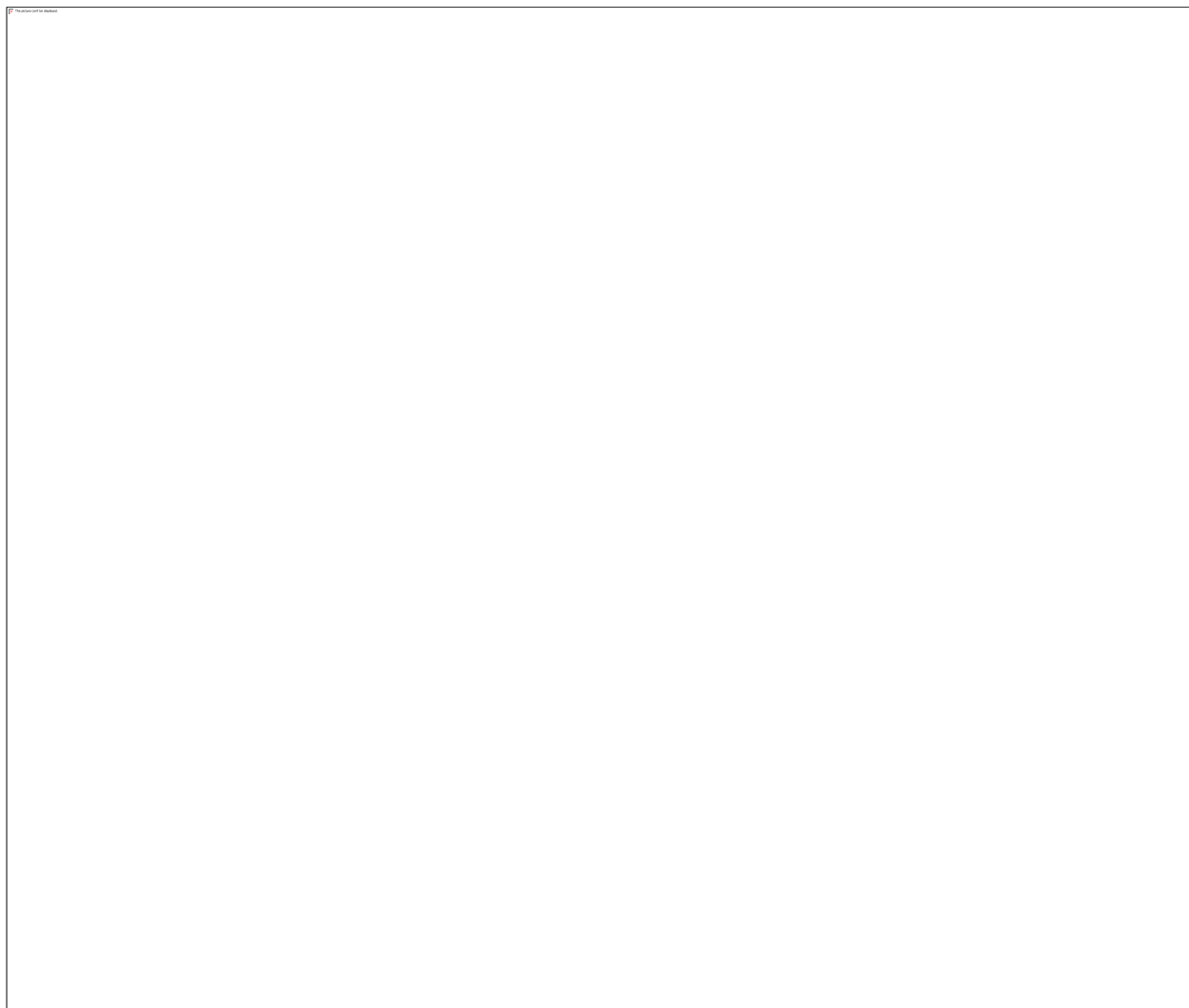


Figure 4.5 Scatter plots of the perceived importance (Y-axes) and trends of water-related ecosystem services (X-axes) based on participants' responses across the three zones in the South West Mau (n=217). The quadrants indicate perceptions of WES as very important-decreasing (critical), very important-increasing (important but not vulnerable), not important-decreasing (vulnerable but not important), and not important-increasing (less relevant). The five most important WES are represented in different colors and ranked from the most to least important based on the number of times they were mentioned by participants.

4.6.4 Linkages between importance of WES and perceived trends

Figure 4.5 shows that all the highly prioritised WES including water provisioning, climate regulation, water purification, water regulation, groundwater recharge, alongside religious and spiritual values, soil fertility maintenance and aesthetic values were perceived with a decreasing

trend, making them the most *critical* ecosystem services that need to be addressed. The study further revealed that some regulating services, including erosion prevention and flood protection, and cultural services, such as education and knowledge systems, were perceived as very important with an increasing trend (*important but not vulnerable*). Although recreation, social relations, and food provisioning were considered not important, they were perceived to have a decreasing trend (*vulnerable but not important*), while sense of place was perceived as not important with an increasing trend (*less relevant*).

However, there were clear differences in perceived importance and trends in provision of WES among the three zones (Figure 4.4). A key finding was that more services were considered *critical* (very important with decreasing trends) in the lower zone (n=11) compared to middle (n=7) and upper zone (n=7), respectively. On the other hand, aesthetics were regarded as *vulnerable but not important* and flood protection as *less relevant* in the upper zone. Whilst social relations were considered as *less relevant* in the middle zone, they were perceived as *vulnerable but not important* in the upper and lower zone.

4.6.5 Socio-demographic and environmental variables on the perception of ecosystem services

The logit regression analysis revealed that different variables explained participants' perceptions for individual WES. Location was identified as a factor that influenced the perceptions of a broad array of ecosystem services (Table 4.4). Young people were more likely to perceive water purification as less important while older people had a slightly higher perceived importance of flood protection and spiritual and religious values. Men were generally more likely to perceive the importance of food provisioning and sense of place compared to women. Participants with formal education i.e. those who had attained primary education and above were more likely to perceive flood protection, aesthetics and climate regulation as important. Furthermore, participants with a higher income were more likely to have a higher perceived importance for education and knowledge systems, erosion prevention, flood protection, religious and spiritual values, and sense of place while those who depended on off-farm activities as their main source of income were less likely to perceive aesthetics as an important service.

Participants' who were not voluntarily undertaking conservation activities on their farms reported a lower perceived importance of regulating services (erosion prevention, soil fertility maintenance, and climate regulation) and cultural services (religious and spiritual values and sense of place). Moreover, participants who did not receive any training or information about forest and water resources management would perceive sense of place and education and knowledge systems as less important compared to those who did. Similarly, participants who did not belong to an environmental or social organization had a lower perceived importance for recreation than members of such groups.

Table 4.4 Logistic regression results showing the socio-economic and environmental factors influencing the perceived importance of WESs in the South-West Mau. Coefficients from the model with standard errors (in parentheses) are provided. The significance level is indicated as follows: * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$.

Variable	Food provisioning	Water purification	Erosion prevention	Soil fertility maintenance	Flood protection	Water regulation	Groundwater recharge	Climate regulation	Recreation	Aesthetics	Religious and spiritual values	Social relations	Sense of place	Education and knowledge
Zone: Upper	- 1.07*			- 0.88*	- 0.60*	-1.56*	-1.07*		-0.88*	-1.23**		-1.11*		
	(0.45)			(0.36)	(0.35)	(0.8)	(0.46)		(0.37)	(0.38)		(0.49)		
Zone: Middle	- 0.47			- 0.51	- 0.93*	-1.14	- 0.46		-0.46	-0.77*		-0.56		
	(0.40)			(0.37)	(0.35)	(0.83)	(0.49)		(0.36)	(0.36)		(0.43)		
Age		- 0.04*			0.02*						0.02*			
		(0.02)			(0.01)						(0.01)			
Years of residence													-0.02	
													(0.01)	
Gender: Male	1.03**												0.74*	
	(0.36)												(0.33)	
Education: Primary								3.44**		0.22				
								(1.26)		(0.72)				
Education: Secondary								2.66*		1.01				
								(1.06)		(0.73)				
Education: College/Polytechnic										1.01				
										(0.78)				
Education: University								1.69		2.0*				
								(1.27)		(0.86)				

Variable	Food provisioning	Water purification	Erosion prevention	Soil fertility maintenance	Flood protection	Water regulation	Groundwater recharge	Climate regulation	Recreation	Aesthetics	Religious and spiritual values	Social relations	Sense of place	Education and knowledge
Income: Mid			1.18 ** (0.38)		0.58 (0.33)						0.80* (0.35)		1.15*** (0.34)	0.94** (0.33)
Income: High			1.42 (0.79)		1.59 * (0.64)						0.97 (0.68)		0.73 (0.58)	1.72* (0.68)
Source of income: off-farm										- 1.19* (0.51)				
Training: No													- 0.93** (0.32)	- 0.94** (0.30)
Conservation: No			- 0.82* (0.35)	- 1.15*** (0.34)				-1.87* (0.88)			- 0.68* (0.34)		- 0.87* (0.40)	
Membership: No									- 0.74* (0.39)					

4.7 Willingness to pay

The study revealed that approximately 17.5 % of households surveyed were unwilling to contribute towards conservation purposes. Among the 38 participants who were not willing to pay, the majority cited that it was the responsibility of the government to support management initiatives (n=24) while others could not afford to pay (n=15). Some of the households were not interested (n=3), did not trust the implementation and success of the payment plan (n=5), while one participant indicated that they were not directly affected by the changes in forest and water resources. About 63% of households showed their willingness to pay <5,000 KES (approximately 50 \$USD) for watershed management to improve water quality, while 29.8% of the households were willing to contribute amounts above 5,000 KES. The willingness to pay was higher in the lower zone (88.9%), followed by the middle (80.8%) and upper zone (77.8%) (Figure 4.6).

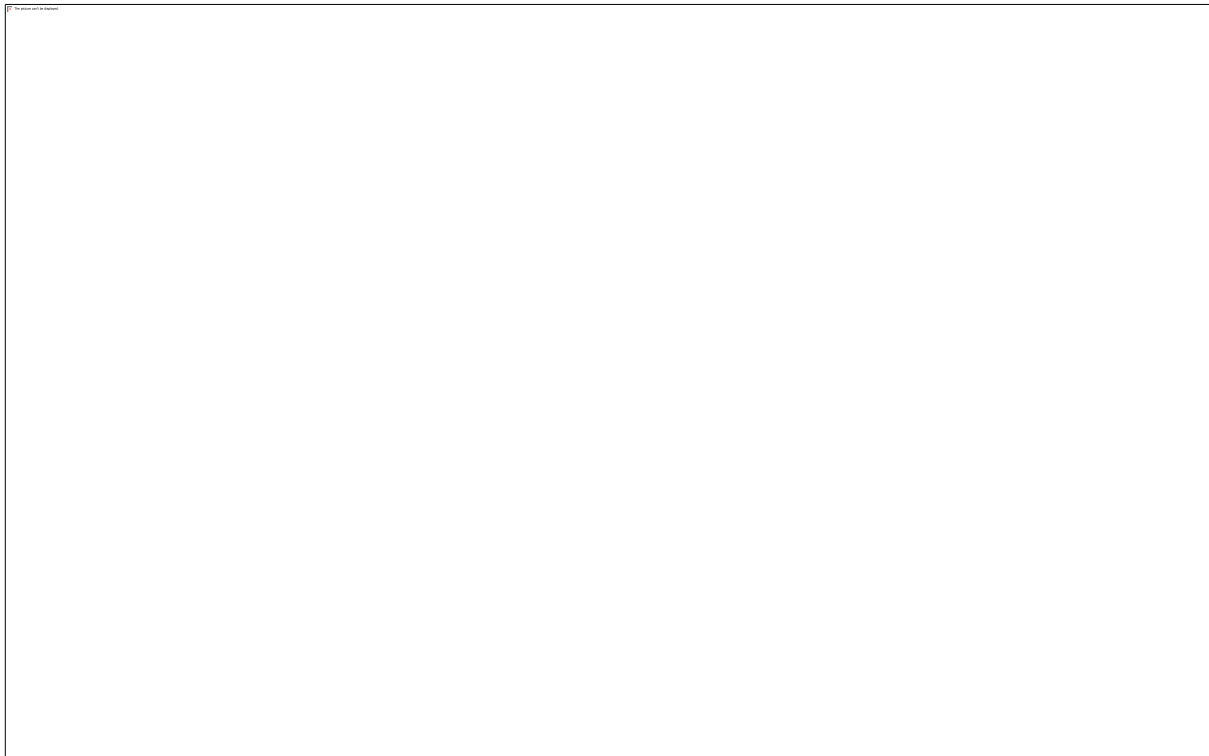


Figure 4.6 Proportion of participants showing willingness to pay for WES (a) and reasons for those not willing to pay (b).

4.8 Discussion

4.8.1 Socio-cultural values of WES provided by forests

In recent years, an increasing emphasis has been placed on the need to incorporate socio-cultural valuation in the assessment of ecosystem services in order to understand nature's contributions to people (de Groot et al., 2010). However, social-cultural values are still inadequately integrated into land-use management, policy and decision making processes (de Groot et al., 2010). The identification of priority and critical WES based on socio-cultural values can guide decision-making and development of management strategies that can enhance provision of multiple services (Dave et al., 2017; Mahjoubi et al., 2022).

The findings of our study show that the local community recognised and valued a wide range of WES provided by the South-West Mau, based on their contribution to the livelihoods and well-being of the society. Nonetheless, regulating services were perceived as more important, followed by provisioning and cultural services, as was also reported for other regions (Báliková et al., 2020; Paletto et al., 2021). With the majority of the participants (88%) depending on-farm activities for subsistence, it is understandable that regulating services associated with forests were perceived more important, as these services are very crucial for agricultural production. Regulating services are however often ignored in socio-cultural assessments of ecosystem services because they are associated with less tangible benefits (Dave et al., 2017) and based on the assumption that rural people are more concerned about the provisioning services as they provide direct and immediate benefits (Dorji et al., 2019). However, the results of this study support the argument that rural people are equally capable of identifying and valuing ecosystem services with indirect benefits (Martín-López et al., 2014). Our findings also corroborate those of other studies conducted in Thailand and India (Wilk, 2000), Ethiopia (Gebrehiwot et al., 2014), Madagascar (Dave et al., 2017), and Italy (Paletto et al., 2021), that reported similar locally held perceptions on the role of forests in providing certain WES. Furthermore, the perceived role of forests corresponds to the general scientific studies on the relationship between forests and delivery of hydrological services (Brauman et al., 2007; Bruijnzeel, 2004; Calder, 2002; Ellison et al., 2017). Ongoing efforts run by various organisations to conserve the South-West Mau, including capacity-building programs, awareness campaigns, and media coverage of water issues, may have contributed to this perception

by improving the local knowledge of the forest-water linkages and climate change impacts (GoK, 2009; MoALF, 2018).

Among the WES provided by the forest, water provision was identified as the most important service for the rural households, similar to a previous study in the region (Miller et al., 2021). The high importance of climate regulation could be related to increasing incidences of water shortages, longer dry spell, unreliable rainfall, changes in planting dates, crop failures and low land productivity, mostly associated with changing weather patterns (MoALF, 2018). Previous studies that alluded that the social demand for cultural services is less in rural areas than in urban areas, primarily because local livelihoods are highly connected with extractive activities and subsistence economies, and thus they might have limited time to experience these cultural services (García-Llorente et al., 2020). However, we found that religious and spiritual values and aesthetics were assigned a higher value among the cultural services provided by the forest which was consistent to the findings reported by Mahjoubi et al. (2022). In contrast, food provisioning obtained the lowest socio-cultural value. This may be related to the fact that fishing is limited or non-existent in the area, and although this activity was reportedly common in the past, this may indicate possible impacts of climate and land use changes on the aquatic ecosystem (Kapiyo et al., 2003).

We found that the top five most important WES for individual well-being were also among the highest valued services perceived as very important for societal well-being across the zones, although in a slightly different order (Figure 4.5). The heavy and direct dependence of many households on streams, springs, rainfall, and wells as the main source of water for domestic and agricultural purposes, underscores the importance of these services to the livelihood and well-being of society in the area (Miller et al., 2021). More importantly, the results reveal some kind of interrelationship between shared community values and individually held values for specific ecosystem services that could be a motivating factor for environmental stewardship (Irvine et al., 2016).

4.8.2 Vulnerability of ecosystem services

Figure 4.5 shows that most WES were found to be *critical* in the area because they were perceived as both important and with a decreasing trend over the last 10 years, hence vulnerable to loss. Previous scientific studies in the same area have closely linked the changes in Mau forest to the

decreasing river discharges and groundwater recharge (Mango et al., 2010; Mati et al., 2008), increased erosion and frequent flooding due reduced soil water infiltration rates (Owuor et al., 2018), and water quality deterioration due to elevated nutrient and sediment loads in streams and rivers (Jacobs et al., 2017; Njue et al., 2021; Stenfert Kroese et al., 2020b). Nutrient loss from agricultural lands and declining rainfall, along with water shortages due to increased vulnerability and risks related to climate change, are also major issues of concern in the area (Mwangi et al., 2020; Stenfert Kroese et al., 2021). Consequently, these changes maybe affecting the delivery of cultural services such as religious and spiritual values and aesthetics. The local community in the region ascribe religious and spiritual values to water and water sources, whereby in some, clean water from springs is viewed as sacred and a symbol for purification. Flowing water such as waterfalls, rivers and wetlands, on the other hand, are perceived to have aesthetic values (Mahjoubi et al., 2022). Hence, changing visual properties such as water levels and water color due to high turbidity levels and the loss of features symbolizing the cultural identity could explain why these services were perceived to be decreasing (Mahjoubi et al., 2022; Nyingi et al., 2013). As such, the study emphasises the need to incorporate and prioritise *critical* WES in forest ecosystem management and land-use planning decisions.

The perceived increasing trend in cultural services (in particular education and knowledge systems, sense of place and social relations) may reflect the positive impacts of the ongoing collaborative conservation efforts and the participation of local community in environmental organizations and social groups to preserve the Mau Forest Complex (Ombogoh et al., 2022). Similarly, the increasing trend observed for erosion prevention and flood protection could be attributed to the reducing deforestation rates in the region in the recent years, reforestation programs and the adoption of best land management techniques at the farm level (Akanga et al., 2022; Watene et al., 2021). The latter is also confirmed by the findings in our study, which shows that the majority of the households (77%) were voluntarily engaging in conservation activities such as agroforestry on their farms. Recreation and food provisioning were considered as vulnerable but not important. This can be attributed to the significant changes in land use in the area, that might be impacting the aquatic systems and reducing number of features and attributes within the landscape that are valued for recreation (Nyingi et al., 2013).

4.8.3 Contrasting perceptions of WES: Does proximity to the forest matter?

Understanding the similarities and contrasting perceptions of WES can help to visualise potential trade-offs and synergies between services which is essential in the management of ecosystems to avoid social conflicts (Zhang et al., 2021). The results indicate that despite participants across the three zones sharing similar perceptions of the importance of WES provided by the forest, there were contrasting perceptions for certain WES (as shown in Figure 4.4). The differences point to the heterogeneity in WES values and in the supply and demand of these services across space. Generally, the perceived importance of all WES as well as for specific WES (Table 4.3 & Figure 4.4) was significantly higher in lower zone compared to other zones, despite being located farther away from the forest. This contradicts other studies that reported that the perceived importance of ecosystem services decreases with distance from the forest (Mikusiński and Niedziałkowski, 2020).

According to Muhamad et al. (2014), spatial heterogeneity within a landscape can lead to changes in flows of ecosystem services. Depending on the place of residence, this may have strong influence on local communities' perceptions of ecosystem services (Miller et al., 2021). This may suggest that changes in WES delivery may be more pronounced in the lower catchment thus posing adverse effects on communities living downstream. As a result, participants are more aware of environmental issues, which explains why more WES were perceived as *critical* in this region. The results point to the need for incentive-based mechanisms such as payment for ecosystem services (PES) to promote cooperation between upstream and downstream communities and encourage sustainable management of forests and water resources.

Also, the duration of residence could have influenced the perceptions of WES, as most respondents in the lower zone had lived in the study area longer (30.5 ± 17.4) compared to those in the upper zone (16.9 ± 10.1). The length of residence in the upper zone coincides with the period when this part of the forest was excised in 2001, which could mean that they had migrated to the area during that period. Muhamad et al. (2014), reported that people who were natives or had lived in the same place for a longer time were more likely to place more value on ecosystem services provided by the forest than those who had migrated or lived in the area for a short time. This could be because residence duration in an area promotes a sense of place as people tend to have a higher experience, local knowledge and physical connection with their environment (Shoyama and Yamagata, 2016).

4.8.4 Factors influencing the perceptions of WES

Socio-cultural values of ecosystem services are site-specific and vary among the respondents due to a complex set of factors including biophysical conditions (Miller et al., 2021), cultural characteristics, and socio-economic settings (Ketema et al., 2021). Our study revealed that geographical location was an important factor influencing perceptions of WES (as explained in section 4.8.3). As such, spatial heterogeneity of biophysical and socio-economic characteristics needs to be taken into account when valuing ecosystem services, as this can help in developing adaptive management strategies based on the needs and priorities of the local community in different areas. The influence of age on perceptions of certain WES could imply that older people were more concerned about the impacts of land use change on water quality and flood risk, had greater awareness and strong religious traditions based on their long-term experience and knowledge (Martín-López et al., 2012; Moutouama et al., 2019).

Our findings further revealed gender differences in the perceptions of WES, with men perceiving food provisioning and sense of place as more important than women. This could be attributed to the gender-differentiated roles in the society as men are actively involved in fishing activities and participatory management of forest and water resources initiatives compared to women (Martín-López et al., 2012; Njue et al., 2021; Ombogoh et al., 2022). The participants with higher formal education and higher income were more likely to perceive WES, especially those with indirect benefits, as important (Table 4.4) (Acharya et al., 2019; Lima and Bastos, 2019). Participants who depended on off-farm activities as their source of income were likely to have a lower valuation for ecosystem services provided by nature such as aesthetics, which could be because they do not directly depend on this service for their income (Mahjoubi et al., 2022). Lack of training, not engaging in conservation activities and non-membership to an environmental conservation organization or social group were negatively associated with the perceptions of certain cultural services and regulating services (Table 4.4). This could indicate a strong association between environmental behaviour and perceived importance of ecosystem services, with participants exhibiting positive environmental behaviour more likely to recognize and place more value to water-related ecosystem services provided by the forest (Martín-López et al., 2012).

4.8.5 Potential for payment for ecosystem services

PES has been promoted as an alternative and cost-effective approach to managing of forested watersheds through incentive-based mechanisms (Waruingi et al., 2022). Yet, an important factor determining the success of PES programs is the participants' willingness to pay. Because willingness to pay depends largely on the preferences and societal demand for ecosystem services, effective PES design requires careful consideration of the social perception values regarding these services (Bhandari et al., 2016; Waruingi et al., 2022). According to Börner et al.(2017), PES programs with direct local support tend to achieve better results, especially when the conservation targets highly valued and critical ecosystem services and is adapted to local circumstances.

In our study, water purification was considered among the *critical* WES. This may indicate that the participants' recognition of the forest's capacity to generate water purification benefits, its vulnerability due to changing landscapes, and their dependence on surface water for domestic use, contributed to their willingness to pay for conservation strategies aimed at improving water quality (Bhandari et al., 2016; Khan et al., 2019). Nonetheless, a higher proportion of the participants were willing to pay less than 50 \$USD/month, which may be related to participants' financial resource constraints given that majority of the participants (63%) were low-income earners. This highlights the need to consider non-monetary payments methods such as labour when eliciting willingness to pay, especially in developing countries (Waruingi et al., 2022). The participants' willingness to pay to conserve highly prioritised and critical WES justifies that the perceived value of WES can promote pro-environmental behaviours, which can support future development of PES programs to promote cooperation and participatory management of ecosystems in the region.

4.9 Conclusion and management implications

Regulating services are sometimes undervalued, as most land-use management decisions tend to favour provisioning services (Grizzetti et al., 2016; Mengist et al., 2020). This can be explained by the nature of the provisioning services being highly tangible with a significant economic returns that contribute to subsistence livelihoods (Dorji et al., 2019; Wilk, 2000). Spatial trade-offs were particularly noticeable between the upper and lower zones as there were contrasting perceptions for certain WES such as food provisioning, soil fertility, flood protection, groundwater recharge, recreation, aesthetics and religious and spiritual values. Thus, management decisions should

effectively take into account the spatial synergies and trade-offs of ecosystem services to avoid potential conflicts among people with different priorities (Martín-López et al., 2012).

In recent decades, collaborative engagement of local communities has gained widespread recognition as a cost-effective approach for integrating into hydrological monitoring, forest management and decision-making processes, especially in remote regions, to ensure long-term environmental sustainability (Njue et al., 2019). Whilst there is increasing recognition and inclusion of community participation in management and utilization of forest and water resources in the South West Mau (Ombogoh et al., 2022), the success of co-management initiatives largely depends on the willingness of the people to participate. This study provides valuable insights into the socio-cultural value of WES that can guide policy and decision-makers in designing effective incentive-based mechanisms such as PES programs that can promote co-management of forested watersheds and improve provision of ecosystem services.

Of particular importance in this context are the five highly valued WES, which were also considered among the most *critical* WES. Since the demand for these services is expected to rise with population growth, and to avoid social conflicts that may arise from competing needs and interests, there is need to incorporate and prioritise these services in the decision making process regarding forest management and landscape planning. Moreover, the socio-cultural values of WES were context-dependent and demonstrate the need to understand the spatial heterogeneity and the role of socio-demographic and environmental characteristics in the socio-cultural valuation of WES, as this can guide in development of management interventions that are more adaptable to local contexts.

As socio-cultural values by nature vary among stakeholders, values of stakeholders than local communities should also be taken into account in the development of management interventions. This is required to identify synergies and trade-offs that emerge among stakeholders with conflicting values. Through the identification and prioritisation of interventions that improve the provisioning and address the drivers of change of WES which are identified as *critical*, effective management strategies could be developed that support and are supported by stakeholders that depend most on forest for their well-being and livelihoods.

Acknowledgements

This work was supported by the German Academic Exchange Service (DAAD) in collaboration with National Research Fund, Kenya in the form of a PhD scholarship for Naomi Njue. Lutz Breuer would like to acknowledge funding of the Deutsche Forschungsgemeinschaft, grant number BR2238/23-1/ and 23/-2. We thank all the participants who devoted their time to respond to the questionnaire and the enumerators who helped administer the questionnaire. We are grateful to the local administration for allowing and supporting us to conduct the survey in the South-West Mau.

Appendix 4.1 Selected water-related ecosystem services considered in the study according to (MEA, 2005) and proxy indicators to monitor the trends in the supply of water related ecosystem services.

Category	WES	Description	Benefits	Indicator of ecosystem services change
<i>Provisioning</i>				
Provisioning	Water provisioning	The forest is the major source of water for streams and rivers relied upon by the community	Water supply for domestic purposes and other uses such as irrigation and for livestock	Availability of clean water supply throughout the year.
	Food provisioning	The rivers from the forest supply fish for the community	Availability of food from the river like fish for consumption	Amount of fish collected
Regulating	Water purification	The forest keeps the water clean	Clean water for use	Overall water quality in streams springs and other water sources e.g. clarity of water
	Erosion prevention	The forest protects land from erosion and reduces the amount of soil in rivers	Erosion prevention from farms and reduced amount of soil in rivers	Soil erosion
	Soil fertility maintenance	The forest maintains soil productivity and reduces the need for fertilizer use	Soil fertility and increased land productivity	Land productivity
	Flood protection	The forest reduces flooding during heavy rainfall	Protection from floods during heavy rainfall	Number of places affected by floods
	Water regulation	The forest ensures there is water in rivers and springs throughout the year	Water availability in rivers and springs throughout the year	Water flow in rivers and springs

	Groundwater recharge	The forest ensures there is water in wells throughout the year	Water availability in wells throughout the year	Water level in the wells throughout the year
	Climate regulation	The forest creates a cool climate and brings rain	Cool climate and reliable rainfall	Rainfall
Cultural	Recreation	The forest provide spots for water-related outdoor activities like swimming by ensuring water supply in rivers	Outdoor activities such as swimming, river viewing, relaxing near rivers	Number of recreational places along rivers, lakes and wetlands
	Aesthetics	Because of the forest we have beautiful places along the rivers, lakes and wetlands	The existence of beautiful places like lakes and waterfalls	Places to enjoy environment
	Religious and spiritual values	The forest provides places for sacred and religious activities (like baptism) and materials like holy water	Places for sacred and religious activities	Number of sacred or religious sites
	Social relations	Because of the forest we have places like rivers, lakes and wetlands where people socialize	Spaces for meeting with friends	Number of social meeting places
	Sense of place	The forest creates opportunities for cooperatives and joint community activities related to water management	Opportunities for joint community activities	Number of joint community activities
	Education and knowledge systems	Forests provide opportunities where we can learn on the value of forests for good water resource management	Learning new things about the value of forest in conserving water resources	Number of places to learn about environment

Appendix 4.2 List of explanatory variables used in the logistic regression.

	Variable	Description	Type	Coding
Dependent variable	WES	Perceived importance of each WES	Binary	1: if the respondent perceives WES as important (4/5), or otherwise 0
Explanatory variables				
Socio-demographics	ZONE	Location	Nominal	If the respondent resides in (1: lower zone, 2: middle zone, 3: upper zone)
	GEN	Gender of the respondent	Nominal	If the respondent is (0: male or 1: female)
	AGE	Age of the respondent	Continuous	Number of years
	YOR	Years of residence	Continuous	Number of years the respondent has resided in the area
	EDU	Education level of the respondent	Ordinal	If the respondent has attained (0: No formal education, 1: Primary 2. Secondary 3: College/Polytechnic 4: University)
	HHSZ	Household size	Continuous	Number of family members in the household
	SRC	Source of income	Nominal	If the respondent main source of income is from (1: on-farm activities 2. off-farm activities)
	INCOME	Income	Ordinal	If the respondents annual income [KES] is (1: low-income 2: middle-income 3: high-income)
	LNDSZ	Land size	Continuous	The size of land the respondent owns in (ha)
Environmental behaviour	MMBR	Membership to an environmental conservation organization or social group	Dummy	1:if the respondent belongs to a conservation group, otherwise 0

ADPTR	Adoption of conservation activities	Dummy	1: if the respondent is voluntarily undertaking conservation activities on their farm, otherwise 0
TRNG	Training or information about forest and water	Dummy	1: if the respondent has received training/information about forest and water resources, otherwise 0

Appendix 4.3 Survey questionnaire

General Information

Date

Village

Sub location

Section 1: Socio-demographic

1. Respondent's gender

Male

Female

2. Age of respondent

[] years

3. How long have you lived in this village?

[] years

4. What is the highest level of education?

No formal education

Primary school

Secondary school

College/Polytechnic

University

5. How many people currently live in this household?

[] persons

6. What is the main source of income in your household?

On-farm activities

Off-farm activities

7. a) Do you own land?

Yes

No

b) If yes, how much land do you own?

[] (ha)

Section 2:

a) Role of forests in providing water-related benefits

8. To what extent do you think/feel the forest in your region provide water-related benefits that contribute to local livelihoods and well-being?

To a great extent Somewhat Very little extent Not at all

9. To what extent do you agree with the following statements on water-related benefits provided by the forest?

Role of forest	Strongly disagree	Disagree	Neither agree or disagree	Agree	Strongly agree	I don't know
The forest is the major source of water for streams and rivers relied upon by the community for domestic uses and other purposes						
The rivers from the forest supply fish for the community						
The forest keeps the water clean						
The forest protects land from erosion and reduces the amount of soil in rivers						
The forest maintains soil productivity and reduces the need for fertilizer use.						
The forest reduces flooding during heavy rainfall						

The forest ensures there is water in rivers and springs throughout the year.						
The forest ensures there is water in wells throughout the year.						
The forest creates a cool climate and brings rain.						
The forest provide spots for outdoor activities like swimming.						
Because of the forest we have beautiful places along the rivers, lakes and wetlands.						
The forest provides places for sacred and religious activities (like baptism) and materials like holy water.						
Because of the forest we have beautiful places like rivers, lakes and wetlands where people socialize						
The forest creates opportunities for cooperatives and joint community activities related to water management and conservation of water resources such as. Water Resource Users Associations						
Forests provide opportunities where we can learn on the value of forests for good water resource management						

b) Importance of water-related benefits provided by forests

10. On the scale of 1-5, how would rate the importance of the following benefits from the forest to the community? (1= not important, 5= very important)

	1	2	3	4	5
Water provisioning for domestic purposes and other uses by the community is					
Food from the river like fish is					
Clean water for use by the community is					
Erosion prevention from farms and reduced amount of soil in rivers is					
Soil fertility and increased land productivity is					
Protection from floods during heavy rainfall is					

Water availability in rivers and springs throughout the year is					
Water availability in wells throughout the year is					
Cool climate and reliable rainfall is					
Outdoor activities such as swimming, river viewing, relaxing near rivers is					
The existence of beautiful places like lakes and waterfalls are					
Places for sacred and religious activities are					
Spaces for meeting with friends					
Opportunities for joint community activities are					
Learning new things about the value of forest in conserving water resources is					

11. Can you please select and rank the five most important water-related benefits delivered by the forest to you (from most important to least important).

Water-related benefit	1	2	3	4	5
Water supply					
Fishing					
Clean water					
Soil erosion control					
Soil fertility					
Flood control					
Water in rivers					
Water in wells					
Cool climate and rainfall					
Outdoor activities					
Beautiful environment					
Spiritual wellness					
Social trust with family, friends and community members					
Learning					

c) Changes in water-related benefits over the last 10 years

12. In your opinion, how has the following water-related benefits provided by the forest changed for the last 10 years?

Water-related benefits	Declining	No change	Increasing	I don't know
Availability of clean water throughout the year				
Amount of fish collected				
Overall water quality in streams springs and other water sources e.g. Clarity of water				
Soil erosion				
Land productivity				
Number of places affected by floods				
Water flow in rivers and springs				
Water level in the wells throughout the year.				
Rainfall				
Number of recreational places along rivers, lakes and wetlands.				
Number of places to enjoy environment.				
Number of sacred or religious sites				
Number of social meeting places				
Number of joint community activities				
Number of places to learn about environment				

Section 3: Environmental behavior and willingness to pay

13. Are you voluntarily undertaking any forest or water conservation activities on your farm?

- Yes
 No

14. a) How much would you be willing to pay to ensure clean water supply to ensure clean water throughout the year? (KES/per month)

- < 1,000
 1,000-5,000
 > 5,000
 none

b) If 'none', what is the reason for your answer?

- I can't afford to pay
 It is the responsibility of the government to conserve forest and water resources

- I'm not interested in forest and water conservation
- I don't trust the implementation and the success of the payment plan to conserve forest and water resources
- The changes in forest and water resources do not directly affect me thus no impact on my livelihood
- Other

15. Are you a member of any community-based initiative, such as CFA or WRUAs?

Yes [] No []

16. Did you receive any information/training on forest and water conservation?

Yes [] No []

References

- Abbott, B.W., Moatar, F., Gauthier, O., Fovet, O., Antoine, V., Ragueneau, O., 2018. Trends and seasonality of river nutrients in agricultural catchments: 18years of weekly citizen science in France. *Science of The Total Environment* 624, 845–858. <https://doi.org/10.1016/j.scitotenv.2017.12.176>
- Aceves-Bueno, E., Adeleye, A., Feraud, M., Huang, Y., Tao, M., Yang, Y., Anderson, S., 2017. The Accuracy of Citizen Science Data: A Quantitative Review. *The Bulletin of the Ecological Society of America* 98, 278–290. <https://doi.org/10.1002/bes2.1336>
- Aceves-Bueno, E., Adeleye, A.S., Bradley, D., Brandt, W.T., Callery, P., Feraud, M., Garner, K.L., Gentry, R., Huang, Y., McCullough, I., Pearlman, I., Sutherland, S.A., Wilkinson, W., Yang, Y., Zink, T., Anderson, S.E., Tague, C., 2015. Citizen Science as an Approach for Overcoming Insufficient Monitoring and Inadequate Stakeholder Buy-in in Adaptive Management: Criteria and Evidence. *Ecosystems* 18, 493–506. <https://doi.org/10.1007/s10021-015-9842-4>
- Acharya, R.P., Maraseni, T.N., Cockfield, G., 2019. Local Users and Other Stakeholders' Perceptions of the Identification and Prioritization of Ecosystem Services in Fragile Mountains: A Case Study of Chure Region of Nepal. *Forests* 10, 421. <https://doi.org/10.3390/f10050421>
- Akanga, D.O., Dahlin, K.M., Moore, N.J., 2022. Accelerating agricultural expansion in the greater Mau Forest Complex, Kenya. *Remote Sensing Applications: Society and Environment* 28, 100860. <https://doi.org/10.1016/j.rsase.2022.100860>
- Alba-Patino, D., Carabassa, V., Castro, H., Gutiérrez-Briceño, I., García-Llorente, M., Giagnocavo, C., Gómez-Tenorio, M., Cabello, J., Aznar-Sánchez, J.A., Castro, A.J., 2021. Social indicators of ecosystem restoration for enhancing human wellbeing. *Resources, Conservation and Recycling* 174, 105782.
- Alfonso, L., Lobbrecht, A., Price, R., 2010. Using mobile phones to validate models of extreme events, in: 9th International Conference on Hydroinformatics, Tianjin, China, pp. 1447–1454.
- Allamano, P., Croci, A., Laio, F., 2015. Toward the camera rain gauge. *Water Resources Research* 51, 1744–1757. <https://doi.org/10.1002/2014WR016298>
- Anderson, P., Davie, R.D., 2004. Use of Transparency Tubes for Rapid Assessment of Total Suspended Solids and Turbidity in Streams. *Lake and Reservoir Management* 20, 110–120. <https://doi.org/10.1080/07438140409354355>
- Apps, D., Elmore, K., Grams, H., 2014. Using mPING Observations to Verify Surface Precipitation Type Forecasts From Numerical Models, in: 26th Conference on Weather Analysis and Forecasting. pp. 2–6.
- Araújo Costa, R.C., Pereira, G.T., Tarlé Pissarra, T.C., Silva Siqueira, D., Sanches Fernandes, L.F., Vasconcelos, V., Fernandes, L.A., Pacheco, F.A.L., 2019. Land capability of multiple-landform watersheds with environmental land use conflicts. *Land Use Policy* 81, 689–704. <https://doi.org/10.1016/j.landusepol.2018.11.041>
- Assumpção, T.H., Popescu, I., Jonoski, A., Solomatine, D.P., 2018. Citizen observations contributing to flood modelling: opportunities and challenges. *Hydrology and Earth System Sciences* 22, 1473–1489. <https://doi.org/10.5194/hess-22-1473-2018>
- Atkinson, A.B., 1970. On the measurement of inequality. *Journal of economic theory* 2, 244–263.
- Babbie, E., Mouton, J., 2001. *The practice of social research: South African edition*. Cape Town: Oxford University Press Southern Africa.

- Baldyga, T.J., Miller, S.N., Driese, K.L., Gichaba, C.M., 2008. Assessing land cover change in Kenya's Mau Forest region using remotely sensed data. *African Journal of Ecology* 46, 46–54. <https://doi.org/10.1111/j.1365-2028.2007.00806.x>
- Báliková, K., Červená, T., De Meo, I., De Vreese, R., Deniz, T., El Mokaddem, A., Kayacan, B., Larabi, F., Lībiete, Z., Lyubenova, M., Pezdevšek Malovrh, Š., Potočki, K., Pelyukh, O., Rugani, B., Sarvasova, Z., Šálka, J., Stevanov, M., Stojnic, S., Jarský, V., Vuletić, D., Zahvoyska, L., Paletto, A., 2020. How Do Stakeholders Working on the Forest–Water Nexus Perceive Payments for Ecosystem Services? *Forests* 11, 12. <https://doi.org/10.3390/f11010012>
- Bardaji, R., Sánchez, A.-M., Simon, C., Wernand, M., Piera, J., Bardaji, R., Sánchez, A.-M., Simon, C., Wernand, M.R., Piera, J., 2016. Estimating the Underwater Diffuse Attenuation Coefficient with a Low-Cost Instrument: The KdUIINO DIY Buoy. *Sensors* 16, 373. <https://doi.org/10.3390/s16030373>
- Barrows, A.P.W., Christiansen, K.S., Bode, E.T., Hoellein, T.J., 2018. A watershed-scale, citizen science approach to quantifying microplastic concentration in a mixed land-use river. *Water Res.* 147, 382–392. <https://doi.org/10.1016/j.watres.2018.10.013>
- Bell, S., Cornford, D., Bastin, L., 2015. How good are citizen weather stations? Addressing a biased opinion. *Weather* 70, 75–84. <https://doi.org/10.1002/wea.2316>
- Bell, S., Cornford, D., Bastin, L., 2013. The state of automated amateur weather observations. *Weather* 68, 36–41. <https://doi.org/10.1002/wea.1980>
- Berihun, M.L., Tsunekawa, A., Haregeweyn, N., Meshesha, D.T., Adgo, E., Tsubo, M., Masunaga, T., Fenta, A.A., Sultan, D., Yibeltal, M., 2019. Exploring land use/land cover changes, drivers and their implications in contrasting agro-ecological environments of Ethiopia. *Land Use Policy* 87, 104052. <https://doi.org/10.1016/j.landusepol.2019.104052>
- Bhandari, P., Kc, M., Shrestha, S., Aryal, A., Shrestha, U.B., 2016. Assessments of ecosystem service indicators and stakeholder's willingness to pay for selected ecosystem services in the Chure region of Nepal. *Applied Geography* 69, 25–34. <https://doi.org/10.1016/j.apgeog.2016.02.003>
- Bird, T.J., Bates, A.E., Lefcheck, J.S., Hill, N.A., Thomson, R.J., Edgar, G.J., Stuart-Smith, R.D., Wotherspoon, S., Krkosek, M., Stuart-Smith, J.F., Pecl, G.T., Barrett, N., Frusher, S., 2014. Statistical solutions for error and bias in global citizen science datasets. *Biological Conservation* 173, 144–154. <https://doi.org/10.1016/j.biocon.2013.07.037>
- Bonney, R., Ballard, H.L., Jordan, R., McCallie, E., Phillips, T.B., Shirk, J.L., Wilderman, C.C., 2009a. Public Participation in Scientific Research: Defining the Field and Assessing Its Potential for Informal Science Education. (A CAISE Inquiry Group Report). Center for Advancement of Informal Science Education (CAISE), Washington, D.C.
- Bonney, R., Cooper, C.B., Dickinson, J., Kelling, S., Phillips, T.B., Rosenberg, K.V., Shirk, J.L., 2009b. Citizen Science: A Developing Tool for Expanding Science Knowledge and Scientific Literacy. *BioScience* 59, 977–984. <https://doi.org/10.1525/bio.2009.59.11.9>
- Börner, J., Baylis, K., Corbera, E., Ezzine-de-Blas, D., Honey-Rosés, J., Persson, U.M., Wunder, S., 2017. The Effectiveness of Payments for Environmental Services. *World Development* 96, 359–374. <https://doi.org/10.1016/j.worlddev.2017.03.020>
- Boursicaud, R.L., Pénard, L., Hauet, A., Thollet, F., Coz, J.L., 2016. Gauging extreme floods on YouTube: application of LSPIV to home movies for the post-event determination of stream discharges. *Hydrological Processes* 30, 90–105. <https://doi.org/10.1002/hyp.10532>
- Brandt, P., Hamunyela, E., Herold, M., De Bruin, S., Verbesselt, J., Rufino, M.C., 2018. Sustainable intensification of dairy production can reduce forest disturbance in Kenyan montane forests. *Agriculture, ecosystems & environment* 265, 307–319.

- Brauman, K.A., Daily, G.C., Duarte, T.K., Mooney, H.A., 2007. The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services. *Annual Review of Environment and Resources* 32, 67–98. <https://doi.org/10.1146/annurev.energy.32.031306.102758>
- Breuer, L., Hiery, N., Kraft, P., Bach, M., Aubert, A.H., Frede, H.-G., 2015. HydroCrowd: a citizen science snapshot to assess the spatial control of nitrogen solutes in surface waters. *Sci Rep* 5, 16503. <https://doi.org/10.1038/srep16503>
- Brouwer, S., Hessels, L.K., 2019. Increasing research impact with citizen science: The influence of recruitment strategies on sample diversity. *Public Understanding of Science* 28, 606–621.
- Brouwer, S., Paul W.J.J, van der W., Merijn, S., Maarten, C., Jos, F., 2018. Public Participation in Science: The Future and Value of Citizen Science in the Drinking Water Research. *Water* 10, 284. <https://doi.org/10.3390/w10030284>
- Brucks, J.T., 1971. Currents of the Caribbean and adjacent regions as deduced from drift-bottle studies. *Bulletin of Marine Science* 21, 455–465.
- Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems & Environment, Environmental Services and Land Use Change: Bridging the Gap between Policy and Research in Southeast Asia* 104, 185–228. <https://doi.org/10.1016/j.agee.2004.01.015>
- Burek, P., Langan, S., Cosgrove, W., Fischer, G., Kahil, T., Magnuszewski, P., Satoh, Y., Tramberend, S., Wada, Y., Wiberg, D., 2016. The water futures and solutions initiative of IIASA.
- Burgess, H.K., DeBey, L.B., Froehlich, H.E., Schmidt, N., Theobald, E.J., Ettinger, A.K., HilleRisLambers, J., Tewksbury, J., Parrish, J.K., 2017. The science of citizen science: Exploring barriers to use as a primary research tool. *Biological Conservation, The role of citizen science in biological conservation* 208, 113–120. <https://doi.org/10.1016/j.biocon.2016.05.014>
- Burnham, K.P., Anderson, D.R. (Eds.), 2004. *Model Selection and Multimodel Inference*. Springer, New York, NY. <https://doi.org/10.1007/b97636>
- Buytaert, W., Dewulf, A., De Bièvre, B., Clark, J., Hannah, D.M., 2016. Citizen science for water resources management: toward polycentric monitoring and governance? *Journal of Water Resources Planning and Management* 142. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000641](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000641)
- Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T.C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., 2014. Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science* 2, 26. <https://doi.org/10.3389/feart.2014.00026>
- Caldas, A., Pissarra, T., Costa, R., Neto, F., Zanata, M., Parahyba, R., Sanches Fernandes, L., Pacheco, F., 2018. Flood vulnerability, environmental land use conflicts, and conservation of soil and water: A study in the Batatais SP municipality, Brazil. *Water* 10, 1357. <https://doi.org/10.3390/w10101357>
- Calder, I.R., 2002. Forests and Hydrological Services: Reconciling public and science perceptions. *Land Use and Water Resources Research* 2. <https://doi.org/10.22004/ag.econ.47860>
- Camberlin, P., 2018. Climate of eastern Africa, in: *Oxford Research Encyclopedia of Climate Science*.
- Canfield Jr, D.E., Brown, C.D., Bachmann, R.W., Hoyer, M.V., 2002. Volunteer Lake Monitoring: Testing the Reliability of Data Collected by the Florida LAKEWATCH Program. *Lake and Reservoir Management* 18, 1–9. <https://doi.org/10.1080/07438140209353924>

- Carlson, T., Cohen, A., 2018. Linking community-based monitoring to water policy: Perceptions of citizen scientists, in: *Journal of Environmental Management*. pp. 168–177.
- Carvalho-Santos, C., Honrado, J.P., Hein, L., 2014. Hydrological services and the role of forests: Conceptualization and indicator-based analysis with an illustration at a regional scale. *Ecological Complexity* 20, 69–80. <https://doi.org/10.1016/j.ecocom.2014.09.001>
- Castilla, E.P., Cunha, D.G.F., Lee, F.W.F., Loiselle, S., Ho, K.C., Hall, C., 2015. Quantification of phytoplankton bloom dynamics by citizen scientists in urban and peri-urban environments. *Environ. Monit. Assess.* 187, 690. <https://doi.org/10.1007/s10661-015-4912-9>
- Castro, A.J., Vaughn, C.C., Julian, J.P., García-Llorente, M., 2016. Social Demand for Ecosystem Services and Implications for Watershed Management. *J Am Water Resour Assoc* 52, 209–221. <https://doi.org/10.1111/1752-1688.12379>
- Catlin-Groves, C.L., 2012. The citizen science landscape: from volunteers to citizen sensors and beyond. *International Journal of Zoology* 2012. <http://dx.doi.org/10.1155/2012/349630>
- Chacon-Hurtado, J.C., Alfonso, L., Solomatine, D.P., 2017. Rainfall and streamflow sensor network design: a review of applications, classification, and a proposed framework. *Hydrology and Earth System Sciences* 21, 3071–3091. <https://doi.org/10.5194/hess-21-3071-2017>
- Chandler, D.M., Lerner, D.N., 2015. A low cost method to detect polluted surface water outfalls and misconnected drainage. *Water and Environment Journal* 29, 202–206. <https://doi.org/10.1111/wej.12112>
- Chapman, L., Bell, S.J., 2018. High-Resolution Monitoring of Weather Impacts on Infrastructure Networks Using the Internet of Things. *Bull. Amer. Meteor. Soc.* 99, 1147–1154. <https://doi.org/10.1175/BAMS-D-17-0214.1>
- Church, S.P., Payne, L.B., Peel, S., Prokopy, L.S., 2019. Beyond water data: benefits to volunteers and to local water from a citizen science program. *Journal of Environmental Planning and Management* 62, 306–326. <https://doi.org/10.1080/09640568.2017.1415869>
- Cifelli, R., Doesken, N., Kennedy, P., Carey, L.D., Rutledge, S.A., Gimmestad, C., Depue, T., 2005. The community collaborative rain, hail, and snow network: Informal education for scientists and citizens. *Bulletin of the American Meteorological Society* 86, 1069–1078. <https://doi.org/DOI:10.1175/BAMS-86-8-I069>
- Cochran, W.G., 1977. *Cochran-Sampling Technique*, third edition. ed. John Wiley and Sons, New York.
- Community Science Institute, 2017. The Water Bulletin Winter 2017-Special Maps Issue [WWW Document]. URL <http://www.communityscience.org/outreach-and-education/newsletters-annual-reports/> (accessed 10.4.18).
- Compas, E.D., Wade, S., 2018. Testing the Waters: A Demonstration of a Novel Water Quality Mapping System for Citizen Science Groups. *Citizen Science: Theory and Practice* 3, 6. <https://doi.org/10.5334/cstp.124>
- Conrad, C.C., Hilchey, K.G., 2011. A review of citizen science and community-based environmental monitoring: issues and opportunities. *Environ Monit Assess* 176, 273–291. <https://doi.org/10.1007/s10661-010-1582-5>
- Cunha, D.G.F., Casali, S.P., de Falco, P.B., Thornhill, I., Loiselle, S.A., 2017. The contribution of volunteer-based monitoring data to the assessment of harmful phytoplankton blooms in Brazilian urban streams. *Science of The Total Environment* 584, 586–594. <https://doi.org/10.1016/j.scitotenv.2017.01.080>
- Curtis, V., 2018. *Online Citizen Science and the Widening of Academia. Distributed Engagement with Research and Knowledge Production*. Springer.

- Danielsen, F., Burgess, N.D., Balmford, A., 2005. Monitoring matters: examining the potential of locally-based approaches. *Biodiversity & Conservation* 14, 2507–2542.
- Danielsen, F., Burgess, N.D., Balmford, A., Donald, P.F., Funder, M., Jones, J.P.G., Alviola, P., Balete, D.S., Blomley, T., Brashares, J., Child, B., Enghoff, M., Fjeldså, J., Holt, S., Hübertz, H., Jensen, A.E., Jensen, P.M., Massao, J., Mendoza, M.M., Ngaga, Y., Poulsen, M.K., Rueda, R., Sam, M., Skielboe, T., Stuart-Hill, G., Topp-Jørgensen, E., Yonten, D., 2009. Local Participation in Natural Resource Monitoring: a Characterization of Approaches. *Conservation Biology* 23, 31–42. <https://doi.org/10.1111/j.1523-1739.2008.01063.x>
- Daume, S., Albert, M., von Gadow, K., 2014. Forest monitoring and social media – Complementary data sources for ecosystem surveillance? *Forest Ecology and Management, Forest Observational Studies: “Data Sources for Analysing Forest Structure and Dynamics”* 316, 9–20. <https://doi.org/10.1016/j.foreco.2013.09.004>
- Dave, R., Tompkins, E.L., Schreckenber, K., 2017. Forest ecosystem services derived by smallholder farmers in northwestern Madagascar: Storm hazard mitigation and participation in forest management. *Forest Policy and Economics, Forest, Food, and Livelihoods* 84, 72–82. <https://doi.org/10.1016/j.forpol.2016.09.002>
- de Groot, R.S., Alkemade, R., Braat, L., Hein, L., Willems, L., 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity* 7, 260–272. <https://doi.org/10.1016/j.ecocom.2009.10.006>
- Degrossi, L.C., de Albuquerque, J.P., Fava, M.C., Mendiondo, E.M., 2014. Flood Citizen Observatory: a crowdsourcing-based approach for flood risk management in Brazil., in: *Proceedings of 26th International Conference on Software Engineering and Knowledge Engineering (SEKE)*, Vancouver, Canada, pp. 570–575.
- Deutsch, W., Busby, A., Orprecio, J., Labis, J., Cequina, E., 2001. Community-based water quality monitoring: from data collection to sustainable management of water resources. Los Baños, Philippines: Philippine Council for Agriculture, Forestry and Natural Resources Research and Development.
- Deutsch, W.G., Busby, A.L., Orprecio, J.L., Bago-Labis, J.P., Cequina, E.Y., 2005. Community-based hydrological and water quality assessments in Mindanao, Philippines, in: *Forest, Water and People in the Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management*. Cambridge University Press, Cambridge, pp. 134–149.
- Deutsch, W.G., Ruiz-Córdova, S.S., 2015. Trends, challenges, and responses of a 20-year, volunteer water monitoring program in Alabama. *Ecology and Society* 20. <http://dx.doi.org/10.5751/ES-07578-200314>
- Devictor, V., Whittaker, R.J., Beltrame, C., 2010. Beyond scarcity: citizen science programmes as useful tools for conservation biogeography. *Diversity and Distributions* 16, 354–362. <https://doi.org/10.1111/j.1472-4642.2009.00615.x>
- Dickinson, J.L., Shirk, J., Bonter, D., Bonney, R., Crain, R.L., Martin, J., Phillips, T., Purcell, K., 2012. The current state of citizen science as a tool for ecological research and public engagement. *Frontiers in Ecology and the Environment* 10, 291–297. <https://doi.org/10.1890/110236>
- Domroese, M.C., Johnson, E.A., 2017. Why watch bees? Motivations of citizen science volunteers in the Great Pollinator Project. *Biological Conservation, The role of citizen science in biological conservation* 208, 40–47. <https://doi.org/10.1016/j.biocon.2016.08.020>

- Dorea, C.C., Simpson, M.R., 2011. Turbidity tubes for drinking water quality assessments. *Journal of Water, Sanitation and Hygiene for Development* 1, 233–241.
- Dorji, T., Brookes, J.D., Facelli, J.M., Sears, R.R., Norbu, T., Dorji, K., Chhetri, Y.R., Baral, H., 2019. Socio-Cultural Values of Ecosystem Services from Oak Forests in the Eastern Himalaya. *Sustainability* 11, 2250. <https://doi.org/10.3390/su11082250>
- Dorset Environmental Science Centre, 2015. Lake partner program report card 2015.
- Dutton, C.L., Subalusky, A.L., Anisfeld, S.C., Njoroge, L., Rosi, E.J., Post, D.M., 2018. The influence of a semi-arid sub-catchment on suspended sediments in the Mara River, Kenya. *PLOS ONE* 13, e0192828. <https://doi.org/10.1371/journal.pone.0192828>
- EarthEcho, 2015. EarthEcho Water Challenge [WWW Document]. URL <http://www.worldwatermonitoringday.org/> (accessed 5.1.19).
- Edwards, P.M., 2016. The value of long-term stream invertebrate data collected by citizen scientists. *PloS one* 11. <https://doi.org/10.1371/journal.pone.0156435>
- Edwards, P.M., Shaloum, G., Bedell, D., 2018. A unique role for citizen science in ecological restoration: a case study in streams. *Restoration ecology* 26, 29–35. <https://doi.org/10.1111/rec.12622>
- Eitzel, M., Cappadonna, J., Santos-Lang, C., Duerr, R., West, S.E., Virapongse, A., Kyba, C., Bowser, A., Cooper, C., Sforzi, A., Metcalfe, A., Harris, E., Thiel, M., Haklay, M., Ponciano, L., Roche, J., Ceccaroni, L., Shilling, F., Dorler, D., Heigl, F., Kiessling, T., Davis, B., Jiang, Q., 2017. Citizen Science Terminology Matters: Exploring Key Terms. *Citizen Science: Theory and Practice* 1–20.
- Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarsa, D., Gutierrez, V., Noordwijk, M. van, Creed, I.F., Pokorny, J., Gaveau, D., Spracklen, D.V., Tobella, A.B., Ilstedt, U., Teuling, A.J., Gebrehiwot, S.G., Sands, D.C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., Sullivan, C.A., 2017. Trees, forests and water: Cool insights for a hot world. *Global Environmental Change* 43, 51–61. <https://doi.org/10.1016/j.gloenvcha.2017.01.002>
- Elmore, K.L., Flamig, Z.L., Lakshmanan, V., Kaney, B.T., Farmer, V., Reeves, H.D., Rothfus, L.P., 2014. MPING: Crowd-Sourcing Weather Reports for Research. *Bull. Amer. Meteor. Soc.* 95, 1335–1342. <https://doi.org/10.1175/BAMS-D-13-00014.1>
- Elwood, S., Goodchild, M.F., Sui, D.Z., 2012. Researching Volunteered Geographic Information: Spatial Data, Geographic Research, and New Social Practice. *Annals of the Association of American Geographers* 102, 571–590. <https://doi.org/10.1080/00045608.2011.595657>
- Engel, S.R., Voshell, J.R., 2002. Volunteer Biological Monitoring: Can It Accurately Assess the Ecological Condition of Streams? *Am Entomol* 48, 164–177. <https://doi.org/10.1093/ae/48.3.164>
- English, P.B., Richardson, M.J., Garzón-Galvis, C., 2018. From Crowdsourcing to Extreme Citizen Science: Participatory Research for Environmental Health. *Annual Review of Public Health* 39, 335–350. <https://doi.org/10.1146/annurev-publhealth-040617-013702>
- Esteves, M., Legout, C., Navratil, O., Evrard, O., 2019. Medium term high frequency observation of discharges and suspended sediment in a Mediterranean mountainous catchment. *Journal of Hydrology* 568, 562–574. <https://doi.org/10.1016/j.jhydrol.2018.10.066>
- European Commission, 2013. Green paper on Citizen Science for Europe: Towards a society of empowered citizens and enhanced research.
- Everard, M., 2012. Safeguarding the provision of ecosystem services in catchment systems. *Integrated Environmental Assessment and Management* 9, 252–259. <https://doi.org/10.1002/ieam.1386>

- Falcone, J.A., Carlisle, D.M., Weber, L.C., 2010. Quantifying human disturbance in watersheds: Variable selection and performance of a GIS-based disturbance index for predicting the biological condition of perennial streams. *Ecological Indicators* 10, 264–273. <https://doi.org/10.1016/j.ecolind.2009.05.005>
- FAO, 2020. Global Forest Resources Assessment 2020 - Main report. FAO, Rome, Italy. <https://doi.org/10.4060/ca8753en>
- FAO, 2013. Forests and Water: International Momentum and Action, Illustrated edition. ed. FAO, Rome.
- Farnham, D.J., Gibson, R.A., Hsueh, D.Y., McGillis, W.R., Culligan, P.J., Zain, N., Buchanan, R., 2017. Citizen science-based water quality monitoring: Constructing a large database to characterize the impacts of combined sewer overflow in New York City. *Science of the Total Environment* 580, 168–177. <https://doi.org/10.1016/j.scitotenv.2016.11.116>
- Fava, C., Santana, G., Bressiani, D.A., Rosa, A., Horita, F.E.A., Souza, V.C.B., Mendiondo, E.M., 2014. Integration of information technology systems for flood forecasting with hybrid data sources, in: International Conference of Flood Management, Sao Paulo, Brazil.
- Flores-Díaz, A.C., Chacón, A.Q., Bistrain, R.P., Ramírez, M.I., de la Vía, A.P.L., 2018. Community-Based Monitoring in Response to Local Concerns: Creating Usable Knowledge for Water Management in Rural Land. *Water* 10, 542. <https://doi.org/10.3390/w10050542>
- Fohringer, J., Dransch, D., Kreibich, H., Schröter, K., 2015. Social media as an information source for rapid flood inundation mapping. *Nat. Hazards Earth Syst. Sci.* 15, 2725–2738. <https://doi.org/10.5194/nhess-15-2725-2015>
- Follett, R., Strezov, V., 2015. An analysis of citizen science based research: usage and publication patterns. *PloS one* 10, e0143687. <https://doi.org/10.1371/journal.pone.0143687>
- Fore, L.S., Paulsen, K., O’Laughlin, K., 2001. Assessing the performance of volunteers in monitoring streams. *Freshwater Biology* 46, 109–123. <https://doi.org/10.1111/j.1365-2427.2001.00640.x>
- Fritz, S., Fonte, C.C., See, L., 2017. The role of citizen science in earth observation. Multidisciplinary Digital Publishing Institute.
- Fritz, S., See, L., Carlson, T., Haklay, M. (Muki), Oliver, J.L., Fraisl, D., Mondardini, R., Brocklehurst, M., Shanley, L.A., Schade, S., Wehn, U., Abrate, T., Anstee, J., Arnold, S., Billot, M., Campbell, J., Espey, J., Gold, M., Hager, G., He, S., Hepburn, L., Hsu, A., Long, D., Masó, J., McCallum, I., Muniafu, M., Moorthy, I., Obersteiner, M., Parker, A.J., Weisspflug, M., West, S., 2019. Citizen science and the United Nations Sustainable Development Goals. *Nat Sustain* 2, 922–930. <https://doi.org/10.1038/s41893-019-0390-3>
- Fuccillo, K.K., Crimmins, T.M., Rivera, C.E. de, Elder, T.S., 2015. Assessing accuracy in citizen science-based plant phenology monitoring. *Int J Biometeorol* 59, 917–926. <https://doi.org/10.1007/s00484-014-0892-7>
- Gallart, F., Cid, N., Latron, J., Llorens, P., Bonada, N., Jeuffroy, J., Jiménez-Argudo, S.-M., Vega, R.-M., Solà, C., Soria, M., Bardina, M., Hernández-Casahuga, A.-J., Fidalgo, A., Estrela, T., Munné, A., Prat, N., 2017. TREHS: An open-access software tool for investigating and evaluating temporary river regimes as a first step for their ecological status assessment. *Science of The Total Environment* 607–608, 519–540. <https://doi.org/10.1016/j.scitotenv.2017.06.209>
- Gallo, T., Waite, D., 2011. Creating a Successful Citizen Science Model to Detect and Report Invasive Species. *BioScience* 61, 459–465. <https://doi.org/10.1525/bio.2011.61.6.8>

- Gao, P., Pasternack, G.B., Bali, K.M., Wallender, W.W., 2007. Suspended-sediment transport in an intensively cultivated watershed in southeastern California. *Catena* 69, 239–252. <https://doi.org/10.1016/j.catena.2006.06.002>
- García, C.E.R., Brown, S., 2009. Assessing water use and quality through youth participatory research in a rural Andean watershed. *Journal of Environmental Management* 90, 3040–3047. <https://doi.org/10.1016/j.jenvman.2009.04.014>
- García-Llorente, M., J. Castro, A., Quintas-Soriano, C., Oteros-Rozas, E., Iniesta-Arandia, I., González, J.A., García del Amo, D., Hernández-Arroyo, M., Casado-Arzuaga, I., Palomo, I., Gómez-Baggethun, E., Onaindia, M., Montes, C., Martín-López, B., 2020. Local Perceptions of Ecosystem Services Across Multiple Ecosystem Types in Spain. *Land* 9, 330. <https://doi.org/10.3390/land9090330>
- Gebrehiwot, S.G., Bewket, W., Bishop, K., 2014. Community perceptions of forest–water relationships in the Blue Nile Basin of Ethiopia. *GeoJournal* 79, 605–618. <https://doi.org/10.1007/s10708-013-9519-5>
- Goddijn-Murphy, L., Dailloux, D., White, M., Bowers, D., Goddijn-Murphy, L., Dailloux, D., White, M., Bowers, D., 2009. Fundamentals of in Situ Digital Camera Methodology for Water Quality Monitoring of Coast and Ocean. *Sensors* 9, 5825–5843. <https://doi.org/10.3390/s90705825>
- GoK, 2009. Rehabilitation of the Mau Forest Ecosystem.
- Golumbic, Y.N., Baram-Tsabari, A., Koichu, B., 2020. Engagement and communication features of scientifically successful citizen science projects. *Environmental Communication* 14, 465–480. <https://doi.org/10.1080/17524032.2019.1687101>
- Gomani, M.C., Dietrich, O., Lischeid, G., Mahoo, H., Mahay, F., Mbilinyi, B., Sarmett, J., 2010. Establishment of a hydrological monitoring network in a tropical African catchment: An integrated participatory approach. *Physics and Chemistry of the Earth, Parts A/B/C* 35, 648–656. <https://doi.org/10.1016/j.pce.2010.07.025>
- Good, S.P., Mallia, D.V., Lin, J.C., Bowen, G.J., 2014. Stable isotope analysis of precipitation samples obtained via crowdsourcing reveals the spatiotemporal evolution of Superstorm Sandy. *PloS one* 9, e91117. <https://doi.org/10.1371/journal.pone.0091117>
- Goodchild, M.F., 2007. Citizens as voluntary sensors: spatial data infrastructure in the world of Web 2.0. *IJSDIR* 2: 24–32.
- Göransson, G., Larson, M., Bendz, D., 2013. Variation in turbidity with precipitation and flow in a regulated river system – river Göta Älv, SW Sweden. *Hydrology and Earth System Sciences* 17, 2529–2542. <https://doi.org/10.5194/hess-17-2529-2013>
- Gräf, J., 2018. Potentials and limitations of community based water monitoring - A case study in the Sondu Catchment, Kenya (Master Thesis). Justus-Liebig University, Giessen, Germany.
- Gray, J., Glysson, G., Turcios, M., Schwarz, E., 2000. Comparability of suspended-sediment concentration and total suspended solids data. US Geological Survey Water-Resources Investigations Report 00-4191 20. <https://doi.org/10.3133/sir20055193>
- Grizzetti, B., Lanzanova, D., Liqueste, C., Reynaud, A., Cardoso, A.C., 2016. Assessing water ecosystem services for water resource management. *Environmental Science & Policy* 61, 194–203. <https://doi.org/10.1016/j.envsci.2016.04.008>
- Guo, B., Yu, Z., Zhou, X., Zhang, D., 2014. From participatory sensing to mobile crowd sensing, in: *Pervasive Computing and Communications Workshops (PERCOM Workshops)*, 2014 IEEE International Conference On. IEEE, pp. 593–598.
- Haines-Young, R., Potschin, M., 2010. The links between biodiversity, ecosystem services and human well-being. *Ecosystem Ecology: a new synthesis* 1, 110–139.

- Haklay, M., 2015. Citizen Science and Policy: A European Perspective (No. 4), Case Study. Woodrow Wilson International Center for Scholars, Washington, DC.
- Haklay, M., 2013. Citizen science and volunteered geographic information: Overview and typology of participation, in: *Crowdsourcing Geographic Knowledge*. Springer Science+Business Media Dordrecht 2013, pp. 105–122.
- Hannah, D.M., Demuth, S., Lanen, H.A.J. van, Looser, U., Prudhomme, C., Rees, G., Stahl, K., Tallaksen, L.M., 2011. Large-scale river flow archives: importance, current status and future needs. *Hydrological Processes* 25, 1191–1200. <https://doi.org/10.1002/hyp.7794>
- Hildebrandt, A., Lacorte, S., Barceló, D., 2006. Sampling of water, soil and sediment to trace organic pollutants at a river-basin scale. *Anal Bioanal Chem* 386, 1075–1088. <https://doi.org/10.1007/s00216-006-0486-2>
- Ho, S.Y.-F., Xu, S.J., Lee, F.W.-F., 2020. Citizen science: An alternative way for water monitoring in Hong Kong. *PLOS ONE* 15, e0238349. <https://doi.org/10.1371/journal.pone.0238349>
- Hobbs, S.J., White, P.C.L., 2012. Motivations and barriers in relation to community participation in biodiversity recording. *Journal for Nature Conservation* 20, 364–373. <https://doi.org/10.1016/j.jnc.2012.08.002>
- Hochachka, W.M., Fink, D., Hutchinson, R.A., Sheldon, D., Wong, W.-K., Kelling, S., 2012. Data-intensive science applied to broad-scale citizen science. *Trends in Ecology & Evolution, Ecological and evolutionary informatics* 27, 130–137. <https://doi.org/10.1016/j.tree.2011.11.006>
- Hohenthal, J., Owidi, E., Minoia, P., Pellikka, P., 2015. Local assessment of changes in water-related ecosystem services and their management: DPASER conceptual model and its application in Taita Hills, Kenya. *International Journal of Biodiversity Science, Ecosystem Services & Management* 11, 225–238. <https://doi.org/10.1080/21513732.2014.985256>
- Howe, J., 2006. The rise of crowdsourcing. *Wired magazine* 14, 1–4.
- Hoyer, M.V., Bigham, D.L., Bachmann, R.W., Canfield Jr, D.E., 2014. Florida LAKEWATCH: Citizen Scientists protecting Florida’s aquatic systems. *Florida Scientist* 184–197.
- Illingworth, S.M., Muller, C.L., Graves, R., Chapman, L., 2014. UK Citizen Rainfall Network: a pilot study. *Weather* 69, 203–207. <https://doi.org/10.1002/wea.2244>
- iMoMo, 2018. Non-traditional data collection [WWW Document]. Non-traditional data collection. URL <https://www.imomohub.com> (accessed 5.1.19).
- Iniesta-Arandia, I., García-Llorente, M., Aguilera, P.A., Montes, C., Martín-López, B., 2014. Socio-cultural valuation of ecosystem services: uncovering the links between values, drivers of change, and human well-being. *Ecological Economics* 108, 36–48. <https://doi.org/10.1016/j.ecolecon.2014.09.028>
- Irvine, K.N., O’Brien, L., Ravenscroft, N., Cooper, N., Everard, M., Fazey, I., Reed, M.S., Kenter, J.O., 2016. Ecosystem services and the idea of shared values. *Ecosystem Services, Shared, plural and cultural values* 21, 184–193. <https://doi.org/10.1016/j.ecoser.2016.07.001>
- Isaac, N.J.B., van Strien, A.J., August, T.A., de Zeeuw, M.P., Roy, D.B., 2014. Statistics for citizen science: extracting signals of change from noisy ecological data. *Methods in Ecology and Evolution* 5, 1052–1060. <https://doi.org/10.1111/2041-210X.12254>
- Jacobs, S.R., Breuer, L., Butterbach-Bahl, K., Pelster, D.E., Rufino, M.C., 2017. Land use affects total dissolved nitrogen and nitrate concentrations in tropical montane streams in Kenya. *Science of The Total Environment* 603–604, 519–532. <https://doi.org/10.1016/j.scitotenv.2017.06.100>
- Jacobs, S.R., Weeser, B., Guzha, A.C., Rufino, M.C., Butterbach-Bahl, K., Windhorst, D., Breuer, L., 2018. Using High-Resolution Data to Assess Land Use Impact on Nitrate Dynamics in

- East African Tropical Montane Catchments. *Water Resources Research* 54, 1812–1830. <https://doi.org/10.1002/2017WR021592>
- Jaetzold, R., Schmidt, H., 1983. *Farm Management Handbook of Kenya. Volume II: Natural Conditions and Farm Management Information, Part B Central Kenya (Rift Valley and Central Provinces)*. Ministry of agriculture, Kenya, in cooperation with the German Agricultural Team (GAT) of the GTZ, Nairobi.
- Jebiwott, A., Ogendi, G.M., Agbeja, B.O., Alo, A.A., Kibet, R., 2021. Mapping the trends of forest cover change and associated drivers in Mau Forest, Kenya. *Remote Sensing Applications: Society and Environment* 23, 100586. <https://doi.org/10.1016/j.rsase.2021.100586>
- Jiang, S., Babovic, V., Zheng, Y., Xiong, J., 2019. Advancing Opportunistic Sensing in Hydrology: A Novel Approach to Measuring Rainfall With Ordinary Surveillance Cameras. *Water Resources Research*. <https://doi.org/10.1029/2018WR024480>
- Johnson, M.F., Hannah, C., Acton, L., Popovici, R., Karanth, K.K., Weinthal, E., 2014. Network environmentalism: Citizen scientists as agents for environmental advocacy. *Global Environmental Change* 29, 235–245. <https://doi.org/10.1016/j.gloenvcha.2014.10.006>
- Johnson, R.K., Furse, M.T., Hering, D., Sandin, L., 2007. Ecological relationships between stream communities and spatial scale: implications for designing catchment-level monitoring programmes. *Freshwater Biology* 52, 939–958. <https://doi.org/10.1111/j.1365-2427.2006.01692.x>
- Jollymore, A., Haines, M.J., Satterfield, T., Johnson, M.S., 2017. Citizen science for water quality monitoring: Data implications of citizen perspectives. *Journal of environmental management* 200, 456–467. <https://doi.org/10.1016/j.jenvman.2017.05.083>
- Kampf, S., Strobl, B., Hammond, J., Anenberg, A., Etter, S., Martin, C., Puntenney-Desmond, K., Seibert, J., van Meerveld, I., 2018. Testing the waters: mobile apps for crowdsourced streamflow data. *Eos* 99. <https://doi.org/doi:10.1029/2018EO096355>
- Kapiyo, D., Abila, R., Kibwage, J., 2003. The status of fisheries and fishing activities of the Sondu-Miriu river.
- Kenya Water Towers Agency, 2020. *Kenya Water Towers Status Report for South West Mau*. Kenya Water Towers Agency.
- Ketema, H., Wei, W., Legesse, A., Zinabu, W., Temesgen, H., Yirsaw, E., 2021. Ecosystem service variation and its importance to the wellbeing of smallholder farmers in contrasting agro-ecological zones of East African Rift. *Food Energy Secur* 10. <https://doi.org/10.1002/fes3.310>
- Khamis, K., R. Sorensen, J.P., Bradley, C., M. Hannah, D., J. Lapworth, D., Stevens, R., 2015. In situ tryptophan-like fluorometers: assessing turbidity and temperature effects for freshwater applications. *Environmental Science: Processes & Impacts* 17, 740–752. <https://doi.org/10.1039/C5EM00030K>
- Khan, S.U., Khan, I., Zhao, M., Chien, H., Lu, Q., Ali, M.A.S., Khan, A.A., Fahad, S., 2019. Spatial heterogeneity of ecosystem services: a distance decay approach to quantify willingness to pay for improvements in Heihe River Basin ecosystems. *Environ Sci Pollut Res* 26, 25247–25261. <https://doi.org/10.1007/s11356-019-05691-0>
- Kidd, C., Becker, A., Huffman, G.J., Muller, C.L., Joe, P., Skofronick-Jackson, G., Kirschbaum, D.B., 2017. So, how much of the Earth’s surface is covered by rain gauges? *Bull Am Meteorol Soc* 98, 69–78. <https://doi.org/10.1175/BAMS-D-14-00283.1>
- Kim, S., Robson, C., Zimmerman, T., Pierce, J., Haber, E.M., 2011. Creek watch: pairing usefulness and usability for successful citizen science, in: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, pp. 2125–2134.

- Kinyanjui, M.J., 2011. NDVI-based vegetation monitoring in Mau forest complex, Kenya. *African Journal of Ecology* 49, 165–174. <https://doi.org/10.1111/j.1365-2028.2010.01251.x>
- Kinyanjui, M.J., 2009. The Effect of Human Encroachment on Forest Cover, Composition and Structure in the Western Blocks of the Mau Forest Complex. Unpublished Ph D thesis, Department of Natural Resources of Egerton University. <http://dx.doi.org/10.13140/2.1.2110.4964>.
- Kinyanjui, M.J., Kigomo, M.K., Mburu, D.M., Thuo, A.D.M., Mundia, C.N., 2020. Carbon Sequestration by the Above Ground Biomass Pool in the South West Mau Forest of Kenya, 1985-2015.
- Klang, J.L., Heiskary, S., 2000. Minnesota methods for analyzing, applying and disseminating volunteer lake monitoring data, in: NWQMC National Monitoring Conference 2000, April 25-27, 2000, Austin, Texas: Monitoring for the Millennium. The Council, p. 1.
- Klaver, D., Mote, T., Leathers, D., Henderson, G.R., Chan, W., Robinson, D.A., 2015. Creation and Validation of a Comprehensive 1° by 1° Daily Gridded North American Dataset for 1900–2009: Snowfall. *J. Atmos. Oceanic Technol.* 33, 857–871. <https://doi.org/10.1175/JTECH-D-15-0027.1>
- KNBS, 2019. 2019 Kenya Population and Housing Census Volume II: Distribution of Population by Administrative Units:
- Koch, J., Stisen, S., 2017. Citizen science: A new perspective to advance spatial pattern evaluation in hydrology. *PloS one* 12. <https://doi.org/10.1371/journal.pone.0178165>
- Kongo, V.M., Kosgei, J.R., Jewitt, G.P.W., Lorentz, S.A., 2010. Establishment of a catchment monitoring network through a participatory approach in a rural community in South Africa. *Hydrology and Earth System Sciences* 14, 2507–2525. <https://doi.org/10.5194/hess-14-2507-2010>
- Kosgei, J.R., Jewitt, G.P.W., Kongo, V.M., Lorentz, S.A., 2007. The influence of tillage on field scale water fluxes and maize yields in semi-arid environments: A case study of Potshini catchment, South Africa. *Phys Chem Earth* 32, 1117–1126. <https://doi.org/10.1016/j.pce.2007.07.027>
- Koskelo, A.I., Fisher, T.R., Utz, R.M., Jordan, T.E., 2012. A new precipitation-based method of baseflow separation and event identification for small watersheds (<50km²). *Journal of Hydrology* 450–451, 267–278. <https://doi.org/10.1016/j.jhydrol.2012.04.055>
- Kotovirta, V., Toivanen, T., Järvinen, M., Lindholm, M., Kallio, K., 2014. Participatory surface algal bloom monitoring in Finland in 2011–2013. *Environ Syst Res* 3, 24. <https://doi.org/10.1186/s40068-014-0024-8>
- Krell, N.T., Giroux, S.A., Guido, Z., Hannah, C., Lopus, S.E., Caylor, K.K., Evans, T.P., 2020. Smallholder farmers’ use of mobile phone services in central Kenya. *Climate and Development* 1–13. <https://doi.org/10.1080/17565529.2020.1748847>
- Krhoda, G.O., 1988. The impact of resource utilization on the hydrology of the Mau Hills forest in Kenya. *Mountain Research and Development* 193–200. <https://doi.org/10.2307/3673447>
- Kuhnle, R.A., Wren, D.G., 2005. Cross-stream variations in suspended sediment transport over dunes, implications for sampling, in: Proceedings of the Federal Interagency Sediment Monitoring Instrument and Analysis Research Workshop, Flagstaff, AZ: US Geological Survey Circular.
- Kullenberg, C., Kasperowski, D., 2016. What Is Citizen Science? – A Scientometric Meta-Analysis. *PLOS ONE* 11, e0147152. <https://doi.org/10.1371/journal.pone.0147152>
- Kundu, P.M., Olang, L.O., 2008. Automated extraction of morphologic and hydrologic properties for River Njoro catchment in Eastern Mau, Kenya. *AGSE* 2011 147.

- Langat, D., Cheboiwo, J., Okoth, S., Kiprop, J., Kisiwa, A., Guzha, A., Smith, N., DeMeo, T., Gatama, S., Kerkering, J., Doud, B., 2021. The value of forest ecosystem services of Mau complex, Cherangany and Mt. Elgon, Kenya.
- Latimore, J.A., Steen, P.J., 2014. Integrating freshwater science and local management through volunteer monitoring partnerships: the Michigan Clean Water Corps. *Freshwater Science* 33, 686–692. <https://doi.org/10.1086/676118>
- Le Coz, J., Patalano, A., Collins, D., Guillén, N.F., García, C.M., Smart, G.M., Bind, J., Chiaverini, A., Le Boursicaud, R., Dramais, G., 2016. Crowdsourced data for flood hydrology: Feedback from recent citizen science projects in Argentina, France and New Zealand. *Journal of Hydrology* 541, 766–777. <https://doi.org/10.1016/j.jhydrol.2016.07.036>
- Lee, V., 1994. Volunteer monitoring: a brief history. *The Volunteer Monitor* 6, 29–33.
- Leeuw, T., Boss, E., 2018. The HydroColor app: Above water measurements of remote sensing reflectance and turbidity using a smartphone camera. *Sensors* 18, 256. <https://doi.org/10.3390/s18010256>
- Lévesque, D., Cattaneo, A., Deschamps, G., Hudon, C., 2017. In the eye of the beholder: assessing the water quality of shoreline parks around the island of Montreal through citizen science. *Sci. Total Environ.* 579, 978–988. <https://doi.org/10.1016/j.scitotenv.2016.10.175>
- Li, Z., Wang, C., Emrich, C.T., Guo, D., 2018. A novel approach to leveraging social media for rapid flood mapping: a case study of the 2015 South Carolina floods. *Cartography and Geographic Information Science* 45, 97–110. <https://doi.org/10.1080/15230406.2016.1271356>
- Lima, F.P., Bastos, R.P., 2019. Perceiving the invisible: Formal education affects the perception of ecosystem services provided by native areas. *Ecosystem Services* 40, 101029. <https://doi.org/10.1016/j.ecoser.2019.101029>
- Lincoln, W.S., Thomason, R.F.L., Stackhouse, M., Schlotzhauer, D.S., 2017. Utilizing Crowd-Sourced Rainfall and Flood Impact Information to Improve the Analysis of the North Central Gulf Coast Flood Event of April 2014. *J. Oper. Meteorol.* 5, 26–41. <https://doi.org/10.15191/nwajom.2017.0503>
- Little, K.E., Hayashi, M., Liang, S., 2016. Community-Based Groundwater Monitoring Network Using a Citizen-Science Approach. *Groundwater* 54, 317–324. <https://doi.org/10.1111/gwat.12336>
- Liu, H.-Y., Kobernus, M., Broday, D., Bartonova, A., 2014. A conceptual approach to a citizens' observatory – supporting community-based environmental governance. *Environ Health* 13. <https://doi.org/10.1186/1476-069X-13-107>
- Loiselle, S.A., Cunha, D.G.F., Shupe, S., Valiente, E., Rocha, L., Heasley, E., Belmont, P.P., Baruch, A., 2016. Micro and Macroscale Drivers of Nutrient Concentrations in Urban Streams in South, Central and North America. *PLOS ONE* 11, e0162684. <https://doi.org/10.1371/journal.pone.0162684>
- Loperfido, J.V., Beyer, P., Just, C.L., Schnoor, J.L., 2010. Uses and biases of volunteer water quality data. *Environmental science & technology* 44, 7193–7199. <https://doi.org/10.1021/es100164c>
- Lowry, C.S., Fienen, M.N., 2013. CrowdHydrology: crowdsourcing hydrologic data and engaging citizen scientists. *GroundWater* 51, 151–156. <https://doi.org/10.1111/j.1745-6584.2012.00956.x>
- Lowry, C.S., Fienen, M.N., Hall, D.M., Stepenuck, K.F., 2019. Growing Pains of Crowdsourced Stream Stage Monitoring Using Mobile Phones: The Development of CrowdHydrology. *Front. Earth Sci.* 7. <https://doi.org/10.3389/feart.2019.00128>

- Luedemann, E.F., 1967. Preliminary results of drift-bottle releases and recoveries in the Western Tropical Atlantic. *Boletim do Instituto Oceanográfico* 16, 13–22. <http://dx.doi.org/10.1590/S0373-55241967000100002>
- Luz, E.F., Correa, F.R., González, D.L., Grey, F., Ramos, F.M., 2014. The forestwatchers: a citizen cyberscience project for deforestation monitoring in the tropics. *Human Computation* 1, 137–145. <https://doi.org/DOI: 10.15346/hc.v1i2.5>
- Maes, J., Liqueste, C., Teller, A., Erhard, M., Paracchini, M.L., Barredo, J.I., Grizzetti, B., Cardoso, A., Somma, F., Petersen, J.-E., Meiner, A., Gelabert, E.R., Zal, N., Kristensen, P., Bastrup-Birk, A., Biala, K., Piroddi, C., Egoh, B., Degeorges, P., Fiorina, C., Santos-Martín, F., Naruševičius, V., Verboven, J., Pereira, H.M., Bengtsson, J., Gocheva, K., Marta-Pedroso, C., Snäll, T., Estreguil, C., San-Miguel-Ayanz, J., Pérez-Soba, M., Grêt-Regamey, A., Lillebø, A.I., Malak, D.A., Condé, S., Moen, J., Czúcz, B., Drakou, E.G., Zulian, G., Lavalle, C., 2016. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. *Ecosystem Services* 17, 14–23. <https://doi.org/10.1016/j.ecoser.2015.10.023>
- Mahjoubi, I., Bossenbroek, L., Berger, E., Frör, O., 2022. Analyzing Stakeholder Perceptions of Water Ecosystem Services to Enhance Resilience in the Middle Drâa Valley, Southern Morocco. *Sustainability* 14, 4765. <https://doi.org/10.3390/su14084765>
- Malthus, T.J., Ohmsen, R., Woerd, H.J. van der, 2020. An Evaluation of Citizen Science Smartphone Apps for Inland Water Quality Assessment. *Remote Sensing* 12, 1578. <https://doi.org/10.3390/rs12101578>
- Mango, L.M., Melesse, A.M., McClain, M.E., Gann, D., Setegen, S.G., 2010. Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: results of a modeling study to support better resource management.
- Martín-López, B., Gómez-Baggethun, E., García-Llorente, M., Montes, C., 2014. Trade-offs across value-domains in ecosystem services assessment. *Ecological Indicators* 37, 220–228. <https://doi.org/10.1016/j.ecolind.2013.03.003>
- Martín-López, B., Iniesta-Arandia, I., García-Llorente, M., Palomo, I., Casado-Arzuaga, I., Amo, D.G.D., Gómez-Baggethun, E., Oteros-Rozas, E., Palacios-Agundez, I., Willaarts, B., González, J.A., Santos-Martín, F., Onaindia, M., López-Santiago, C., Montes, C., 2012. Uncovering Ecosystem Service Bundles through Social Preferences. *PLOS ONE* 7, e38970. <https://doi.org/10.1371/journal.pone.0038970>
- Masese, F.O., Raburu, P.O., Mwasi, B.N., Etiegni, L., 2012. Effects of Deforestation on Water Resources: Integrating Science and Community Perspectives in the Sondu-Miriu River Basin, Kenya, in: *New Advances and Contributions to Forestry Research*, InTech, Rijeka. pp. 1–18.
- Mati, B.M., Mutie, S., Gadain, H., Home, P., Mtaló, F., 2008. Impacts of land-use/cover changes on the hydrology of the transboundary Mara River, Kenya/Tanzania. *Lakes & Reservoirs: Research & Management* 13, 169–177. <https://doi.org/10.1111/j.1440-1770.2008.00367.x>
- Mazzoleni, M., Verlaan, M., Alfonso, L., Monego, M., Norbiato, D., Ferri, M., Solomatine, D.P., 2017. Can assimilation of crowdsourced data in hydrological modelling improve flood prediction? *Hydrology & Earth System Sciences* 21. <https://doi.org/doi:10.5194/hess-21-839-2017>
- Mbeche, R., Ateka, J., Herrmann, R., Grote, U., 2021. Understanding forest users' participation in participatory forest management (PFM): Insights from Mt. Elgon forest ecosystem, Kenya. *Forest Policy and Economics* 129, 102507. <https://doi.org/10.1016/j.forpol.2021.102507>
- McDougall, K., 2011. Using volunteered information to map the Queensland floods, in: *Proceedings of the 2011 Surveying and Spatial Sciences Conference: Innovation in Action:*

- Working Smarter (SSSC 2011). Presented at the 2011 Surveying and Spatial Sciences Conference: Innovation in Action: Working Smarter (SSSC 2011), Surveying and Spatial Sciences Institute, Adelaide, Australia, pp. 13–23.
- McGoff, E., Dunn, F., Cachazo, L.M., Williams, P., Biggs, J., Nicolet, P., Ewald, N.C., 2017. Finding clean water habitats in urban landscapes: professional researcher vs citizen science approaches. *Science of the Total Environment* 581, 105–116. <https://doi.org/10.1016/j.scitotenv.2016.11.215>
- McKinley, D.C., Briggs, R.D., Bartuska, A.M., 2012. When peer-reviewed publications are not enough! Delivering science for natural resource management. *Forest Policy and Economics* 21, 1–11. <https://doi.org/10.1016/j.forpol.2012.03.007>
- McKinley, D.C., Miller-Rushing, A.J., Ballard, H.L., Bonney, R., Brown, H., Cook-Patton, S.C., Evans, D.M., French, R.A., Parrish, J.K., Phillips, T.B., Ryan, S.F., Shanley, L.A., Shirk, J.L., Stepenuck, K.F., Weltzin, J.F., Wiggins, A., Boyle, O.D., Briggs, R.D., Chapin, S.F., Hewitt, D.A., Preuss, P.W., Soukup, M.A., 2017. Citizen science can improve conservation science, natural resource management, and environmental protection. *Biological Conservation*, The role of citizen science in biological conservation 208, 15–28. <https://doi.org/10.1016/j.biocon.2016.05.015>
- MEA, 2005. Millennium Ecosystem Assessment: Ecosystems and Human Well-being: Synthesis. Island Press, Washington DC.
- Meier, F., Fenner, D., Grassmann, T., Jänicke, B., Otto, M., Scherer, D., 2015. Challenges and benefits from crowd sourced atmospheric data for urban climate research using Berlin, Germany, as testbed, in: ICUC9–9th International Conference on Urban Climate Jointly with 12th Symposium on the Urban Environment.
- Mello, K. de, Valente, R.A., Randhir, T.O., dos Santos, A.C.A., Vettorazzi, C.A., 2018. Effects of land use and land cover on water quality of low-order streams in Southeastern Brazil: Watershed versus riparian zone. *CATENA* 167, 130–138. <https://doi.org/10.1016/j.catena.2018.04.027>
- Mengist, W., Soromessa, T., Feyisa, G.L., 2020. A global view of regulatory ecosystem services: existed knowledge, trends, and research gaps. *Ecological Processes* 9, 40. <https://doi.org/10.1186/s13717-020-00241-w>
- Michelsen, N., Dirks, H., Schulz, S., Kempe, S., Al-Saud, M., Schüth, C., 2016. YouTube as a crowd-generated water level archive. *Science of The Total Environment* 568, 189–195. <https://doi.org/10.1016/j.scitotenv.2016.05.211>
- Miguel-Chinchilla, L., Heasley, E., Loiselle, S., Thornhill, I., 2019. Local and landscape influences on turbidity in urban streams: a global approach using citizen scientists. *Freshwater Science* 38, 303–320. <https://doi.org/10.1086/703460>
- Mikusiński, G., Niedziałkowski, K., 2020. Perceived importance of ecosystem services in the Białowieża Forest for local communities – Does proximity matter? *Land Use Policy* 97, 104667. <https://doi.org/10.1016/j.landusepol.2020.104667>
- Milder, J., Moroge, M., Shames, S., 2015. Operationalizing climate-smart agricultural landscapes: the case of a tea-producing landscape in Kericho, Kenya. pp. 319–333.
- Miller, E.F., Doolittle, A.A., Cerutti, P.O., Naimark, J., Rufino, M.C., Ashton, M.S., Mwangi, E., 2021. Spatial distribution and perceived drivers of provisioning service values across an East African montane forest landscape. *Landscape and Urban Planning* 207, 103995. <https://doi.org/10.1016/j.landurbplan.2020.103995>
- Miller-Rushing, A., Primack, R., Bonney, R., 2012. The history of public participation in ecological research. *Frontiers in Ecology and the Environment* 10, 285–290. <https://doi.org/10.1890/110278>

- Mishra, A.K., Coulibaly, P., 2009. Developments in hydrometric network design: A review. *Reviews of Geophysics* 47. <https://doi.org/10.1029/2007RG000243>
- Mitchell, A., Brodie, J., Faithful, J., 2007. Testing Simple Sediment and Nutrient Methods for Landholder Use.
- MoALF, 2018. Climate Risk Profile for Kericho County. Kenya County Climate Risk Profile Series (Report).
- Moffett, E.R., Neale, M.W., 2015. Volunteer and professional macroinvertebrate monitoring provide concordant assessments of stream health. *New Zealand journal of marine and freshwater research* 49, 366–375. <https://doi.org/10.1080/00288330.2015.1018913>
- Moor, T.D., Rijpma, A., López, M.P., 2019. Dynamics of Engagement in Citizen Science: Results from the “Yes, I do!”-Project. *Citizen Science: Theory and Practice* 4, 38. <https://doi.org/10.5334/cstp.212>
- Moutouama, F.T., Biaou, S.S.H., Kyereh, B., Asante, W.A., Natta, A.K., 2019. Factors shaping local people’s perception of ecosystem services in the Atacora Chain of Mountains, a biodiversity hotspot in northern Benin. *Journal of Ethnobiology and Ethnomedicine* 15, 38. <https://doi.org/10.1186/s13002-019-0317-0>
- Muenich, R., Peel, S., Bowling, L., Haas, M., Turco, R., Frankenberger, J., Chaubey, I., 2016. The Wabash Sampling Blitz: A Study on the Effectiveness of Citizen Science. *Citizen Science: Theory and Practice*. 1. <https://doi.org/10.5334/cstp.1>
- Muhamad, D., Okubo, S., Harashina, K., Parikesit, Gunawan, B., Takeuchi, K., 2014. Living close to forests enhances people’s perception of ecosystem services in a forest–agricultural landscape of West Java, Indonesia. *Ecosystem Services* 8, 197–206. <https://doi.org/10.1016/j.ecoser.2014.04.003>
- Mwangi, K.K., Musili, A.M., Otieno, V.A., Endris, H.S., Sabiiti, G., Hassan, M.A., Tsehayu, A.T., Guleid, A., Atheru, Z., Guzha, A.C., 2020. Vulnerability of Kenya’s water towers to future climate change: an assessment to inform decision making in watershed management. *American Journal of Climate Change* 9, 317–353.
- Nadal-Romero, E., Peña-Angulo, D., Regüés, D., 2018. Rainfall, run-off, and sediment transport dynamics in a humid mountain badland area: Long-term results from a small catchment. *Hydrological Processes* 32, 1588–1606. <https://doi.org/10.1002/hyp.11495>
- Nardi, F., Cudenneq, C., Abrate, T., Allouch, C., Annis, A., Assumpção, T.H., Aubert, A.H., Berod, D., Braccini, A.M., Buytaert, W., Dasgupta, A., Hannah, D.M., Mazzoleni, M., Polo, M.J., Sæbø, Ø., Seibert, J., Tauro, F., Teichert, F., Teutonico, R., Uhlenbrook, S., Vargas, C.W., Grimaldi, S., 2020. Citizens AND HYdrology (CANDHY): conceptualizing a transdisciplinary framework for citizen science addressing hydrological challenges. *Hydrological Sciences Journal* 0, null. <https://doi.org/10.1080/02626667.2020.1849707>
- Nerbonne, J.F., Vondracek, B., 2003. Volunteer Macroinvertebrate Monitoring: Assessing Training Needs through Examining Error and Bias in Untrained Volunteers. *J N Am Benthol Soc* 22, 152–163. <https://doi.org/10.2307/1467984>
- Newman, G., Wiggins, A., Crall, A., Graham, E., Newman, S., Crowston, K., 2012. The future of citizen science: emerging technologies and shifting paradigms. *Frontiers in Ecology and the Environment* 10, 298–304. <https://doi.org/10.1890/110294>
- Nicholson, E., Ryan, J., Hodgkins, D., 2002. Community data-where does the value lie? Assessing confidence limits of community collected water quality data. *Water Science and Technology* 45, 193–200. <https://doi.org/10.2166/wst.2002.0395>
- Njue, N.K., Gräf, J., Weeser, B., Rufino, M.C., Breuer, L., Jacobs, S., 2021. Monitoring of suspended sediments in a tropical forested landscape with citizen science. *Frontiers in Water* 3, 56. <https://doi.org/10.3389/frwa.2021.656770>

- Njue, N.K., Koech, E., Hitimana, J., Sirmah, P., 2016. Influence of Land Use Activities on Riparian Vegetation, Soil and Water Quality: An Indicator of Biodiversity Loss, South West Mau Forest, Kenya. *Open Journal of Forestry* 06, 373–385. <https://doi.org/10.4236/ojf.2016.65030>
- Njue, N.K., Kroese, J.S., Gräf, J., Jacobs, S.R., Weeser, B., Breuer, L., Rufino, M.C., 2019. Citizen science in hydrological monitoring and ecosystem services management: State of the art and future prospects. *Science of the Total Environment* 693, 133531. <https://doi.org/10.1016/j.scitotenv.2019.07.337>
- NTZDC, 2016. Nyayo Tea Zones Development Corporation (NTZDC), Mau and Embobut tea buffer belt.
- Nyingi, D.W., Gichuki, N., Ogada, M.O., 2013. Freshwater Ecology of Kenyan Highlands and Lowlands. *Developments in Earth Surface Processes, Kenya: A Natural Outlook* 16, 199–218. <https://doi.org/10.1016/B978-0-444-59559-1.00016-5>
- Obati, G.O., 2007. An Investigation of Forest Ecosystem Health in Relation to Anthropogenic Disturbance in the South-western Mau Forest Reserve, Kenya (PhD Thesis). Universität Bremen.
- Ochoa-Tocachi, B.F., Buytaert, W., Antiporta, J., Acosta, L., Bardales, J.D., Célleri, R., Crespo, P., Fuentes, P., Gil-Ríos, J., Gualpa, M., Llerena, C., Olaya, D., Pardo, P., Rojas, G., Villacís, M., Villazón, M., Viñas, P., Bièvre, B.D., 2018. High-resolution hydrometeorological data from a network of headwater catchments in the tropical Andes. *Scientific Data* 5, 180080. <https://doi.org/10.1038/sdata.2018.80>
- Olang, L.O., Fürst, J., 2011. Effects of land cover change on flood peak discharges and runoff volumes: model estimates for the Nyando River Basin, Kenya. *Hydrological Processes* 25, 80–89. <https://doi.org/10.1002/hyp.7821>
- Olang, L.O., Kundu, P.M., 2011. Land degradation of the Mau forest complex in Eastern Africa: a review for management and restoration planning. *Environmental Monitoring* 245–262.
- Ombogoh, D.B., Mwangi, E., Larson, A.M., 2022. Community participation in forest and water management planning in Kenya: challenges and opportunities. *Forests, Trees and Livelihoods* 1–19.
- Otuoma, J., Langat, D., Maina, Johnson, Maina, G., Maina, James, Mwanje, P., 2012. Effects of watershed degradation on hydrological functions in the Sondu river catchment.
- Ou, Y., Wang, X., Wang, L., Rousseau, A.N., 2016. Landscape influences on water quality in riparian buffer zone of drinking water source area, Northern China. *Environmental Earth Sciences* 75, 114. <https://doi.org/10.1007/s12665-015-4884-7>
- Ouellet-Proulx, S., St-Hilaire, A., Courtenay, S.C., Haralampides, K.A., 2016. Estimation of suspended sediment concentration in the Saint John River using rating curves and a machine learning approach. *Hydrological Sciences Journal* 1–14. <https://doi.org/10.1080/02626667.2015.1051982>
- Ouma, K.O., Mungai, N.W., Vuai, S. a. H., Ibembe, J.D., 2011. Spatial-temporal variation of nitrogen, phosphorus and sediments in surface runoff and adjacent river system in Sondu-Miriu basin, Kenya., in: *Natural Resources Management and Land Use. Proceedings of the Cluster Workshop, Nairobi, Kenya, 30th November - 2nd December 2011.* pp. 147–157.
- Owuor, S.O., Butterbach-Bahl, K., Guzha, A.C., Jacobs, S., Merbold, L., Rufino, M.C., Pelster, D.E., Díaz-Pinés, E., Breuer, L., 2018. Conversion of natural forest results in a significant degradation of soil hydraulic properties in the highlands of Kenya. *Soil and Tillage Research* 176, 36–44. <https://doi.org/10.1016/j.still.2017.10.003>

- Pacheco, F.A.L., Sanches Fernandes, L.F., 2016. Environmental land use conflicts in catchments: A major cause of amplified nitrate in river water. *Science of The Total Environment* 548–549, 173–188. <https://doi.org/10.1016/j.scitotenv.2015.12.155>
- Pacheco, F.A.L., Varandas, S.G.P., Sanches Fernandes, L.F., Valle Junior, R.F., 2014. Soil losses in rural watersheds with environmental land use conflicts. *Science of The Total Environment* 485–486, 110–120. <https://doi.org/10.1016/j.scitotenv.2014.03.069>
- Paletto, A., Bálíková, K., De Meo, I., 2021. Opinions towards the water-related Payments for Ecosystem Services (PES) schemes: The stakeholders' point of view. *Water and Environment Journal* 35, 1051–1062. <https://doi.org/10.1111/wej.12697>
- Palmer Fry, B., 2011. Community forest monitoring in REDD+: the 'M' in MRV? *Environmental Science & Policy, Governing and Implementing REDD+* 14, 181–187. <https://doi.org/10.1016/j.envsci.2010.12.004>
- Pandeya, B., Buytaert, W., Potter, C., 2021. Designing citizen science for water and ecosystem services management in data-poor regions: Challenges and opportunities. *Current Research in Environmental Sustainability* 3, 100059. <https://doi.org/10.1016/j.crsust.2021.100059>
- Paul, J.D., Buytaert, W., Allen, S., Ballesteros-Cánovas, J.A., Bhusal, J., Cieslik, K., Clark, J., Dugar, S., Hannah, D.M., Stoffel, M., 2018. Citizen science for hydrological risk reduction and resilience building. *Wiley Interdisciplinary Reviews: Water* 5, e1262. <https://doi.org/10.1002/wat2.1262>
- Pfeffer, M.J., Wagenet, L.P., 2007. Volunteer environmental monitoring, knowledge creation and citizen–scientist interaction, in: *The SAGE Handbook of Environment and Society*. Sage, London. pp. 235–250.
- Pham, N.Q., Tran, H.N., Thi, K.V.L., Nong, A.B., Rutten, M.M., 2015. Ecosystem service monitoring using remote sensing, citizen science and other ground observations and current practices in Vietnam, in: *The 4th International Symposium and Exhibition of the Vietnam Cooperation Initiative (VACI) "Water Security in a Changing Area"*, Hanoi, Vietnam, 19–20 October 2015.
- Ponciano, L., Brasileiro, F., Simpson, R., Smith, A., 2014. Volunteers' Engagement in Human Computation for Astronomy Projects. *Computing in Science Engineering* 16, 52–59. <https://doi.org/10.1109/MCSE.2014.4>
- Poudel, D.D., 2016. Surface water quality monitoring of an agricultural watershed for nonpoint source pollution control. *Journal of Soil and Water Conservation* 71, 310–326. <https://doi.org/10.2489/jswc.71.4.310>
- Raddick, M.J., Bracey, G., Gay, P.L., Lintott, C.J., Murray, P., Schawinski, K., Szalay, A.S., Vandenberg, J., 2009. Galaxy zoo: Exploring the motivations of citizen science volunteers. *arXiv preprint arXiv:0909.2925*. <https://doi.org/10.3847/AER2009036>
- Rasin, Z., Abdullah, M.R., 2009. Water quality monitoring system using zigbee based wireless sensor network. *International Journal of Engineering & Technology* 9, 24–28.
- Reges, H.W., Doesken, N., Turner, J., Newman, N., Bergantino, A., Schwalbe, Z., 2016. CoCoRaHS: The Evolution and Accomplishments of a Volunteer Rain Gauge Network. *Bull. Amer. Meteor. Soc.* 97, 1831–1846. <https://doi.org/10.1175/BAMS-D-14-00213.1>
- Reutebuch, E., Deutsch, W., Ruiz-Córdova, S., 2008. Community-Based Water Quality Monitoring—Data Credibility and Applications. Auburn University Alabama (ed) *Alabama Water Watch*. Alabama 24.
- Richards, N., Syallow, D., 2018. Water Resources Users Associations in the Mara Basin, Kenya: Pitfalls and Opportunities for Community Based Natural Resources Management. *Front. Environ. Sci.* 6. <https://doi.org/10.3389/fenvs.2018.00138>

- Rodríguez-Blanco, M.L., Taboada-Castro, M.M., Taboada-Castro, M.T., 2018. Long-Term Suspended Sediment Concentrations and Loads from a Relatively Undisturbed Agroforested Catchment in the Northwest of the Iberian Peninsula. *Water* 10, 1302. <https://doi.org/10.3390/w10101302>
- Ross, N., Potts, M., 2011. ABC's crowdsourced flood-mapping initiative [WWW Document]. ABC: Technology+ Games. URL <http://www.abc.net.au/technology/articles/2011/01/13/3112261.htm>
- Rotman, D., Preece, J., Hammock, J., Procita, K., Hansen, D., Parr, C., Lewis, D., Jacobs, D., 2012. Dynamic changes in motivation in collaborative citizen-science projects, in: *Proceedings of the ACM 2012 Conference on Computer Supported Cooperative Work*. pp. 217–226.
- Royem, A.A., Mui, C.K., Fuka, D.R., Walter, M.T., 2012. Proposing a low-tech, affordable, accurate stream stage monitoring system. *Transactions of the ASABE* 55, 2237–2242. <https://doi.org/doi:10.13031/2013.42512>
- Rügner, H., Schwientek, M., Beckingham, B., Kuch, B., Grathwohl, P., 2013. Turbidity as a proxy for total suspended solids (TSS) and particle facilitated pollutant transport in catchments. *Environ Earth Sci* 69, 373–380. <https://doi.org/10.1007/s12665-013-2307-1>
- Safford, H., Peters, C.A., 2018. Citizen Science for Dissolved Oxygen Monitoring: Case Studies from Georgia and Rhode Island. *Environ. Eng. Sci.* 35, 362–372. <https://doi.org/10.1089/ees.2017.0218>
- Sakai, N., Mohamad, Z.F., Nasaruddin, A., Abd Kadir, S.N., Mohd Salleh, M.S.A., Sulaiman, A.H., 2018. Eco-Heart Index as a tool for community-based water quality monitoring and assessment. *Ecological Indicators* 91, 38–46. <https://doi.org/10.1016/j.ecolind.2018.03.079>
- Sauermann, H., Franzoni, C., 2015. Crowd science user contribution patterns and their implications. *Proceedings of the national academy of sciences* 112, 679–684. <https://doi.org/10.1073/pnas.1408907112>
- Scholte, S.S.K., van Teeffelen, A.J.A., Verburg, P.H., 2015. Integrating socio-cultural perspectives into ecosystem service valuation: A review of concepts and methods. *Ecological Economics* 114, 67–78. <https://doi.org/10.1016/j.ecolecon.2015.03.007>
- Schröter, M., Kraemer, R., Mantel, M., Kabisch, N., Hecker, S., Richter, A., Neumeier, V., Bonn, A., 2017. Citizen science for assessing ecosystem services: Status, challenges and opportunities. *Ecosystem Services* 28, 80–94. <https://doi.org/10.1016/j.ecoser.2017.09.017>
- Scott, A.B., Frost, P.C., 2017. Monitoring water quality in Toronto's urban stormwater ponds: Assessing participation rates and data quality of water sampling by citizen scientists in the FreshWater Watch. *Science of the Total Environment* 592, 738–744. <https://doi.org/10.1016/j.scitotenv.2017.01.201>
- Seibert, J., Strobl, B., Etter, S., Hummer, P., van Meerveld, H.J., 2019. Virtual staff gauges for crowd-based stream level observations. *Frontiers in Earth Science* 7, 70. <https://doi.org/doi:10.3389/feart.2019.00070>
- Serret, H., Deguines, N., Jang, Y., Lois, G., Julliard, R., 2019. Data Quality and Participant Engagement in Citizen Science: Comparing Two Approaches for Monitoring Pollinators in France and South Korea. *Citizen Science: Theory and Practice* 4, 22. <https://doi.org/10.5334/cstp.200>
- Shahady, T., Boniface, H., 2018. Water quality management through community engagement in Costa Rica. *J Environ Stud Sci* 8, 488–502. <https://doi.org/10.1007/s13412-018-0504-7>
- Shirk, J., Ballard, H., Wilderman, C., Phillips, T., Wiggins, A., Jordan, R., McCallie, E., Minarchek, M., Lewenstein, B., Krasny, M., Bonney, Rick, 2012. Public participation in scientific research: a framework for deliberate design. *Ecology and Society* 17. <http://dx.doi.org/10.5751/ES-04705-170229>

- Shoyama, K., Yamagata, Y., 2016. Local perception of ecosystem service bundles in the Kushiro watershed, Northern Japan – Application of a public participation GIS tool. *Ecosystem Services* 22, 139–149. <https://doi.org/10.1016/j.ecoser.2016.10.009>
- Shupe, S.M., 2017. High resolution stream water quality assessment in the Vancouver, British Columbia region: a citizen science study. *Science of The Total Environment* 603, 745–759. <https://doi.org/10.1016/j.scitotenv.2017.02.195>
- Silvertown, J., 2009. A new dawn for citizen science. *Trends in ecology & evolution* 24, 467–471.
- Silvestro, F., Gabellani, S., Giannoni, F., Parodi, A., Rebora, N., Rudari, R., Siccardi, F., 2012. A hydrological analysis of the 4 November 2011 event in Genoa. *Natural Hazards and Earth System Sciences* 12, 2743–2752.
- Simpson, M.J., Hirsch, A., Grempler, K., Lupo, A., 2017. The importance of choosing precipitation datasets. *Hydrological Processes* 31, 4600–4612. <https://doi.org/10.1002/hyp.11381>
- Smith, B.K., Smith, J.A., Baeck, M.L., Miller, A.J., 2015. Exploring storage and runoff generation processes for urban flooding through a physically based watershed model. *Water Resources Research* 51, 1552–1569. <https://doi.org/10.1002/2014WR016085>
- Smith, L., Liang, Q., James, P., Lin, W., 2017. Assessing the utility of social media as a data source for flood risk management using a real-time modelling framework. *Journal of Flood Risk Management* 10, 370–380. <https://doi.org/10.1111/jfr3.12154>
- Smith, P., House, J.I., Bustamante, M., Sobocká, J., Harper, R., Pan, G., West, P.C., Clark, J.M., Adhya, T., Rumpel, C., Paustian, K., Kuikman, P., Cotrufo, M.F., Elliott, J.A., McDowell, R., Griffiths, R.I., Asakawa, S., Bondeau, A., Jain, A.K., Meersmans, J., Pugh, T.A.M., 2016. Global change pressures on soils from land use and management. *Global Change Biology* 22, 1008–1028. <https://doi.org/10.1111/gcb.13068>
- Snik, F., Rietjens, J.H., Apituley, A., Volten, H., Mijling, B., Di Noia, A., Heikamp, S., Heinsbroek, R.C., Hasekamp, O.P., Smit, J.M., 2014. Mapping atmospheric aerosols with a citizen science network of smartphone spectropolarimeters. *Geophysical Research Letters* 41, 7351–7358. <https://doi.org/10.1002/2014GL061462>
- Sombroek, W.G., Braun, H.M.H., Van der Pouw, B.J.A., 1982. Exploratory soil map and agro-climatic zone map of Kenya, 1980. Scale 1: 1,000,000. Kenya Soil Survey.
- Springgay, E., Casallas Ramirez, S., Janzen, S., Vannozzi Brito, V., 2019. The forest–water nexus: An international perspective. *Forests* 10, 915.
- Springgay, E., McNulty, S., Patriarca, C., Casalles-Ramirez, S., Dannunzio, R., Eva, H., Ashutosh, S., Steel, E., Caldwell, B., Shono, K., Pess, G., Funge-Smith, S., Richards, W., Ferraz, S., Neary, D., Long, J., Verbist, B., Leonard, J., Sun, G., Del Campo, A., 2021. A guide to forest-water management. <https://doi.org/10.4060/cb6473en>
- Srivastava, S., Vaddadi, S., Sadistap, S., 2018. Smartphone-based System for water quality analysis. *Appl Water Sci* 8, 130. <https://doi.org/10.1007/s13201-018-0780-0>
- Starkey, E., Parkin, G., Birkinshaw, S., Large, A., Quinn, P., Gibson, C., 2017. Demonstrating the value of community-based (‘citizen science’) observations for catchment modelling and characterisation. *Journal of Hydrology* 548, 801–817. <https://doi.org/10.1016/j.jhydrol.2017.03.019>
- Stenfert Kroese, J., Batista, P.V.G., Jacobs, S.R., Breuer, L., Quinton, J.N., Rufino, M.C., 2020a. Agricultural land is the main source of stream sediments after conversion of an African montane forest. *Scientific Reports* 10, 14827. <https://doi.org/10.1038/s41598-020-71924-9>
- Stenfert Kroese, J., Jacobs, S.R., Tych, W., Breuer, L., Quinton, J.N., Rufino, M.C., 2020b. Tropical Montane Forest Conversion Is a Critical Driver for Sediment Supply in East African Catchments. *Water Resources Research* 56, e2020WR027495. <https://doi.org/10.1029/2020WR027495>

- Stenfert Kroese, J., Quinton, J.N., Jacobs, S.R., Breuer, L., Rufino, M.C., 2021. Particulate macronutrient exports from tropical African montane catchments point to the impoverishment of agricultural soils. *Soil* 7, 53–70. <https://doi.org/10.5194/soil-7-53-2021>
- Stepenuck, K.F., Wolfson, L.G., Liukkonen, B.W., Iles, J.M., Grant, T.S., 2011. Volunteer monitoring of *E. coli* in streams of the upper Midwestern United States: a comparison of methods. *Environ. Monit. Assess.* 174, 625–633. <https://doi.org/10.1007/s10661-010-1483-7>
- Stephens, W., Othieno, C.O., Carr, M.K.V., 1992. Climate and weather variability at the Tea Research Foundation of Kenya. *Agricultural and forest meteorology* 61, 219–235. [https://doi.org/10.1016/0168-1923\(92\)90051-5](https://doi.org/10.1016/0168-1923(92)90051-5)
- Storey, R.G., Wright-Stow, A., 2017. Community-based monitoring of New Zealand stream macroinvertebrates: agreement between volunteer and professional assessments and performance of volunteer indices. *New Zeal J Mar Fresh* 51, 60–77. <https://doi.org/10.1080/00288330.2016.1266674>
- Storey, R.G., Wright-Stow, A., Kin, E., Davies-Colley, R.J., Stott, R., 2016. Volunteer stream monitoring: Do the data quality and monitoring experience support increased community involvement in freshwater decision making? *Ecology and Society* 21. <https://doi.org/10.5751/ES-08934-210432>
- Stosch, K.C., Quilliam, R.S., Bunnefeld, N., Oliver, D.M., 2017. Managing Multiple Catchment Demands for Sustainable Water Use and Ecosystem Service Provision. *Water* 9, 677. <https://doi.org/10.3390/w9090677>
- Swart, R., 2016. Monitoring 40 years of land use change in the Mau forest complex, Kenya: a land use change driver analysis (BSc Thesis). Wageningen University.
- Talavera, J.M., Tobón, L.E., Gómez, J.A., Culman, M.A., Aranda, J.M., Parra, D.T., Quiroz, L.A., Hoyos, A., Garreta, L.E., 2017. Review of IoT applications in agro-industrial and environmental fields. *Computers and Electronics in Agriculture* 142, 283–297. <https://doi.org/10.1016/j.compag.2017.09.015>
- Tanaka, M.O., de Souza, A.L.T., Moschini, L.E., de Oliveira, A.K., 2016. Influence of watershed land use and riparian characteristics on biological indicators of stream water quality in southeastern Brazil. *Agriculture, Ecosystems & Environment* 216, 333–339. <https://doi.org/10.1016/j.agee.2015.10.016>
- Tauro, F., Piscopia, R., Grimaldi, S., 2017. Streamflow Observations From Cameras: Large-Scale Particle Image Velocimetry or Particle Tracking Velocimetry? *Water Resources Research* 53, 10374–10394. <https://doi.org/10.1002/2017WR020848>
- Tetzlaff, D., Carey, S.K., McNamara, J.P., Laudon, H., Soulsby, C., 2017. The essential value of long-term experimental data for hydrology and water management. *Water Resources Research* 53, 2598–2604. <https://doi.org/10.1002/2017WR020838>
- Thatoe Nwe Win, T., Bogaard, T., van de Giesen, N., 2019. A Low-Cost Water Quality Monitoring System for the Ayeyarwady River in Myanmar Using a Participatory Approach. *Water* 11, 1984. <https://doi.org/10.3390/w11101984>
- Theobald, E.J., Ettinger, A.K., Burgess, H.K., DeBey, L.B., Schmidt, N.R., Froehlich, H.E., Wagner, C., HilleRisLambers, J., Tewksbury, J., Harsch, M.A., others, 2015. Global change and local solutions: Tapping the unrealized potential of citizen science for biodiversity research. *Biological Conservation* 181, 236–244. <https://doi.org/10.1016/j.biocon.2014.10.021>
- Thornhill, I., Chautard, A., Loiselle, S., 2018. Monitoring Biological and Chemical Trends in Temperate Still Waters Using Citizen Science. *Water* 10, 839. <https://doi.org/10.3390/w10070839>

- Thornhill, I., Ho, J.G., Zhang, Y., Li, H., Ho, K.C., Miguel-Chinchilla, L., Loiselle, S.A., 2017. Prioritising local action for water quality improvement using citizen science; a study across three major metropolitan areas of China. *Science of The Total Environment* 584–585, 1268–1281. <https://doi.org/10.1016/j.scitotenv.2017.01.200>
- Thornhill, I., Loiselle, S., Lind, K., Ophof, D., 2016. The Citizen Science Opportunity for Researchers and Agencies. *BioScience* 66, 720–721. <https://doi.org/10.1093/biosci/biw089>
- Toivanen, T., Koponen, S., Kotovirta, V., Molinier, M., Chengyuan, P., 2013. Water quality analysis using an inexpensive device and a mobile phone. *Environ Syst Res* 2, 9. <https://doi.org/10.1186/2193-2697-2-9>
- Truong, N.C.Q., Nguyen, H.Q., Kondoh, A., 2018. Land Use and Land Cover Changes and Their Effect on the Flow Regime in the Upstream Dong Nai River Basin, Vietnam. *Water* 10, 1206. <https://doi.org/10.3390/w10091206>
- Tu, J., 2013. Spatial variations in the relationships between land use and water quality across an urbanization gradient in the watersheds of northern Georgia, USA. *Environmental management* 51, 1–17. <https://doi.org/10.1007/s00267-011-9738-9>
- Turkelboom, F., Raquez, P., Dufrière, M., Raes, L., Simoens, I., Jacobs, S., Stevens, M., De Vreese, R., Panis, J.A.E., Hermy, M., Thoonen, M., Liekens, I., Fontaine, C., Dendoncker, N., Biest, K. van der, Casaer, J., Heyrman, H., Meiresonne, L., Keune, H., 2013. Chapter 18 - CICES Going Local: Ecosystem Services Classification Adapted for a Highly Populated Country, in: Jacobs, S., Dendoncker, N., Keune, H. (Eds.), *Ecosystem Services*. Elsevier, Boston, pp. 223–247. <https://doi.org/10.1016/B978-0-12-419964-4.00018-4>
- Turner, D.S., Richter, H.E., 2011. Wet/dry mapping: using citizen scientists to monitor the extent of perennial surface flow in dryland regions. *Environmental management* 47, 497–505. <https://doi.org/10.1007/s00267-010-9607-y>
- UNEP, 2008. UNEP, Kenya Wildlife Service, Kenya Forest Working Group, Ewaso Ngiro South Development Authority, 2008. *Mau Complex Under Siege. Values and Threats*.
- United Nations, 2015. *Transforming our World: The 2030 Agenda for Sustainable Development*.
- USGS, 2000. Shuttle Radar Topography Mission (SRTM) 1 arc-second global Reston. Virginia, USA: U. S. Geological Survey.
- Valera, C.A., Junior, R.V., Varandas, S.G.P., Fernandes, L.S., Pacheco, F.A.L., 2016. The role of environmental land use conflicts in soil fertility: A study on the Uberaba River basin, Brazil. *Science of The Total Environment* 562, 463–473. <https://doi.org/10.1016/j.scitotenv.2016.04.046>
- Valle Junior, R.F., Varandas, S.G., Pacheco, F.A., Pereira, V.R., Santos, C.F., Cortes, R.M., Fernandes, L.F.S., 2015. Impacts of land use conflicts on riverine ecosystems. *Land Use Policy* 43, 48–62. <https://doi.org/10.1016/j.landusepol.2014.10.015>
- Valle Junior, R.F., Varandas, S.G.P., Sanches Fernandes, L.F., Pacheco, F.A.L., 2014. Groundwater quality in rural watersheds with environmental land use conflicts. *Science of The Total Environment* 493, 812–827. <https://doi.org/10.1016/j.scitotenv.2014.06.068>
- van Meerveld, H.J.I., Vis, M.J.P., Seibert, J., 2017. Information content of stream level class data for hydrological model calibration. *Hydrology and Earth System Sciences* 21, 4895–4905.
- van Overloop, P.J., Davids, J.C., Vierstra, M.M., 2014. Mobile monitoring technologies: the mobiletracker and the remotetracker, in: *Proceedings of USCID Conference*, Sacramento, California.
- Vanmaercke, M., Poesen, J., Broeckx, J., Nyssen, J., 2014. Sediment yield in Africa. *Earth-Science Reviews* 136, 350–368. <https://doi.org/10.1016/j.earscirev.2014.06.004>

- Velasco-Muñoz, J.F., Aznar-Sánchez, J.A., Schoenemann, M., López-Felices, B., 2022. An Analysis of the Worldwide Research on the Socio-Cultural Valuation of Forest Ecosystem Services. *Sustainability* 14, 2089. <https://doi.org/10.3390/su14042089>
- Verbrugge, L.N.H., Ganzevoort, W., Fliervoet, J.M., Panten, K., van den Born, R.J.G., 2017. Implementing participatory monitoring in river management: The role of stakeholders' perspectives and incentives. *Journal of Environmental Management, Optimizing the impact of science: Translational research and stakeholder engagement to identify sustainable land management based adaptation for challenges posed by environmental change* 195, 62–69. <https://doi.org/10.1016/j.jenvman.2016.11.035>
- Verschuren, D., Johnson, T.C., Kling, H.J., Edgington, D.N., Leavitt, P.R., Brown, E.T., Talbot, M.R., Hecky, R.E., 2002. History and timing of human impact on Lake Victoria, East Africa. *Proceedings of the Royal Society of London B: Biological Sciences* 269, 289–294. <https://doi.org/10.1098/rspb.2001.1850>
- Villamagna, A.M., Angermeier, P.L., Bennett, E.M., 2013. Capacity, pressure, demand, and flow: A conceptual framework for analyzing ecosystem service provision and delivery. *Ecological Complexity* 15, 114–121. <https://doi.org/10.1016/j.ecocom.2013.07.004>
- Vollmer, D., Burkhard, K., Adem Esmail, B., Guerrero, P., Nagabhatla, N., 2022. Incorporating Ecosystem Services into Water Resources Management—Tools, Policies, Promising Pathways. *Environmental Management* 69, 627–635. <https://doi.org/10.1007/s00267-022-01640-9>
- Vos, L. de, Leijnse, H., Overeem, A., Uijlenhoet, R., 2017. The potential of urban rainfall monitoring with crowdsourced automatic weather stations in Amsterdam. *Hydrology and Earth System Sciences* 21, 765–777. <https://doi.org/doi:10.5194/hess-21-765-2017>
- Vuai, S.A.H., Ibembe, J.D., Mungai, N., 2012. Spatial Variation of Nutrients in Sondu-Miriu and Simiyu-Duma Rivers: Implication on Sources and Factors Influencing their Transportation into the Lake Victoria. *J Earth Sci Climate Change* 3, 2. <http://dx.doi.org/10.4172/2157-7617.1000119>
- Wald, D.M., Longo, J., Dobell, A.R., 2016. Design principles for engaging and retaining virtual citizen scientists. *Conservation Biology* 30, 562–570. <https://doi.org/10.1111/cobi.12627>
- Walker, D., Forsythe, N., Parkin, G., Gowing, J., 2016. Filling the observational void: Scientific value and quantitative validation of hydrometeorological data from a community-based monitoring programme. *Journal of Hydrology* 538, 713–725. <https://doi.org/10.1016/j.jhydrol.2016.04.062>
- Walling, D.E., Collins, A.L., Sickingabula, H.M., Leeks, G.J.L., 2001. Integrated assessment of catchment suspended sediment budgets: a Zambian example. *Land Degrad. Dev.* 12, 387–415. <https://doi.org/10.1002/ldr.461>
- Wang, C., Schneider, R.L., Parlange, J.-Y., Dahlke, H.E., Walter, M.T., 2018. Explaining and modeling the concentration and loading of *Escherichia coli* in a stream—A case study. *Science of The Total Environment* 635, 1426–1435. <https://doi.org/10.1016/j.scitotenv.2018.04.036>
- Waruingi, E., Ateka, J., Mbeche, R., Herrmann, R., 2022. Understanding the nexus between forest dependence and willingness to pay for forest conservation: case of forest dependent households in Kenya. *Forestry Economics Review*. <https://doi.org/10.1108/FER-02-2022-0003>
- Watene, G., Yu, L., Nie, Y., Zhu, J., Ngigi, T., Nambajimana, J. de D., Kenduiywo, B., 2021. Water Erosion Risk Assessment in the Kenya Great Rift Valley Region. *Sustainability* 13, 844. <https://doi.org/10.3390/su13020844>

- Weeser, B., Gräf, J., Njue, N.K., Cerutti, P., Rufino, M.C., Breuer, L., Jacobs, S.R., 2021. Crowdsourced Water Level Monitoring in Kenya’s Sondu-Miriu Basin—Who Is “The Crowd”? *Front. Earth Sci* 8, 602422.
- Weeser, B., Jacobs, S., Kraft, P., Rufino, M.C., Breuer, L., 2019. Rainfall-Runoff Modeling Using Crowdsourced Water Level Data. *Water Resources Research* 55, 10856–10871. <https://doi.org/10.1029/2019WR025248>
- Weeser, B., Stenfert Kroese, J., Jacobs, S.R., Njue, N., Kemboi, Z., Ran, A., Rufino, M.C., Breuer, L., 2018. Citizen science pioneers in Kenya – A crowdsourced approach for hydrological monitoring. *Science of The Total Environment* 631–632, 1590–1599. <https://doi.org/10.1016/j.scitotenv.2018.03.130>
- Wehn, U., Collins, K., Anema, K., Basco-Carrera, L., Lerebours, A., 2018. Stakeholder engagement in water governance as social learning: lessons from practice. *Water International* 43, 34–59. <https://doi.org/10.1080/02508060.2018.1403083>
- Wehn, U., Evers, J., 2015. The social innovation potential of ICT-enabled citizen observatories to increase eParticipation in local flood risk management. *Technology in Society* 42, 187–198. <https://doi.org/10.1016/j.techsoc.2015.05.002>
- Wendt, A.K., Sowers, T., Hynek, S., Lemon, J., Beddings, E., Zheng, G., Li, Z., Williams, J.Z., Brantley, S.L., 2018. Scientist–Nonscientist Teams Explore Methane Sources in Streams Near Oil/Gas Development. *J. Contemp. Water Res. Educ.* 164, 80–111. <https://doi.org/10.1111/j.1936-704X.2018.03286.x>
- Wiggins, A., Newman, G., Stevenson, R.D., Crowston, K., 2011. Mechanisms for data quality and validation in citizen science, in: 2011 IEEE Seventh International Conference on E-Science Workshops. IEEE, pp. 14–19.
- Wilk, J., 2000. Local perceptions about forests and water in two tropical catchments. *GeoJournal* 50, 339–347. <https://doi.org/10.1023/A:1011012420808>
- Wilkinson, D.M., 2008. Strong regularities in online peer production, in: Proceedings of the 9th ACM Conference on Electronic Commerce, EC ’08. Association for Computing Machinery, New York, NY, USA, pp. 302–309. <https://doi.org/10.1145/1386790.1386837>
- Williams, J., Rummel, S., Lemon, J., Barney, M., Smith, K., Fesenmyer, K., Schoen, J., 2016. Engaging a community of interest in water quality protection: Anglers monitoring wadeable streams. *Journal of Soil and Water Conservation* 71, 114A–119A. <https://doi.org/10.2489/jswc.71.5.114A>
- Wilson, N.J., Mutter, E., Inkster, J., Satterfield, T., 2018. Community-Based Monitoring as the practice of Indigenous governance: A case study of Indigenous-led water quality monitoring in the Yukon River Basin. *Journal of Environmental Management* 210, 290–298. <https://doi.org/10.1016/j.jenvman.2018.01.020>
- Wiwatwattana, N., Sangkhatad, K., Srivatanakul, T., 2015. An analysis and case study of using mobile crowdsourcing for weather forecast verification, in: 2015 6th IEEE International Conference on Software Engineering and Service Science (ICSESS). Presented at the 2015 6th IEEE International Conference on Software Engineering and Service Science (ICSESS), IEEE, Beijing, China, pp. 251–254. <https://doi.org/10.1109/ICSESS.2015.7339048>
- Wolters, D., Brandsma, T., 2012. Estimating the Urban Heat Island in Residential Areas in the Netherlands Using Observations by Weather Amateurs. *J. Appl. Meteor. Climatol.* 51, 711–721. <https://doi.org/10.1175/JAMC-D-11-0135.1>
- Xu, Y., Li, A.J., Qin, J., Li, Q., Ho, J.G., Li, H., 2017. Seasonal patterns of water quality and phytoplankton dynamics in surface waters in Guangzhou and Foshan, China. *Sci. Total Environ.* 590–591, 361–369. <https://doi.org/10.1016/j.scitotenv.2017.02.032>

- Zemadim, B., McCartney, M., Langan, S., Sharma, B., 2013. A Participatory Approach for Hydrometeorological Monitoring in the Blue Nile River Basin of Ethiopia. Colombo, Sri Lanka: International Water Management Institute (IWMI). (IWMI Research Report 155), 32p. <https://doi.org/10.5337/2014.200>
- Zhang, G., Zhang, X., Xie, L., Zhang, Q., Liu, D., Wu, H., Li, S., 2021. Perceived Importance and Bundles of Ecosystem Services in the Yangtze River Middle Reaches Megalopolis, China. *Frontiers in Environmental Science* 9. <https://doi.org/doi:10.3389/fenvs.2021.739876>
- Zhang, J., Qi, Y., Langston, C., Kaney, B., Howard, K., 2014. A Real-Time Algorithm for Merging Radar QPEs with Rain Gauge Observations and Orographic Precipitation Climatology. *J. Hydrometeor.* 15, 1794–1809. <https://doi.org/10.1175/JHM-D-13-0163.1>
- Zhang, Y., Ma, R., Hu, M., Luo, J., Li, J., Liang, Q., 2017. Combining citizen science and land use data to identify drivers of eutrophication in the Huangpu River system. *Science of The Total Environment* 584–585, 651–664. <https://doi.org/10.1016/j.scitotenv.2017.01.093>
- Zheng, F., Tao, R., Maier, H.R., See, L., Savic, D., Zhang, T., Chen, Q., Assumpção, T.H., Yang, P., Heidari, B., Rieckermann, J., Minsker, B., Bi, W., Cai, X., Solomatine, D., Popescu, I., 2018. Crowdsourcing Methods for Data Collection in Geophysics: State of the Art, Issues, and Future Directions. *Reviews of Geophysics* 56, 698–740. <https://doi.org/10.1029/2018RG000616>
- Zheng, H., Hong, Y., Long, D., Jing, H., 2017. Monitoring surface water quality using social media in the context of citizen science. *Hydrology and Earth System Sciences* 21, 949–961. <https://doi.org/10.5194/hess-21-949-2017>
- Zhou, M., Brandt, P., Pelster, D., Rufino, M.C., Robinson, T., Butterbach-Bahl, K., 2014. Regional nitrogen budget of the Lake Victoria Basin, East Africa: syntheses, uncertainties and perspectives. *Environmental Research Letters* 9, 105009.
- Ziegler, A.D., Benner, S.G., Tantasirin, C., Wood, S.H., Sutherland, R.A., Sidle, R.C., Jachowski, N., Nullet, M.A., Xi, L.X., Snidvongs, A., 2014. Turbidity-based sediment monitoring in northern Thailand: Hysteresis, variability, and uncertainty. *Journal of hydrology* 519, 2020–2039. <https://doi.org/10.1016/j.jhydrol.2014.09.010>

Acknowledgement

The completion of this Ph.D. marks the end of a long journey that was made possible by the support I received from several people and various institutions.

This dissertation was part of a joint research project of the Centre for International Forestry Research (CIFOR) and the Justus Liebig University Giessen and contributes to the CGIAR. The research project was partially funded by the CGIAR programme on Forest, Trees and Agroforestry led by CIFOR. Additional funding was provided by Deutsche Forschungsgemeinschaft DFG (BR2238/23-1 and 23/-2), Deutsche Gesellschaft für Internationale Zusammenarbeit GIZ and German Federal Ministry for Economic Cooperation and Development (Grants 81195001 and 81206682). Besides, I received funding from a scholarship by the German Academic Exchange Service (DAAD) in collaboration with Kenya National Research Fund (NRF), via the Kenya-German postgraduate training programme. In addition, I gratefully acknowledge the participation of the involved local communities and the assistance of local authorities including Kenyan Water Resources Authority (WRA) and Water Resources Users Associations (WRUAs), who consented and supported my research work.

My sincere gratitude go to my advisors Prof. Rufino Mariana and Prof. Lutz Breuer for their guidance, unwavering support, and patience throughout my PhD studies, both at professional and personal level. I appreciate their invaluable input and feedback on my research work, which helped in developing and improving my research and writing skills. Thank you for giving me an opportunity to be part of your research team in this project, which allowed me to engage and network with other scholars. Special thanks to Prof. Lutz Breuer for providing additional financial support for my fieldwork. Thank you to Prof. Jan Siemens for accepting to be my second supervisor.

I would also like to express my thanks to the research team that I worked with more closely in the project. Special thanks to Suzanne Jacobs for always willing to assist me in any way whenever I needed help, providing insightful suggestions on my work, helping out with data analysis, and guiding me throughout the process. I gained the confidence to wade in deep waters thanks to you.

Acknowledgement

I appreciate your patience as you trained me on how to handle the monitoring stations. Thank you Jaqueline Stenfert for our friendly chats and personal assistance during my PhD journey. Your generosity, hospitality and check-ins during my visit in Germany are truly appreciated. I would also like to thank Björn Weeser and Jan Gräf for their help with my research, especially throughout the process of developing and setting up the citizen science-monitoring network. And thank you, Miriam Kasebele, for always willing to offer help whenever I needed it, especially printing my documents and hosting me in your apartment while I was looking for a place to stay. I am also grateful to the drivers, Maurice Otieno and Bernard Ng'eno, who were so helpful during my fieldwork.

I would like to thank all my colleagues in the Department of Landscape Ecology and Environmental Resources for the time we had working and socialising together. Additionally, I would also like to extend my gratitude to Ann Wekesa, Dorothy Syallow and Sheila Wachiye for their encouragement and for providing a writing support network. Thank you Ann, for constantly encouraging us in the group to 'write no matter what', which we eventually adopted as our tagline. Special thanks to Prof.Koech and Dr. Hitimana, I feel very fortunate to have you as my mentors.

To my Kenyan friends in Germany who have since become family: Nixon, Simon, Taita, Tabitha, Lucy, Erick, Agnes, Maryanne and Jane, thank you for the good times and great conversations we had when we got together for cooking and dining, birthday celebrations, or church events. This not only made my study time and stay in Germany more enjoyable, but your friendship has added a lot into my life. Grace Wang'ang'a, thank you for being a shoulder to lean on in my time of need.

Lastly, I would like to extend my sincere appreciation to my entire family for their prayers and unconditional support all through my studies and life in general. Special thanks to Dad and Mum, who have travelled with me throughout my academic life. I am also pleased to say thank you to my nanny Mercy, my cousin Mercy, and sister Eunice for taking good care of my baby, as well as my niece Blessing for being a good company to her while I was away from home. To my baby Alyssa, I am sorry for the days I was away from you during my studies and I thank you for putting up with my absence. My sincere gratitude also go out to my husband Francis, who has been my biggest cheerleader throughout this journey.

Declaration

I declare that I have completed this dissertation single-handedly without the unauthorized help of a second party and only with the assistance acknowledged therein. I have appropriately acknowledged and cited all text passages that are derived verbatim from or are based on the content of published work of others, and all information relating to verbal communications. I consent to the use of an anti-plagiarism software to check my thesis. I have abided by the principles of good scientific conduct laid down in the charter of the Justus Liebig University Giessen “Satzung der Justus-Liebig-Universität Giessen zur Sicherung guter wissenschaftlicher Praxis” in carrying out the investigations described in the dissertation.

Place, Date

Naomi Karimi Njue