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Exploring water quality management with a socio-hydrological model: a case study from Burkina Faso

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ABSTRACT

Models that can integrate aspects of society such as institutions, perceptions and behaviours with aspects of the natural system such as rainfall, runoff and water quality may help us understand and manage complex human–water systems. In this paper, a socio-hydrological model is developed for the Black Volta (Mouhoun) watershed in Burkina Faso. The model captures the relationships between the awareness of water quality issues and capacity of local organizations, land use in the riparian zone, agricultural practices and suspended sediment concentration as an indicator of water quality. Scenarios are generated for the current situation and for plausible pathways to achieve improved water quality through different riparian land management strategies. Scenario comparison show how water quality improvements are generated if institutional support, resources and capacity of local level organizations are substantially increased compared to current levels.

1 Introduction

Water resource management must balance multiple priorities, needs and uses of water. The complexity of the human system (how people use water and how their actions impact water resources) coupled with the complexity of the natural system (how much water is available and how it responds to contamination and use) requires an integrated, holistic and interdisciplinary approach that can analytically explore existing and emerging challenges and solutions (Walker *et al.* 2015).

Socio-hydrology, broadly defined as the study of the dynamic interactions between people and water, offers an integrated approach for system analysis (Sivapalan *et al.* 2012). It is based on the premise that societal changes and alterations in water resources evolve in a highly interconnected way (Pande and Sivapalan 2017). Socio-hydrological modelling aims to capture system interactions and feedbacks using mathematically based models (Di Baldassarre *et al.* 2013). While classic hydrological models may aim to develop predictions of future water availability and quality based on plausible scenarios for hydrological, economic and social changes, socio-hydrological models integrate the human responses to changes in the system within their structure (Blair and Buytaert 2016). Such socio-hydrological models build on the established field of systems dynamics (Forrester 1993) and can be used to explore how the water and human systems interact and what might happen if, for example, a new policy to provide subsidies for less water-intensive crops or regulations forbidding the release of untreated wastewater into the river are implemented (European Commission 2000, Balana *et al.* 2011a).

Much work has been conducted over recent years to devise models that can explore the nonlinear dynamics between people and water (Blair and Buytaert 2016, Pande and Sivapalan 2017). However, many gaps remain that offer important research opportunities (Barendrecht *et al.* 2019). Firstly, only a few studies have used empirically derived data from a case study analysis approach to develop and verify the models generated (Barendrecht *et al.* 2017, Mostert 2018). Thus, most models remain untested and their accuracy and reliability, even for the setting in which they have been developed, remains unknown (Troy *et al.* 2015, Mostert 2018).

Secondly, to date only limited socio-hydrological modelling work has been conducted on the evolving relationships between people and water quality. Of particular interest is how societal awareness of water resource degradation drives societal willingness to protect the resource and thus improve the river basin environment. Empirical studies from the environmental psychology literature have demonstrated the strong link between education, which enables individuals to understand environmental issues, and their willingness to take action to address them (Hoffmann and Muttarak 2020). However, in the context of farmer decision making, work has shown that willingness to adopt pro-environmental behaviour needs to exist alongside ability (e.g. financial, labour and time resources)

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and support networks (e.g. advisors, local famer networks) (Mills *et al.* 2017). In socio-hydrological modelling, the societal responses to water issues are frequently placed in abstract terms and lumped, for example as community sensitivity (Yu *et al.* 2020). Broad social processes lead to the so-called "pendulum swing" effect whereby societal strategies shift from control and exploitation of a resource to restoration and preservation (Elshafei *et al.* 2014, Kandasamy *et al.* 2014, Liu *et al.* 2015, Chen *et al.* 2016, Han *et al.* 2017, Mostert 2018, Di Baldassarre *et al.* 2019). This has also been called the "impair then repair" paradigm, whereby intense use and exploitation of water resources leads to their impairment, which, out of necessity for human health and well-being, is followed by strategies to enable their repair (Vörösmarty *et al.* 2015).

Thirdly, existing socio-hydrological models have much unrealized potential to better capture aspects of institutions and water governance (Di Baldassarre *et al.* 2019). Some works have included societal risk awareness and the impacts of governance strategies such as raising awareness about floods and insurance requirements regarding flood damages (Viglione *et al.* 2014, Barendrecht *et al.* 2019, Ridolfi *et al.* 2020). Yu *et al.* (2017) captured how communities collectively maintain and repair polders and levees affected by regular flooding in Bangladesh. Yet whether these models can specifically address institutional capacity, and its impact on water resources through policy and practice, remains to be tested.

The aims of this study are therefore: (i) to develop a socio-hydrological model that can describe the dynamics between suspended sediment concentration, institutions, policy and land-use based on observed relationships in a case study region; and (ii) to use the model to explore how water quality might change as a response to different management strategies and different levels of institutional support.

2 The study area and institutional setting

2.1 Study area description

The study area is located in the upper part of the Black Volta (Mouhoun) watershed in southwest (SW) Burkina Faso (Fig. 1). The Agence de l'Eau du Mouhoun (AEM; Mouhoun River Basin Authority) is responsible for the management of the basin, and in order to engage local stakeholders in watershed management the basin is divided into 13 Local Water Committees (also known as CLEs, from the French *Comités Locaux de l'Eau*). Three of the CLEs (CLE Mouhoun Tâ, CLE Kou, and CLE Bougouriba 7) provide the case study materials for this research (Fig. 1).

Water resources in the study catchments are used for a variety of domestic purposes such as drinking, washing and laundry, fishing, irrigation, and small-scale hydropower generation in some of the study sites. Cultivation of riparian areas close to the water bodies and application of agrochemicals,
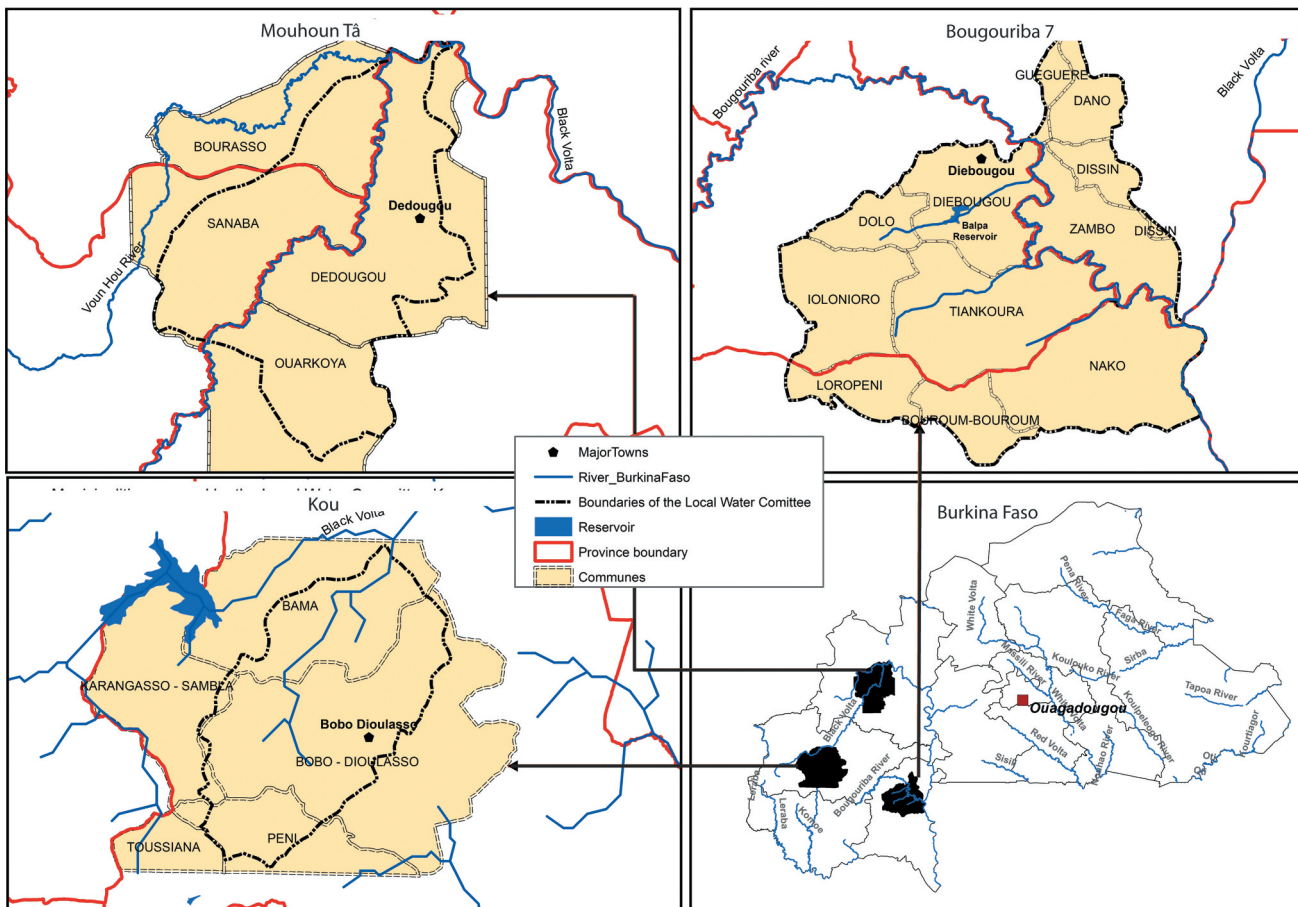

Figure 1. Map showing the Black Volta in southwest Burkina Faso and boundaries of the three Local Water Committees (CLEs)/the case study catchments.

uncontrolled cattle grazing and lack of designated watering points for animal drinking, and commercial and traditional gold mining activities were identified as the major causes of water pollution in the study catchments (Balana *et al.* 2019). Water pollution through agricultural practices may impact fish stocks and contaminate water used for domestic purposes. Sediment movement to water bodies has been shown to increase in Burkina Faso as land is converted to agriculture (Op de Hipt *et al.* 2019). Suspended sediment is correlated with a decrease in water quality, and riverbed siltation can lead to changes in river flow dynamics, raise the risk of flooding, impact on hydropower generation, and negatively affect ecosystem health (Beusen *et al.* 2005, Grove *et al.* 2015).

2.2 Water management institutions

A number of management strategies have been adopted in the study catchments with the aim to reduce pollution and sediment transfer from the riparian zone to the rivers and reservoirs. Throughout Burkina Faso, a 100-m-wide riparian buffer zone, also known in the region as an easement strip or "bande de servitude," was established in 2009 (Fig. 2). According to article 6 of joint decree N°2009-073/MECV/MAHRH regulating agricultural land clearing in Burkina Faso, "land clearing on the periphery or along watercourses, classified forests, reserves, lakes, ponds, springs and their reception basins are formally prohibited on a protection or easement strip one hundred (100) metres wide."

This is further explained by Koudougou (2018), as

> [. . . a] safety distance of at least one hundred (100) metres to be respected between the major bed of streams and water bodies and agricultural operations. It is a precautionary measure imposed to avoid silting of watercourses, water pollution due to pesticides used by farmers and evaporation of water due to the absence of vegetation.

Farmers may sometimes be encouraged to leave the 100-m zone through the provision of alternative land or compensation. Furthermore, in some catchments, there are attempts to encourage farmers to change the types of crops grown in the 100-m zone, replacing those requiring much soil disturbance (such as vegetables) with those that stabilize soil and sediment (such as tree crops), and to reduce pollution from fertilizer and pesticide use. The CLEs play a key role in promoting pollution reduction strategies through activities such as awareness-raising campaigns; marking the 100-m zone with signposts,

barriers or shrubs; supporting farmers to replace vegetables and other plants in the 100-m zone with tree crops such as mango; and encouraging farmers not to release agrochemical waste into the river or reservoir. The CLE is a decentralized entity that is supposed to act as a forum for consultation at the local level among all stakeholders with an interest in water management at the sub-basin level (Roncoli *et al.* 2009, Venot *et al.* 2014, Torou *et al.* 2018). The CLE comprises a General Assembly, an Executive Board and a control unit. Three types of stakeholders are involved, in three colleges: the college of decentralized government administration, college of local authorities, and college of water users. The latter is where the primary users, such as farmers, pastoralists, and domestic users, are represented (Somda *et al.* 2019).

Additionally, Water Police are in the process of being established in various areas across the country to monitor and enforce the 100-m zone. The Water Police was created by a government decree in July 2008, in application of the 2001 Water Management Act.[1] Its role is to coordinate the activities of various institutions that work to implement water legislation. It includes officers and agents of the judicial police as well as agents of the state services in charge of water, health, agriculture, and environment. In this sense, it is a cross-cutting body. The Water Police has jurisdiction over all waters and ecosystems in the public and private domain in Burkina Faso. It has the prerogatives of administrative police exercising control and surveillance missions and of judicial police in charge of noting offences, gathering evidence and searching for perpetrators. The first operational Water Police unit was created in 2014 in the Mouhoun River basin, and more specifically in the region of Haut Bassins (the region of CLE Kou). It began operations in 2015 (Fig. 2). The Water Police are funded from resources allocated by the central government via the River Basin Authority in which they operate (Koudougou *et al.* 2019).

3 Model conceptualization and data

3.1 Development of the socio-hydrological model

The first step in building the socio-hydrological model was to develop a schematic conceptual model depicting the changes in river and reservoir water quality as a result of agricultural activities in the riparian areas. The initial model was based on background information from various research reports from the study region. Then in September 2018, 15 semi-structured
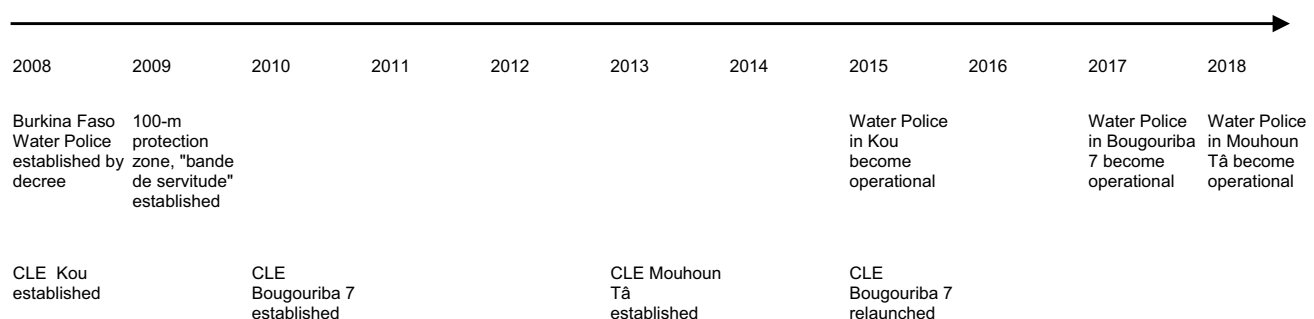
2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Burkina Faso Water Police established by decree	100-m protection zone, "bande de servitude" established						Water Police in Kou become operational		Water Police in Bougouriba 7 become operational	Water Police in Mouhoun Tâ become operational
CLE Kou established	CLE Bougouriba 7 established				CLE Mouhoun Tâ established		CLE Bougouriba 7 relaunched			

Figure 2. Time line of relevant institutional developments in the study catchments (based on Koudougou 2018, Somda *et al.* 2019).

interviews were conducted with stakeholders including members of the CLEs, government stakeholders and local water users with the aim to better understand the different water management strategies being implemented and their potential impacts on water quality and river basin health, and to gain feedback on whether the model was perceived to reflect reality. The interviews were recorded, transcribed, translated from French to English, and then coded according to key themes that emerged on the relationships between farmers, policy, institutions and water quality (see the Appendix). These interviews, along with field observations, led to the identification of several necessary changes to the model. These were implemented to create a refined schematic model (Fig. 3).

In addition to the interview data, the technical briefs and data from a number of other studies conducted as part of the project "Participative Planning for a More Inclusive and Sustainable Water Management in Rural Areas of Burkina Faso" (http://pwgbf.iwmi.org/publications-outputs/) were

available and supported the modelling. As part of the project, 201 farmers from the three study catchments (60 from Kou, 60 from Mouhoun Tâ, and 81 from Bougouriba 7) were surveyed in 2018, to determine current practices, perceptions, preferences, and potential incentive mechanisms for land and water management. This data and the resulting technical report provided detailed understanding on attitudes regarding water quality and perceptions of different management approaches that informed model development (Balana *et al.* 2019).

3.2 Model description, variables, and parameters

The basic narrative of the socio-hydrological model is that as soil erosion takes place and the concentration of suspended sediments in the river or reservoir increases, awareness of water quality issues rise, which fuels support for implementing management strategies to address degradation of the water resources. A series of equations were developed to describe
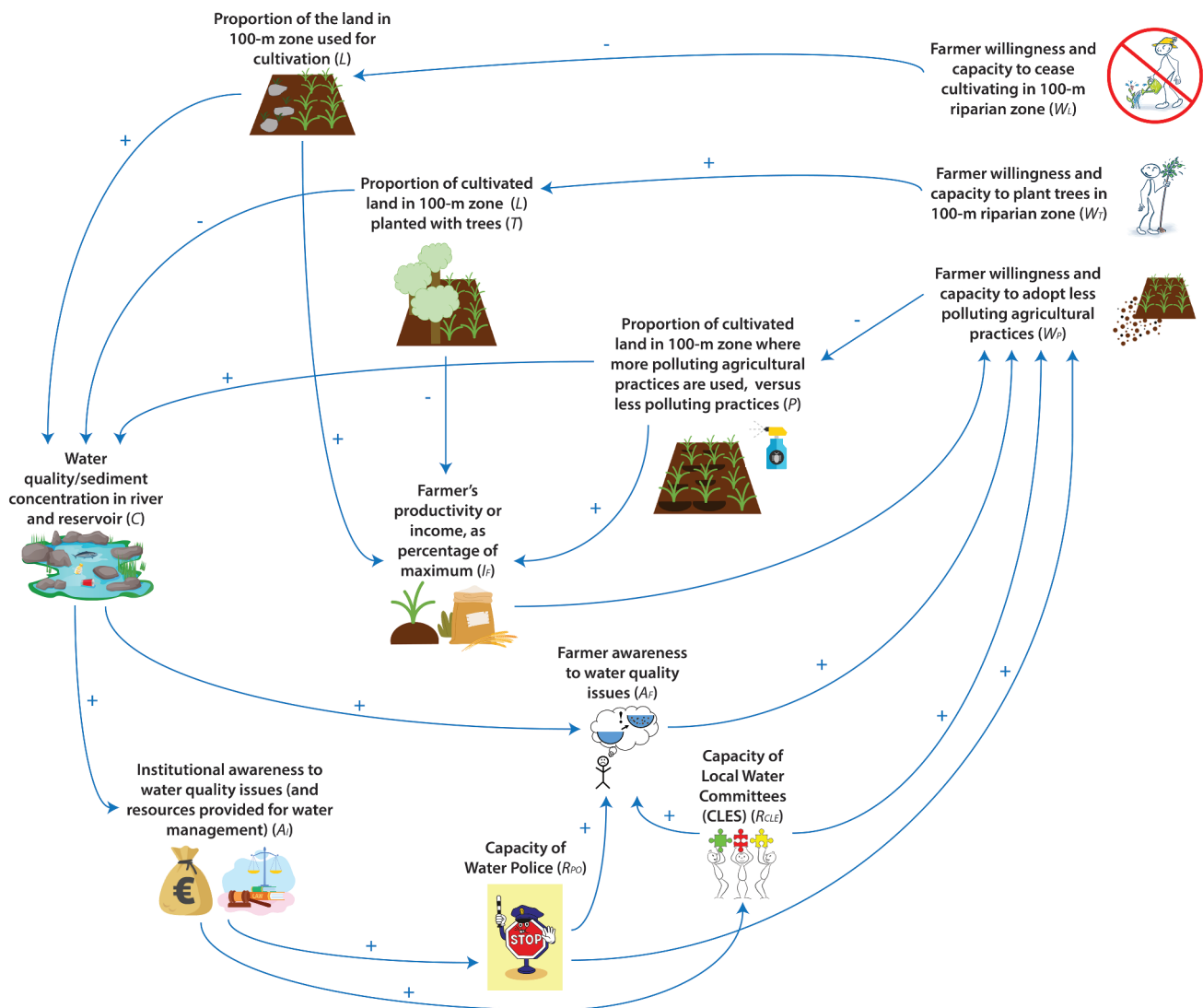

Figure 3. Graphical schematic of the socio-hydrological model. Positive/negative signs indicate the positive/negative impact of each variable on the next variable in the direction of the arrow. (Image credits: Polluted lake: iStock.com/acrylic. Sack of money: iStock.com/vladwel. Scales and books: iStock.com/UnitoneVector. Police stop: iStock.com/strelss. Stick figures with puzzle pieces: dreamstime.com/korenyugin52. Stick figure with tree: dreamstime.com/Udo Schotten. Stick figure with watering can: dreamstime.com/Udo Schotten. Sack with flour: dreamstime.com/Evgenii Naumov. Insecticide bottle: dreamstime.com/Mstjahanara903. All other images created by Carr and Barendrecht).

Table 1. Description of the variables.

Variable	Description and unit
A_I	Institutional awareness level [scaled between 0 (low) and 1 (high)]
R_{PO}	Resources and capacity of the Water Police [scaled between 0 (low) and 1 (high)]
R_{CLE}	Resources and capacity of the CLEs [scaled between 0 (low) and 1 (high)]
A_F	Farmer awareness of water quality issues [scaled between 0 (low) and 1 (high)]
W_L	Farmer willingness and capacity to cease cultivating in the 100-m zone [scaled between 0 (no means and capacity) and 1 (complete means and capacity)] e.g. farmer spends \$50 today versus willingness to spend \$100 if it was available = willingness value of 0.5
W_T	Farmer willingness and capacity to plant trees in the 100-m zone [Unit as with W_L]
W_P	Farmer willingness and capacity to adopt less polluting agricultural practices in 100-m zone [Unit as with W_L]
I_F	Famers' productivity or income [(\$/year achieved under less polluting agricultural system)/(\$/year maximum that could be achieved under more polluting agricultural system)] e.g. reduced productivity due to adoption of a more stringent management approaches is \$50 versus max productivity without management approaches of \$100 = 0.5
L	Proportion of the land in the 100-m zone used for cultivation [m²/m²] e.g. 100-m zone is 1000 m² and cultivation area is 500 m² = 50% of 100-m zone is cultivated
T	Proportion of L planted with trees [m²/m²] e.g. Total cultivated area is 500 m² and area cultivated with trees is 250 m² = 50% of cultivated area is trees
P	Proportion of L on which more polluting agricultural practices versus less polluting practices are applied [m²/m²] e.g. Total cultivated area is 500 m², 250 m² is cultivated using high-polluting practices (fertilizer, pesticide, high tillage etc) and 250 m² is cultivated using low-polluting practices (organic fertilizer, no pesticide, minimal tillage) = 50% of cultivated area uses high-polluting practices
C	Water quality in the river or reservoir [mg/L] e.g. sediment concentration
C_{inF}	Water quality of runoff from 100-m zone [mg/L] e.g. sediment concentration
Q_F	Water flowing into the river/reservoir from the land in the 100-m zone [L/s]
Q_{in}	Water in the river stretch or reservoir [L/s]
Q_{out}	Water flowing out of the river stretch or reservoir [L/s]
S	Water storage in the river stretch or reservoir [L]

$$\frac{dA_I}{dt} = \begin{cases} \alpha_{AI}(C - C_0)\left(1 - \frac{A_I}{A_{IMax}}\right)\frac{A_I}{A_{IMax}} - \mu_{AI}A_I, & C > C_0 \\ -\mu_{AI}A_I, & C \le C_0. \end{cases}$$
(1)

The modelled relationships between sediment concentration and organizational awareness are based on qualitative data from the study sites. Workshop participants in the River Kou baseline study held in July 2017 noted that one of the challenges for water resource management in the area is the government's perception and belief that the region has enough water and therefore water issues, including those of pollution and siltation, are not of concern. This is supported by a comment from an interviewee with the Water Police showing how awareness of pollution is linked to its visibility, or the availability of monitoring data, that can demonstrate water quality:

> Water pollution is not very visible. If, for example, no dead fish are seen, many people will continue to pollute. It is very complicated to understand. But if you see that fish have died, or animals have died, now that is when you are likely to realize that dumping into the water is harmful. But when it is slow pollution, the action is not perceivable like that. And we, in our services, in our public services, do not have [the capacity] to demonstrate great pollution. Since we do not have any measurements, if you see here, for example, we do not have any data that shows, for example, the level of this or that substance in water to be increased. ... I remember when we were promised [from the ministry] equipment, [monitoring] devices to install, even measuring devices for different parameters. We received nothing. All of this could help to demonstrate that water quality has really changed negatively. (Interview with Water Police, Catchment Mouhoun Tâ, October 2018)

The Water Police in Mouhoun Tâ also told a story about pollution and regulation that is summarized here and illustrates how awareness and governance interact: In 2010, pollution in one region forced hippos to jump out of the water to avoid bleaching, and fish were dying. Awareness of water pollution therefore became very high and a new collective consciousness of water pollution was experienced. The governor of the region was able to enforce the 100-m no-cultivation zone, and cultivation ceased for about a year. However, the river banks are very fertile, and in some areas they are often owned by high-ranking and influential people such as politicians and those high in the military hierarchy. In this case, the governor was appointed to a new posting and the banks were cultivated again. This suggests that visible pollution raises awareness, and awareness raises governance capacity to take action. But actions can only be sustained over the longer term with high-level institutional support.

Therefore, in the model, it is assumed that increased government support to address water quality leads to a strengthening of the Water Police and the CLEs (Equation 2 and 3). The **resources or capacity of the Water Police and CLEs** (R_{PO} and R_{CLE}, respectively) are determined by the parameters for provision of institutional support to the Water Police and the CLEs (α_{PO} and α_{CLE}) and the rate of their decline in capacity when support is not provided (μ_{PO} and μ_{CLE}).

the relationships shown in Fig. 3. The model was programmed using the software "R" (R Core Team 2019). An overview of the variables and their units is shown in Table 1.

3.2.1 Awareness of water pollution

The model proposes that as the government's awareness level and recognition of water quality issues increases, the institutional support for mechanisms to address it also increases (Equation 1). Let A_I represent the **level of awareness** of water quality problems of government organizations/agencies, and let C be the concentration of sediment in the river or reservoir (suspended sediment, mg/L). Awareness is further driven by the parameters α_{AI} and μ_{AI}, which determine the influence of C on organizational awareness and the rate of decline in organizational awareness through time, respectively. Decline in awareness is expected if dissemination of observable information is not continually reinforced (e.g. through water quality data or visible water quality issues) to water users or regulatory agents. Awareness, as with many of the variables, is scaled between 0 and 1.

$$\frac{dR_{PO}}{dt} = \alpha_{PO} A_I \frac{R_{PO}}{R_{POMax}} \left(1 - \frac{R_{PO}}{R_{POMax}}\right) - \mu_{PO} R_{PO} \qquad (2)$$

$$\frac{dR_{CLE}}{dt} = \alpha_{CLE} A_I \frac{R_{CLE}}{R_{CLEMax}} \left(1 - \frac{R_{CLE}}{R_{CLEMax}}\right) - \mu_{CLE} R_{CLE} \qquad (3)$$

In the model, the equation for **farmers' awareness** (A_F) (Equation 4) is driven by water quality (C), the capacity of the Water Police (R_{PO}), and the capacity of the Local Water Committees (R_{CLE}) to implement awareness-raising activities, the influence of awareness-raising campaigns on the farmers' awareness (β_{AF}), and the existing awareness of the farmers. The parameter α_{AF} controls the influence of pollution, erosion, and siltation on farmers' awareness, and μ_{AF} controls how rapidly the farmers lose their awareness if it is not continually reinforced.

$$\frac{dA_F}{dt} = \begin{cases} \alpha_{AF}(C-C_0)\beta_{AF}R_{PO}R_{CLE}\left(1-\frac{A_F}{A_{FMax}}\right)\frac{A_F}{A_{FMax}} - \mu_{AF}A_F, C > C_0 \\ \\ \qquad\qquad\qquad\qquad\qquad -\mu_{AF}A_F, C \leq C_0. \end{cases}$$

$$(4)$$

Table 2. Respondents' perceptions of local water problems (Question: "In your view, what are the key water problems in your catchment or community?") (after Balana et al. 2019).

Key water-related problems	Responses (% of respondents)			
	Kou	Mouhoun-Tâ	Bougouiba 7	Mean
Siltation	74.6	80.0	87.6	80.7
Water shortages	17.0	8.3	8.6	11.3
Water pollution	8.5	10.0	2.5	7.0
Others	-	1.7	1.2	1.5

These modelled relationships are based on the observation that one of the aims of the CLEs and the Water Police is to raise awareness amongst water users about the relationships between agriculture and water quality, and this will be directly correlated to the capacity (in terms of both economic and human resources) of the CLEs and Water Police. Based on data from the 2018 socio-economic survey (Balana et al. 2019), farmers' awareness of siltation is expected to be high (because it is visible), while their awareness of water pollution is expected to be low (because it is less visible) (Table 2). Awareness-raising activities are expected to make farmers aware that their actions play a role in soil erosion and high sediment loads in the rivers, to lead to an increase in farmers' understanding and knowledge about (less visible) water pollution and to raise their willingness to implement strategies aimed at improving water quality (Okumah et al. 2018).

3.2.2 Capacity of farmers to address water quality issues

In the model, **farmer willingness and capacity** ([$/$]) to implement management strategies to address water quality is a result of the trade-off farmers make between the impact on their income of implementing a strategy, against their awareness of water quality issues, combined with the support (or fines) they receive from the CLEs or Water Police. In this way, the model reflects the findings of Mills et al. (2017) that environmentally beneficial decisions result from a combination of personal willingness, an ability to adopt the approaches in terms of financial resources and time, and engagement with different networks (such as local farmer groups and government outreach) that provide information and support (Fig. 4).

In the model, the change in farmers' willingness and capacity to cease cultivating in the 100-m riparian zone (dW_L/dt) (Equation 5) decreases when the farmer's income (e.g. their yield or productivity) (I_F, see Equation 8) is lower than their initial income (I_{F0}). It increases when farmers have a higher
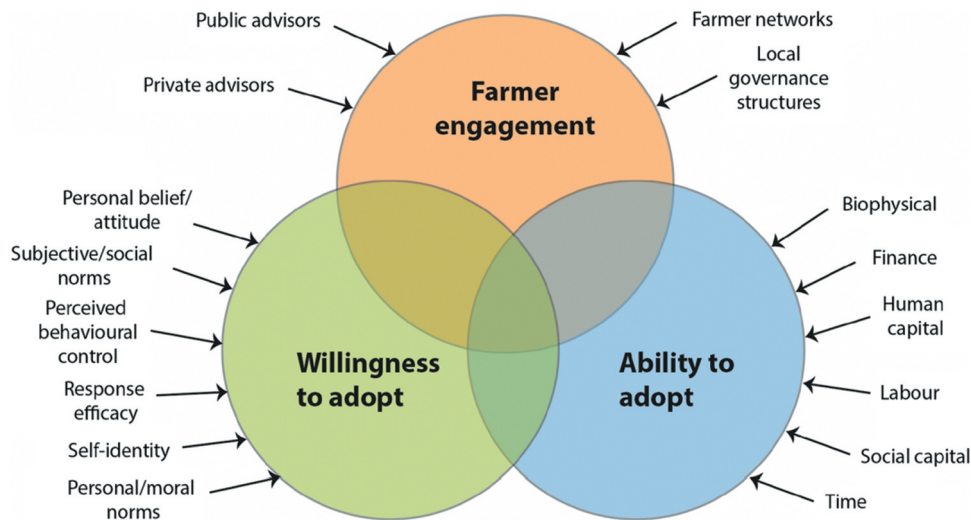

Figure 4. Factors influencing environmental decision making by farmers (from Mills et al. 2017). Reprinted by permission from Springer Nature: Agriculture and Human Values.

awareness (depending on the awareness parameter, α_W), when farmers receive fines (β_{IF}), and when they receive support from the CLEs (α_{IFL}) to cease cultivating in the riparian zone (e.g. support to relocate such as land, pumps, irrigation infrastructure, or compensation). Fines are allocated to farmers who continue to cultivate land in the 100-m zone, according to the percentage of land in the 100-m zone that is used for farming (L) minus the percentage of L occupied by trees (T).

The farmer's willingness and capacity to replace crops with trees (Equation 6) is modelled the same way, but uses a parameter to represent support for tree planting (α_{IFT}), while the farmer's willingness and capacity to implement less polluting agricultural practices (Equation 7) is driven by the level of his/her awareness combined with a parameter for support for implementing less polluting measures provided by the CLEs (α_{IFP}). Note that the use of polluting practices is not fined and therefore the willingness and capacity to implement less polluting strategies is not influenced by the Water Police. The willingness and capacity varies between −1 and +1, with +1 indicating that the farmer is very willing and able to accept the costs of implementing a measure, and −1 indicating that the farmer is extremely unwilling and unable to accept any of the costs and therefore returns to polluting practices.

$$\frac{dW_L}{dt} = \begin{pmatrix} \alpha_W A_F + \alpha_{IFL} R_{CLE} \\ +(1-T)L\beta_{IF} R_{PO} \\ -\alpha_{WI}(I_{F0} - I_F) \end{pmatrix} \left(1 - \frac{W_L}{W_{LMax}}\right)\left(\frac{W_L}{W_{LMax}}\right) \quad (5)$$

$$\frac{dW_T}{dt} = \begin{pmatrix} \alpha_W A_F + \alpha_{IFT} R_{CLE} \\ +(1-T)L\beta_{IF} R_{PO} \\ -\alpha_{WI}(I_{F0} - I_F) \end{pmatrix} \left(1 - \frac{W_T}{W_{TMax}}\right)\left(\frac{W_T}{W_{TMax}}\right) \quad (6)$$

$$\frac{dW_P}{dt} = \begin{pmatrix} \alpha_W A_F + \alpha_{IFP} R_{CLE} \\ -\alpha_{WI}(I_{F0} - I_F) \end{pmatrix} \left(1 - \frac{W_P}{W_{PMax}}\right)\left(\frac{W_P}{W_{PMax}}\right) \quad (7)$$

These modelled relationships are based on the data from the socio-economic study showing that farmers who believe their own economic activity along the river or reservoir contributes to water problems in their watershed are more willing to implement water quality management measures (Balana *et al.* 2019). According to this survey, 79% of farmers surveyed use chemical fertilizers, 81% apply pesticides and 50% cultivate the riverbanks

or areas close to riverbanks. The results show that more than 95% of respondents with awareness of siltation and pollution problems expressed their willingness to undertake one or more management measure to address the water problems in their watersheds. Regarding specific measurement measures, 75% reported they would stop cultivation of riverbanks and 43% were willing to reduce use of agrochemicals. Thus, enhancing farmers' awareness of water pollution, its drivers, and its long-term economic and environmental effects is expected to increase farmers' willingness to implement management measures (Fig. 5).

Interviews with farmers, the Water Police, and CLE members highlighted the complexities of implementing management strategies and drew attention to the important role of regulation and enforcement by the Water Police combined with support from the CLEs. The interviews with Water Police emphasized that while awareness raising and support can encourage farmers to cease cultivating in the 100-m zone, they believed that enforcement of the regulations through fines to farmers who continue to cultivate is also needed to reduce cultivation in this zone.

Farmers highlighted how they do not have alternative options and would need to be provided with alternative means to generate a livelihood or receive compensation to leave their plots. The Kou Baseline Study conducted in 2017, notes how some farmers cultivate next to the river because they lack pumps to transport the water to sites farther away from the banks. Interviews with farmers in the Kou catchment also suggested that training and capacity building could enable farmers to adopt less polluting approaches:

> People have asked for training. Show them how to make organic fertilizer, that is to say, from trees and grasses, they make fertilizer, but they have to be given the tools and material, such as shovels, and so on, and a little money to be able to work their fertilizer, and they will leave the chemical fertilizer, that is what they said. (Translator summarizing interviews with farmers in Kou Basin, Interview 8, October 2018)

The equation for **farmers' productivity** or income (I_F [($/year)/($/year)]) describes the impact on yield of each of the management strategies (Equation 8). Yield and economic
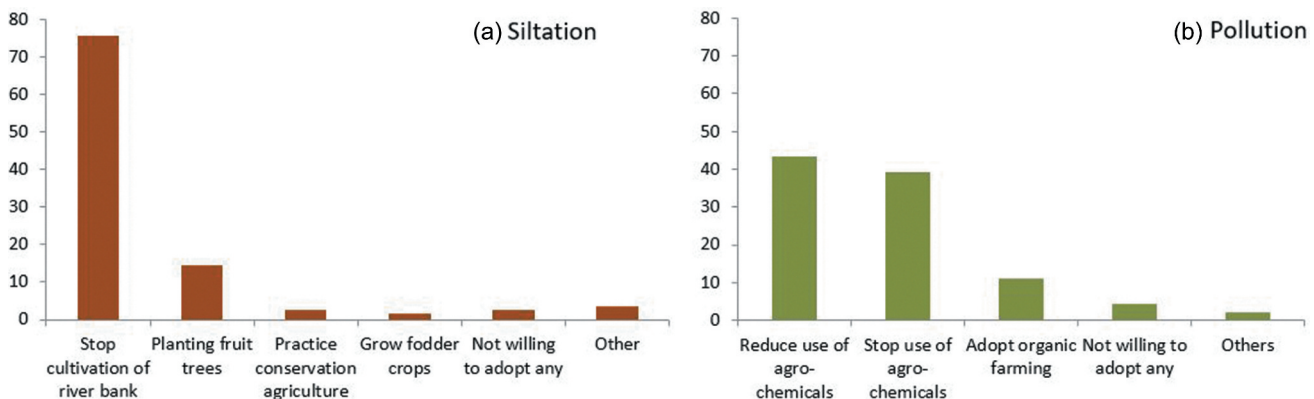

Figure 5. Percentage of farmers willing to adopt different management strategies to address (a) siltation due to river bank cultivation and (b) agricultural water pollution from agrochemicals.

data have been used to estimate how a change in land use/ adoption of management strategies will impact productivity as follows:

(i) Ceasing irrigated agriculture in the 100-m riparian zone and instead cultivating rainfed crops away from the 100-m zone is estimated to be 42.5% less productive. This is derived from the difference in maximum yields of cabbage grown on irrigated plots (85 tonnes/ha) versus those grown on rainfed plots (50 tonnes/ha) (FAO 2020).

(ii) Replacing vegetable crops (cabbage) with fruit trees (mango) is estimated to be 62.5% less productive over a time period of 20 years. This has been calculated by comparing the average annual yield of established mango plantations (12 tonnes/ha) (Griesbach 2003) and the global average price of mango (US$ 2.8 /kg) (www.tridge.com, 2020) to the average annual yield and price of cabbage (85 tonnes/ha, value of US $ 0.79/kg) (FAO 2020; www.tridge.com, 2020).

(iii) Adopting conservation tillage to reduce sediment transfer via runoff, in combination with organic farming, is estimated to reduce yields by 60% compared to conventional agriculture coupled with conventional tillage. This has been approximated using work comparing the yields of cabbage grown with high agricultural inputs on irrigated plots (93 tonnes/ha) versus those grown on irrigated plots without agricultural inputs (47 tonnes/ha) (Šturm *et al.* 2010). Furthermore, a collection of studies have shown that conservation tillage within an organic farming system (without the use of herbicides) reduces yields by 20% compared with organic farming using conventional tillage (Zikeli and Gruber 2017). Therefore, it is estimated that cabbage yields under organic farming coupled with conservation tillage would be around 37.6 tonnes/ha (a 60% yield reduction).

To calculate the impact of a change in land use/adoption of management approaches, calculations are made of the change in the proportion of total land in the 100-m zone that is used for cultivating vegetables (L [m^2/m^2], a percentage), the proportion of cultivated land (L) that is covered with trees (T [m^2/m^2], percentage), and the proportion of cultivated land (L) on which more polluting agricultural practices are used versus less polluting agricultural practices (P [m^2/m^2], percentage). The change in land use (Equations 9–11) results from the farmers' willingness and capacity to change their agricultural practices (W_L [\$/\$], W_T[\$/\$], W_P[\$/\$]), which is itself a result of how the farmers' productivity changes under different land uses/management approaches (Equations 5–7). The effectiveness with which farmers' willingness and capacity generates an actual change in land use and agricultural practice is controlled by a parameter ($\alpha_L, \alpha_T, \alpha_P$). The parameters μ_L, μ_T and μ_P control the rate at which the farmers revert to more polluting behaviour; e.g. μ_L controls the rate at which land in the 100-m zone is converted to agricultural land due to population pressure or economic demands. The literature suggests that in Burkina Faso, land is brought under agriculture at a rate of 0.95% per year (Op de Hipt *et al.* 2019).

$$I_F = 0.575 + (0.425L(0.4 + 0.6P)(0.625(1 - T) + 0.375T)$$
(8)

$$\frac{dL}{dt} = -\alpha_L W_L \frac{L}{L_{Max}} + \mu_L \left(1 - \frac{L}{L_{Max}}\right)$$
(9)

$$\frac{dT}{dt} = \alpha_T W_T \frac{T}{T_{Max}} - \mu_T \left(1 - \frac{T}{T_{Max}}\right)$$
(10)

$$\frac{dP}{dt} = -\alpha_P W_P \frac{P}{P_{Max}} + \mu_P \left(1 - \frac{P}{P_{Max}}\right)$$
(11)

In this model, farmers are considered rational economic agents, in the sense that a change to their current agricultural practices that leads to a loss of short-run economic profitability, due to either an increased cost of production or a fall in productivity, is unlikely to be implemented unless an incentive mechanism is in place, e.g. financial compensation and regulatory instruments. Therefore, there is a need to incentivize farmers to induce behavioural changes through awareness creation and capacity building, economic instruments (e.g. financial compensation), institutional and regulatory mechanisms (e.g. fines and strict enforcement), or infrastructure development (e.g. irrigation infrastructure, transport and access to markets).

3.2.3 Impact on water quality

To model the impact of management approaches on **water quality**, suspended sediment is conceptualized as moving (e.g. via overland flow) from the agricultural land in the 100-m zone to the river or reservoir. The 100-m riparian zone therefore forms the spatial boundary to this model. This is a necessary simplification of a complex system, which is justified because in this region, the 100-m zone forms the primary focus for pollution- and sediment-reduction strategies. While strategies such as afforestation and agricultural pollution reduction implemented beyond the 100-m riparian zone would be expected to also have an impact on water quality, they have not been explicitly included in this model.

The impact of each management strategy on the amount of suspended sediment transferring from the 100-m riparian zone towards the surface water body (C_{inF}, mg/L) (Equation 12) has been estimated as follows:

(i) Ceasing irrigated agriculture in the 100-m riparian zone and instead cultivating rainfed crops away from the 100-m zone is estimated to reduce sediment transfer by 75% compared to intensive cultivation in the 100-m zone. This has been derived from the conservative average in the summary of findings on the impact of vegetated buffer strips on sediment transfer reported by Osborne and Kovacic (1993).

(ii) Replacing vegetable crops (cabbage) with fruit trees (mango) is estimated to reduce sediment transfer by 50%. This is based on a slightly higher sediment transfer being expected than if agriculture completely ceases, because soil disturbance, although low, may still take place.

(iii) Adopting on-farm measures such as low or no tillage is estimated to reduce sediment transfer by 60% compared to conventional tillage. This is based on data on the impact of conservation tillage practices on sediment transfer to waterways (Tiessen *et al.*, 2010, Myers *et al.* 2000, Renwick *et al.* 2018).

$$C_{inF} = (0.25 + (0.75L(0.5 + 0.5(1 - T))(0.4 + 0.6P)))C_{inF0}$$
(12)

To model the water quality of the water body, we assume that the river or lake can be represented as a reservoir with no change in storage and with complete mixing. This is a simplified model of reality. However, since we are not interested in changes in water quality that are caused by hydrological processes but rather in changes caused by interventions made by the farmers, we assume that this simplification does not affect our conclusions on the comparison between those interventions. Since we assume complete mixing, the change in concentration of pollution/sediment in the reservoir can be calculated with Equation (13). There is a certain amount of water in the reservoir or river stretch that we are modelling (Q_{in}) and this water has a certain quality (C_{in}). At the same time, there is water flowing into the river from the land in the 100-m zone (Q_F). This water has a concentration of pollutants/sediment that depends on the measures adopted by the farmers (C_{inF}). After mixing, the water flows out of the river stretch/reservoir with concentration C. The discharge flowing out of the river stretch/reservoir (Q_{out}) depends on the storage (S) and a parameter κ_S (Equation 14). The change in storage is, then, simply the difference between the inflow (Q_{in} and Q_F) and the outflow (Q_{out}) (Equation 15). In this model, the inflow is constant and we fix κ_S so that the outflow is equal to the inflow, therefore there is no change in storage in the river stretch/reservoir.

$$\frac{dC}{dt} = \frac{C_{inF}Q_F + C_{in}Q_{in} - CQ_{out}}{S}$$
(13)

$$Q_{out} = \kappa_S S$$
(14)

$$\frac{dS}{dt} = Q_{in} + Q_F - Q_{out}$$
(15)

3.3 Model parameterization and scenarios

The aim of the socio-hydrological model is to compare how water quality could be improved through (i) prioritization of support for different management strategies, and (ii) the addition of further institutional support for water quality management. To this aim, the model is first set up to generate the evolution of the current scenario (the baseline scenario) in the case study region.

3.3.1 Baseline scenario for southwest Burkina Faso

The baseline scenario, representing the actual evolution of the case study area, consists of three time periods, 1990–2008, 2009–2015, and 2016–2020. For the first time period, initial values for

each variable were set low, but not at zero, to reflect the expected low resources, awareness, and willingness prior to the establishment of water management institutions (Table 3). The initial suspended sediment concentration was set at 70 mg/L based on an estimate derived from published data (Akrasi and Ayibotele 1984). For the second and third time periods, the initial values were set based on the modelled values from the end of the preceding time period.

The parameters for each time period are shown in Table 4 and reflect the institutional developments shown in Fig. 2. Therefore, for the first time period (1990–2008), where neither Water Police nor CLEs were operational, the parameters for institutional support for Water Police (α_{WPO}) and CLEs (α_{CLE}) and for the support for encouraging farmers to cease cultivation in the 100-m zone, replacing vegetables with trees, and for reducing agricultural pollution and siltation are set to 0. The relative values for the other parameters were then manually calibrated to generate an increase of 0.95% per year in the percentage of land used for agriculture and an increase of 1% per year in suspended sediment concentration (based on Op de Hipt et al. 2019, which combines both land-use change and climate change impacts).

In 2008, the first of the CLEs in the study region was established (Fig. 2). Therefore, for the time period 2009–2015, the parameter for the level of institutional support for the CLEs (α_{CLE}) is raised to 0.5, and the parameters for the support that the CLEs provide to farmers for ceasing cultivation, planting trees, and reducing pollution ($\alpha_{IFL}, \alpha_{IFT}, \alpha_{IFP}$) are set at 0.5 each. These parameter values are manually calibrated to achieve a slight impact on farmers' awareness of water quality issues and capacity to implement measures. This was based on the interviews showing that funding is provided to the CLEs to undertake specific activities. For example, in Kou, support for tree planting and awareness raising, e.g. through radio announcements, has been provided. Also, the amount of support for changing agricultural practices (replacing vegetable crops with trees, ceasing cultivation in the 100-m riparian zone, or reducing the use of agrochemicals) was set at 0.5. This is because in all areas, the CLE interviewees described how they have undertaken activities to support farmers to plant fruit trees such as mango (particularly in CLE Kou), raise awareness to encourage farmers to reduce cultivation of the 100-m zone, and reduce agricultural pollution. The parameter for institutional support to the Water Police (α_{PO}) remains at 0.

In 2015, the first Water Police were set up in the region of the CLE Kou study area (Fig. 2). Therefore, for the time period 2016–2020 the parameter for institutional support to the Water Police is raised to 0.5. Interviews with representatives from the Water Police in the three study areas showed that these organizations receive some financial support to undertake awareness raising activities but lack institutional support to enforce the 100-m zone beside the river, e.g. through issuing fines. Therefore, the influence of fines on farmers (β_{IF}) remains at zero.

Table 3. Initial conditions for each time period of the baseline scenario.

Variable	A_I	R_{PO}	R_{CLE}	A_F	W_L	W_T	W_P	L	T	P	C
Initial value (1990)	0.05	0.05	0.05	0.05	0.01	0.01	0.01	0.12	0.1	0.9	70
2009	0.15	0.04	0.04	0.09	0.03	0.03	0.03	0.33	0.12	0.88	82.8
2016	0.23	0.04	0.07	0.12	0.05	0.05	0.05	0.39	0.15	0.85	85.7

Table 4. Parameters and their values used in the baseline scenario. * = value that is fixed and does not change in any scenario.

Parameter	Description	1. Baseline		
		1990–2008	2009–2015	2016–2020
α_{PO}	Level of institutional support for Water Police [1/y]	0	0	0.5
α_{CLE}	Level of institutional support for CLEs [1/y]	0	0.5	0.5
α_{IFT}	Support for planting trees [1/y]	0	0.5	0.5
α_{IFL}	Support (e.g. subsidies) for ceasing agriculture in the 100-m zone [1/y]	0	0.5	0.5
α_{IFP}	Support (e.g. technical, financial) for reducing agricultural pollution and siltation [1/y]	0	0.5	0.5
β_{IF}	Fines as punishment for cultivating in the 100-m zone [1/y]	0	0	0
a_{AI}*	Influence of water quality and siltation on organizational awareness [1/(mg/L)]	2/1000	2/1000	2/1000
μ_{AI}*	Decline of organizational awareness of water quality and siltation over time [1/y]	0.05/1000	0.05/1000	0.05/1000
μ_{PO}*	Decline of Water Police capacity over time [1/y]	0.01	0.01	0.01
μ_{CLE}*	Decline of CLEs' capacity over time [1/y]	0.01	0.01	0.01
a_{AF}*	Influence of water quality and siltation on farmers' awareness [1/(mg/L)]	8/1000	8/1000	8/1000
β_{AF}*	Influence of Water Police and CLE awareness-raising campaigns on awareness of farmers [1/(^{2}/^{2})]	100	100	100
μ_{AF}*	Decline of farmer awareness of water quality and siltation over time [1/y]	20/1000	20/1000	20/1000
a_W*	Influence of awareness on willingness to change [($/$)/y]	1	1	1
a_{WI}*	Influence of loss of income on willingness to change [1/y]	0.05	0.05	0.05
a_T*	Influence of willingness on change in area covered with trees [1/($/$)]	0.2	0.2	0.2
a_L*	Influence of willingness on change in area in the 100-m zone being cultivated [1/($/$)]	0.1	0.1	0.1
a_P*	Influence of willingness on change in polluting practices [1/($/$)]	0.2	0.2	0.2
μ_T*	Decline rate of trees in cultivated area zone [1/y]	0.015	0.015	0.015
μ_L*	Rate of increase of cultivation in 100-m zone [1/y]	0.015	0.015	0.015
μ_P*	Rate of increase of the use of polluting agricultural practices [1/y]	0.015	0.015	0.015

The majority of the parameters remain constant throughout. These have been manually calibrated to achieve a temporal shift in the dynamics that fits the expected temporal shift (i.e. a constant and gradual change in awareness, organizational capacity, famers' willingness and capacity to implement measures, and change in land use and water quality).

3.3.2 Scenarios to achieve pre-1990 suspended sediment concentrations

The model was used to explore how an improvement in water quality, to levels estimated for the pre-1990 condition, could be achieved. Scenarios were generated that enable the impacts of each different management strategy on water quality to be compared:

(1) The baseline scenario as described in Section 3.3.1.
(2) Doubling institutional support to the CLEs and focusing on reducing cultivation in the 100-m zone.
(3) Doubling institutional support to the CLEs and focusing on tree planting.
(4) Doubling institutional support to the CLEs and focusing on reducing polluting practices.
(5) Doubling institutional support to the CLEs and effectively tripling the internal capacity of the CLEs (e.g. through capacity strengthening, more financial support, and gender balance/empowerment in the CLEs) and focusing on all measures.
(6) Doubling institutional support to the CLEs and the Water Police and enabling them to implement law enforcement through fines.

Each scenario starts in the year 2000 using the initial conditions from the baseline for this year. The parameters are adjusted for each scenario so that the level of institutional support to the CLEs (α_{CLE}) is doubled from 0.5 in the baseline scenario to 1 (Table 5). The corresponding support that the CLEs then provide to farmers ($\alpha_{IFL}, \alpha_{IFT}, \alpha_{IFP}$) is also doubled, from a sum of 1.5 in the baseline (0.5 to support trees, 0.5 to pollution reduction, and 0.5 to ceasing cultivation) to a sum of 3. In each scenario, this entire support budget of 3 is applied to support one measure (e.g. Scenario 2 is on tree planting, Scenario 3 is on ceasing cultivation, Scenario 4 is on ceasing cultivation). In Scenario 5, the institutional support to the CLEs is doubled, again to give 3 for α_{CLE}, but in this scenario the internal capacity of the CLEs is tripled, therefore raising the total support to 9. This support is distributed amongst all measures so that $\alpha_{IFL}, \alpha_{IFT}, \alpha_{IFP}$ are each set to 3. The internal capacity of the CLEs could be envisioned to be raised through capacity strengthening (i.e. recruitment and retention of skilled personnel, additional training to personnel), stronger networking capacity at different levels (farmers through to government), enhanced gender balance/empowerment in the CLEs, capacity to secure more financial support or non-financial resources (e.g. donor funding, access to credit for farmers, private sector investment in tree planting). In Scenario 6, the three support parameters $\alpha_{IFL}, \alpha_{IFT}, \alpha_{IFP}$ are set to 1 (i.e. a doubling of the total support, but distributed across measures) and in addition the institutional support for the Water Police (α_{PO}) is increased to 1 and the fines parameter (β_{IF}) is raised to 3.

4 Results and discussion

4.1 Model results

Figure 6 shows the development of the variables over time for the different scenarios. The baseline scenario (black) shows that although the capacity of the CLEs and the Water Police rises, and this leads to a slight increase in awareness and a rise in the capacity of farmers to undertake management measures, this does not translate into actions within the time frame that is modelled. As such, the cultivated area within the 100-m zone continues to rise and, correspondingly, so does the suspended sediment concentration.

Table 5. Parameters and their values used in the scenarios.

Parameter	Description	2. Double support for ceasing cultivation in 100-m zone	3. Double support for tree planting	4. Double support for reducing agricultural pollution	5. Additional support for all three measures	6. Additional support for all three measures and implementation of fines
α_{PO}	Level of institutional support for Water Police [1/y]	0	0	0	0	1
α_{CLE}	Level of institutional support for CLEs [1/y]	1	1	1	1	1
α_{IFL}	Support (e.g. subsidies) for ceasing agriculture in the 100-m zone [1/y]	3	0	0	3	1
α_{IFT}	Support for planting trees [1/y]	0	3	0	3	1
α_{IFP}	Support (e.g. technical, financial) for reducing agricultural pollution and siltation [1/y]	0	0	3	3	1
β_{IF}	Fines as punishment for cultivating in the 100-m zone [1/y]	0	0	0	0	3

Doubling the institutional support to the CLEs (Scenarios 2, 3, and 4 – green circles, orange triangles and blue plus signs, respectively) leads to a decrease in sediment concentration as farmers become capable of implementing actions. Interestingly, based on this model, no particular management approach stands out as being more effective than any other regarding its capacity to reduce sediment concentration over the time scale modelled.

This model suggests that it is only by implementing all three management strategies simultaneously, through an effective tripling of the CLEs' capacity compared to the baseline, that it becomes possible to reduce the pollution to the levels of 1990 within this modelling period (Scenario 5, grey crosses). Realizing this level of pollution reduction would require a significant increase in CLE capacity that could be achieved through funding from new sources and an increase in human and social capital through capacity building.

In scenario 6 (brown diamonds) the total amount of support is lower (i.e. double compared to the baseline, as with scenarios 2, 3, and 4), but it is complemented by the capacity of the Water Police to implement fines. Although, in this scenario, the water quality starts to improve later compared to Scenario 5, at the end of the modelled period it is similar. The addition of fines, in this model, supports a significant rise in farmers' awareness of water quality issues, which can result in rapid changes in agricultural practices when it is coupled with sufficient support to implement measures. Interestingly, the awareness increases less in Scenario 5 than in Scenario 6, yet Scenarios 5 and 6 ultimately have the same impact on water quality. This highlights that awareness alone does not drive an increase in water quality, and both willingness and capacity must be very high to generate a shift in land use and agricultural practices.

It is important to note that in this model, a reduction in sediment concentration corresponds to a reduction in farmers' income. This highlights that economic trade-offs are necessary to secure increases in water quality, and raises the question of how farmers should be compensated for the income losses they suffer. An important policy implication of this finding (the "economic–environment trade-off") is that a sustainable natural resource management approach entails an integrated approach and targeted interventions to offset the negative economic impacts on farmers and other land users (Balana et al. 2011b). The model could be used to identify an optimal strategy that improves water quality with the lowest economic impact on farmers, in this case tree planting.

4.2 Model validity and sensitivity

In calibrating the model, the reasonable expectation has been applied that in the absence of substantial intervention, land continues to be converted to agriculture and suspended sediment concentration correspondingly continues to rise. It is critical that models such as this one, in which social aspects are captured and which therefore provide only one representation of possible reality (Oreskes et al. 1994), are tested in terms of building confidence that the modelled relationships and outcomes reflect the system dynamics occurring in reality (Forrester and Senge 1979, Swaninger and Groesser 2006). Validation in this sense is an ongoing process that not only is essential for this model's development, but also draws attention to its value as an analytical and policy development tool.

The model assumptions, the interactions between the system elements, and the parameters and their values are based on the interview data, field observations, and empirically based literature. They have been revisited often, and presented to different stakeholders who are part of the system being modelled. They have been revised and refined based on new information that has been brought into the model development process, and the modelling team is therefore satisfied that this model is representative of the system of study.

A global sensitivity analysis was conducted in R, to explore the structure and behaviour of the model and how changes in one variable impact on the other variables (Noacco et al. 2019). Three thousand combinations of the values of each parameter were sampled from a uniform distribution using Latin hypercube sampling. This revealed that the model is slightly sensitive to the parameters α_{AF}, β_{AF}, α_{AI}, and α_W. Further analyses were conducted to explore the impact of a change in these parameters on the sediment concentration, from a factor 10 lower to a factor 10 higher than those used in the scenarios. This analysis showed that changes in these parameters changed the timing and magnitude of the peak in sediment concentration, but not the dynamics of the system behaviour (see Supplementary material).
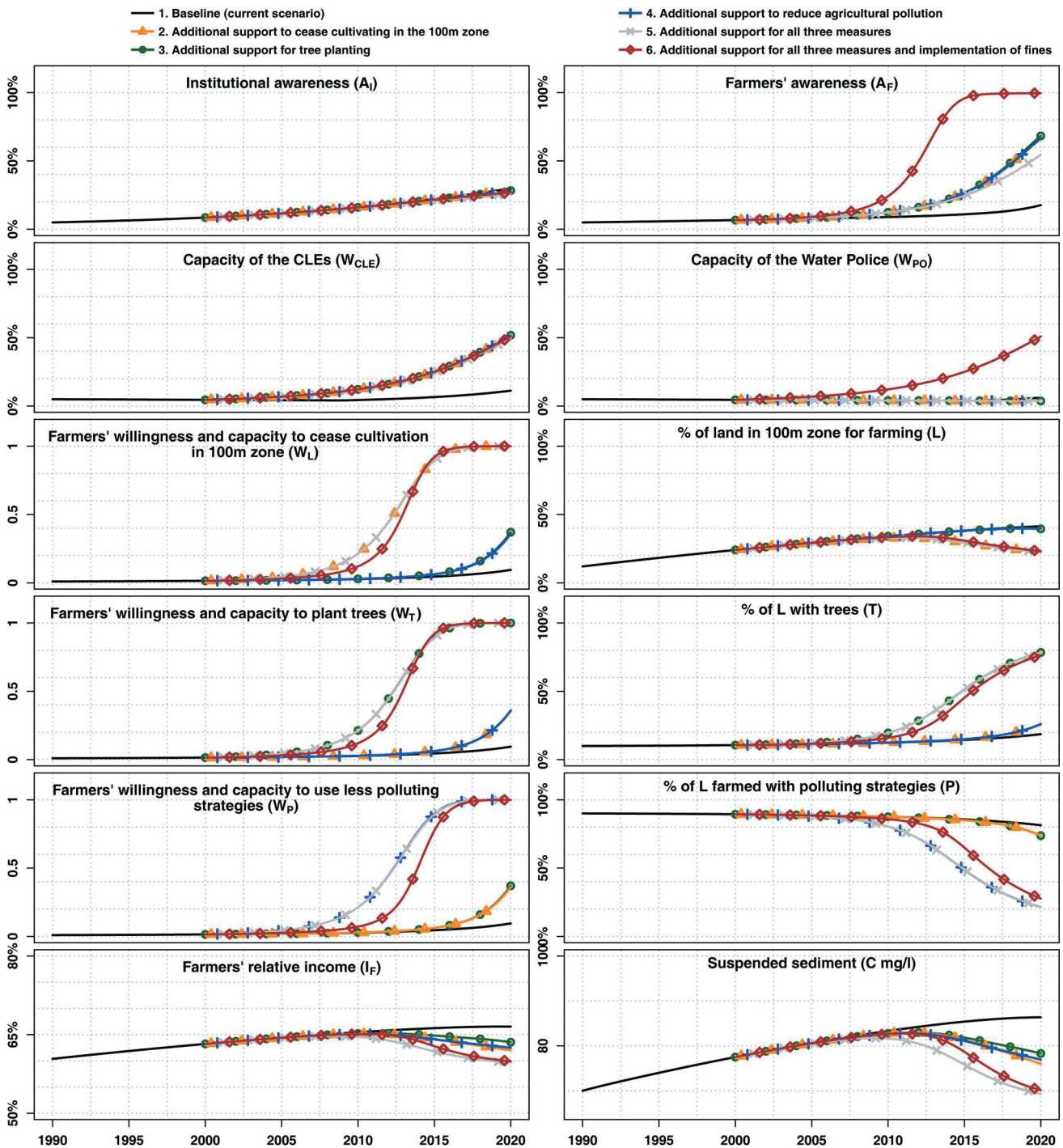
Figure 6. Modelled evolution of awareness, institutional capacity, famers' willingness and capacity to implement measures, and change in land-use and water quality in the study regions for the six scenarios.

4.3 The potential of socio-hydrological models to guide policy interventions

Through the development of this model, and the generation of scenarios, some of the possibilities that socio-hydrological models present for exploring the relationships in complex human–water systems have been illustrated. This model has brought together concepts and data from both the natural and socio-economic sciences. As such, it has integrated the theory that institutional support drives

water quality improvements through resources allocated and actions taken by the CLEs and Water Police to support farmers to manage the land.

The model enables the impacts of different policies and priorities on water quality to be compared. This is extremely useful from a policy perspective, as it can potentially lead to the identification and prioritization of strategies that, compared to others, can have the greatest impact on water quality and are feasible (socially, economically, and environmentally).

However, there remain several elements of uncertainty that highlight the need for additional research. These relate to the structure of the model, the availability of data, and the need to engage stakeholders more strongly with these models.

4.3.1 Model structure

The capacity of the model for exploring how different policy options could impact land use and water quality is highly dependent on both the plausibility of the assumptions on which the model is based and the sensitivity of the model to these assumptions. The series of assumptions are derived from surveys, interviews, observations and the existing literature, sources that have been checked in the field and with stakeholders. However, there remains potential for refining these assumptions as more information becomes available and our understandings improve on the connectivity between the institutions and the actors on the one hand and between the land and water systems on the other.

The initial sensitivity analysis we conducted shows the modelled dynamics remain constant despite changes in parameters, but there is scope to conduct a more extensive analysis of the model structure and exploration of parameter estimation (e.g. as conducted by Li and Sivapalan 2020). Key to this would be developing a much deeper understanding of what the social parameters represent in the real world and how they could be better quantified and parameterized (e.g. one aspect of this model is how to understand and capture the willingness or reluctance to adopt new ideas such as tree planting and how this interacts with the capacity to implement new ideas).

4.3.2 The model as an integrative research tool

For this socio-hydrological model, as well as many other models, one of the greatest challenges is quantifying and strongly linking the modelled relationships through targeted empirical data collection. In this way, the model offers a valuable tool that can help direct research resources towards better understanding of the modelled relationships. For example, establishing a monitoring programme for collecting data on sediment concentrations and coupling this with a time series generated from historic data would both provide input data to the model and act as a calibration resource. The possible impact of suspended sediment concentrations on institutional awareness could also be measured by undertaking surveys of relevant stakeholders (farmers, other land users, and local organizations such as CLE and Water Police) about the level of their awareness of sediment and water quality. The subsequent effects of economic incentives, e.g. allocation of funds to the CLEs and the Water Police for water quality management and other policy interventions could be measured through surveys and interviews. It would, however, need to be attributed specifically to awareness versus a range of other driving aspects, for example, support from international donors for water quality management that is not related to sediment concentrations in the rivers in Burkina Faso, as well as local and regional priorities and how they influence organizations' decision making.

Suspended sediment is a challenging indicator to use, because its relationship to water quality is related to the ecological functioning of the river rather than being set at a constant of e.g. 25 mg/L (Grove et al. 2015). Information would therefore be needed on the critical threshold of suspended sediment concentrations beyond which ecological functioning is impaired in the study catchments, along with other impacts such as flood risk, reservoir capacity reduction, and hydroelectric power production. The impact of the management strategies on sediment concentrations could also be refined.

In this paper, we have made semi-quantitative assessments on the amount of additional support (defined in broad terms) required to achieve tangible improvements in water quality. However, there are several challenges to using models such as this to make quantitative predictions or assessments into the future (Srinivasan et al. 2017). Firstly, the data on which it is based and calibrated encompasses uncertainty due to both data limitations and its lumped nature (i.e. the impact of agriculture in the 100-m zone on suspended sediment concentration is far from certain and likely varies depending on local topographic conditions). Secondly, the modelled scenarios are based on the conditions of the present, where a very small set of variables are modified at a time. The future reality will see many changes brought about simultaneously that complicate model predictions (e.g. increase in agricultural land may rise faster, crop prices may climb higher, climate change may lead to higher sediment concentrations, political stability or instability may lead to more or fewer financial resources being available). Thirdly, institutional support encompasses a wide range of aspects beyond monetary support (e.g. institutional strengthening, human and social capital). Exploring ways to describe these aspects quantitatively is therefore necessary for quantitative modelling and is worthy of further study, specifically in the context of socio-hydrology.

4.3.3 Engaging with stakeholders

As highlighted by Melsen et al. (2018), including stakeholders in the modelling process is critical for several reasons. Firstly, the relationships and assumptions can be challenged and refined. In this research stakeholders were shown several versions of the model at different stages in the research process and asked for their feedback. The suggestions received were highly constructive and led to important model changes. Describing the model pictorially and using straightforward terminology was essential for stakeholder engagement.

Secondly, the model outcomes generated are more likely to be considered realistic by stakeholders if the model accurately reflects their experiences on how the system functions. This should lead to the modelling of land and water management strategies that are both feasible and acceptable. Thirdly, the model may have potential as a tool for shaping stakeholder engagement. It may assist diverse stakeholders to explore necessary tradeoffs in the water system, and may structure creative thinking about how different, or new, strategies could be developed and implemented. For example, this model could be used as a starting point to highlight that water quality improvements come at an economic cost to farmers and that mechanisms to offset those costs need to be explored.

5 Conclusions

This research paper has demonstrated the development of an integrated socio-hydrological model that describes water quality changes as a response to changes in stakeholders' awareness level and institutional capacities. The model captures the current dynamics between institutional support for addressing water quality, the capacity of local organizations (i.e. CLEs and Water Police) to support and encourage farmers to take actions, and farmers' willingness and capacity to undertake measures that result in changes in water quality. The model enables different management approaches to be compared, and also shows that water quality could be improved if institutional support and public resource allocation for water management is raised, and the capacity of local-level organizations is substantially increased compared to current levels.

The modelled scenarios could be considered policy experiments, which demonstrate how changes in policy and planning may affect farmer decision making, actions, and subsequently the water quality. This suggests socio-hydrological models that incorporate the feedbacks between different actors, organizations, and institutions could have potential value for water managers, stakeholders, and water users who wish to explore how the water system may respond to policy changes and resource inputs, or those who wish to identify where and how much additional support or resources are needed to achieve a vision of water quality and river basin health.

In addition to their potential management implications, socio-hydrological models such as the one described in this research paper also support the research process and aid understanding of complex, interdisciplinary systems. Such models support researchers to identify where additional multidisciplinary data is needed to better understand the integrative relationships on which the model is built. As such, they can be used as a springboard to drive data collection and system understanding. Stakeholders' views must also be sufficiently well integrated into the modelling process to ensure that they are active players in the development of a consensus on how the relationships are described and assumptions assigned. This requires attention to communication, developing user-friendly modelling interfaces and user accessibility. If this can be achieved, the resulting model should be able to identify policies, plans, or strategies that, because they have been developed by stakeholders and researchers working together, have high potential for improving resource management.

Notes

1. The law is the basis for the establishment of CLE and Water Police – Loi n° 002–2001/AN portant loi d'orientation relative à la gestion de l'eau au Burkina Faso. (J.O, 7 juin 2001, p. 964).

References

Akrasi, S.A. and Ayibotele, N.B., 1984. An appraisal of sediment transport measurements in Ghanaian rivers. *In*: D.E. Walling, S.S. B. Foster, and P. Wurze, eds. *Challenges in African hydrology and water resources, Proceedings of the Haare symposium*, July 1984 Harare, Zimbabwe. IAHS Publ. No. 144, 301–321. Available from: http://hydrologie.org/redbooks/a144/iahs_144_0301.pdf

Balana, B.B., Debevec, L., and Somda-Kabore, L., 2019. *Technical brief: degradation of water resources in rural Burkina Faso: drivers, local perceptions and solutions*. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE), 8.

Balana, B.B., Vinten, A., and Slee, B., 2011a. A review on cost-effectiveness analysis of agri-environmental measures related to the EU WFD: key issues, methods, and applications. *Ecological Economics*, 70 (6), 1021–1031. doi:10.1016/j.ecolecon.2010.12.020

Balana, B.B., Yatich, T., and Mäkelä, M., 2011b. A conjoint analysis of landholder preferences for reward-based land-management contracts in Kapingazi watershed, Eastern Mount Kenya. *Journal of Environmental Management*, 92 (10), 2634–2646. doi:10.1016/j.jenvman.2011.06.001

Barendrecht, M.H., *et al*., 2019. The value of empirical data for estimating the parameters of a sociohydrological flood risk model. *Water Resources Research*, 55 (2), 1312–1336. doi:10.1029/2018WR024128

Barendrecht, M.H., Viglione, A., and Bloeschl, G., 2017. A dynamic framework for flood risk. *Water Security*, 1, 3–11. doi:10.1016/j.wasec.2017.02.001

Beusen, A.H.W., *et al*., 2005. Estimation of global river transport of sediments and associated particulate C, N, and P. *Global Biogeochemical Cycles*, 19 (4), GB4S05. doi:10.1029/2005GB002453

Blair, P. and Buytaert, W., 2016. Socio-hydrological modelling: a review asking "why, what and how?." *Hydrology and Earth System Sciences*, 20, 443–478. doi:10.5194/hess-20-443-2016

Chen, X., *et al*., 2016. From channelization to restoration: sociohydrologic modeling with changing community preferences in the Kissimmee River Basin, Florida. *Water Resources Research*, 52 (2), 1227–1244. doi:10.1002/2015WR018194

Di Baldassarre, G., *et al*., 2013. Socio-hydrology: conceptualising human-flood interactions. *Hydrology and Earth System Sciences*, 17 (8), 3295–3303. doi:10.5194/hess-17-3295-2013

Di Baldassarre, G., *et al*., 2019. Sociohydrology: scientific challenges in addressing the sustainable development goals. *Water Resources Research*, 55 (8), 6327–6355. doi:10.1029/2018WR023901

Elshafei, Y., *et al.*, 2014. A prototype framework for models of socio-hydrology: identification of key feedback loops and parameterisation approach. *Hydrology and Earth System Sciences*, 18 (6), 2141–2166. doi:10.5194/hess-18-2141-2014

European Commission, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal L 327, 22/12/2000 P. 0001-0073. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060

FAO, 2020. *Land and water database*. Cabbage. Available from: http://www.fao.org/land-water/databases-and-software/crop-information/cabbage/en/

Forrester, J.W., 1993. System dynamics and the lessons of 35 years. *In*, and K.B. De Greene, ed. *A systems-based approach to policymaking*. Boston, MA: Springer, 199–240. doi:10.1007/978-1-4615-3226-2_7

Forrester, J.W. and Senge, P.M., 1979. *Tests for building confidence in system dynamics models*. Cambridge, MA: Massachusetts Institute of Technology.

Griesbach, J., 2003. *Mango growing in Kenya*. Nairobi, Kenya: World Agroforestry Centre (ICRAF).

Grove, M.K., *et al.*, 2015. Suspended sediment regimes in contrasting reference-condition freshwater ecosystems: implications for water quality guidelines and management. *Science of the Total Environment*, 502, 481–492. doi:10.1016/j.scitotenv.2014.09.054

Han, S., *et al.*, 2017. Socio-hydrological perspectives of the co-evolution of humans and groundwater in Cangzhou, North China Plain. *Hydrology and Earth System Sciences*, 21, 3619–3633. doi:10.5194/hess-21-3619-2017

Hoffmann, R. and Muttarak, R., 2020. Greening through schooling: understanding the link between education and pro-environmental behavior in the Philippines. *Environmental Research Letters*, 15 (1), 014009. doi:10.1088/1748-9326/ab5ea0

Kandasamy, J., *et al.*, 2014. Socio-hydrologic drivers of the pendulum swing between agriculture development and environmental health: a case study from Murrumbidgee River Basin, Australia. *Hydrology and Earth System Sciences*, 18 (3), 1027–1041. doi:10.5194/hess-18-1027-2014

Koudougou, V., 2018. *La Police de l'Eau : instrument innovant de protection des ressources en eau au Burkina Faso. Cas de la Région des Hauts-Bassins*. MA Thesis. AGRINOVIA MA Programme. Université de Ouagadougou, 91p.

Koudougou, V., Oumarou, A., and Debevec, L., 2019. *Technical Brief: la Police de l'Eau, instrument de la GIRE au Burkina Faso: réalisations et limites. Colombo, Sri Lanka: international Water Management Institute (IWMI)*. Colombo, Sri Lanka: CGIAR Research Program on Water, Land and Ecosystems (WLE), 8.

Li, B. and Sivapalan, M., 2020. Long-term coevolution of an urban human-water system under climate change: critical role of human adaptive actions. *Water Resources Research*, 56 (11), e2020WR027931. doi:10.1029/2020WR027931

Liu, D., *et al.*, 2015. A conceptual sociohydrological model of the co-evolution of humans and water: case study of the Tarim River basin, western China. *Hydrology and Earth System Sciences*, 19 (2), 1035–1054. doi:10.5194/hess-19-1035-2015

Melsen, L.A., Vos, J., and Boelens, R., 2018. What is the role of the model in socio-hydrology? Discussion of "Prediction in a socio-hydrological world." *Hydrological Sciences Journal*, 63 (9), 1435–1443. doi:10.1080/02626667.2018.1499025

Mills, J., *et al.*, 2017. Engaging farmers in environmental management through a better understanding of behaviour. *Agriculture and Human Values*, 34 (2), 283–299. doi:10.1007/s10460-016-9705-4

Mostert, E., 2018. An alternative approach for socio-hydrology: case study research. *Hydrology and Earth System Sciences*, 22 (1), 317–329. doi:10.5194/hess-22-317-2018

Myers, D.N., Metzker, K.D., and Davis, S., 2000. Status and trends in suspended-sediment discharges, soil erosion, and conservation tillage in the Maumee River Basin–Ohio, Michigan, and Indiana: U.S. Geological Survey Water-Resources Investigations Report 2000–4091, 45p. doi: 10.3133/wri004091

Noacco, V., *et al.*, 2019. Matlab/R workflows to assess critical choices in Global Sensitivity Analysis using the SAFE toolbox. *MethodsX*, 6, 2258–2280. doi:10.1016/j.mex.2019.09.033

Okumah, M., Martin-Ortega, J., and Novo, P., 2018. Effects of awareness on farmers' compliance with diffuse pollution mitigation measures: a conditional process modelling. *Land Use Policy*, 76, 36–45. doi:10.1016/j.landusepol.2018.04.051

Op de Hipt, F., *et al.*, 2019. Modeling the effect of land use and climate change on water resources and soil erosion in a tropical West African catchment (Dano, Burkina Faso) using SHETRAN. *Science of the Total Environment*, 653, 431–445. doi:10.1016/j.scitotenv.2018.10.351

Oreskes, N., Shrader-Frechette, K., and Belitz, K. 1994. Verification, validation, and confirmation of numerical models in the Earth Sciences. *Science (New York, N.Y.)*, 263, 641–646. doi:10.1126/science.263.5147.641

Osborne, L.L. and Kovacic, D.A., 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. *Freshwater Biology*, 29 (2), 243–258. doi:10.1111/j.1365-2427.1993.tb00761.x

Pande, S. and Sivapalan, M., 2017. Progress in socio-hydrology: a meta-analysis of challenges and opportunities. *WIREs Water*, 4 (4), e1193. doi:10.1002/wat2.1193

R Core Team, 2019. *R: a language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Available from: https://www.R-project.org/

Renwick, W.H., *et al.*, 2018. Stream nitrogen, phosphorus, and sediment concentrations show contrasting long-term trends associated with agricultural change. *Journal of Environmental Quality*, 47 (6), 1513–1521. doi:10.2134/jeq2018.04.0162

Ridolfi, E., Albrecht, F., and Di Baldassarre, G., 2020. Exploring the role of risk perception in influencing flood losses over time. *Hydrological Sciences Journal*, 65 (1), 12–20. doi:10.1080/02626667.2019.1677907

Roncoli, C., *et al.*, 2009. From management to negotiation: technical and institutional innovations for integrated water resource management in the upper Comoé River Basin, Burkina Faso. *Environmental Management*, 44 (4), 695–711. doi:10.1007/s00267-009-9349-x

Sivapalan, M., Savenije, H.H.G., and Blöschl, G., 2012. Socio-hydrology: a new science of people and water. *Hydrological Processes*, 26 (8), 1270–1276. doi:10.1002/hyp.8426

Somda, L., Garane, A., and Debevec, L., 2019. *Les CLE, institutions locales pertinentes mais peu fonctionnelles de gestion de l'eau*. Colombo, Sri Lanka: CGIAR Research Program on Water, Land and Ecosystems (WLE), 8p. Available from: https://hdl.handle.net/10568/107050

Srinivasan, V., *et al.*, 2017. Prediction in a socio-hydrological world. *Hydrological Sciences Journal*, 62 (3), 338–345. doi:10.1080/02626667.2016.1253844

Šturm, M., *et al.*, 2010. Effect of different fertilisation and irrigation practices on yield, nitrogen uptake and fertiliser use efficiency of white cabbage (Brassica oleracea var. capitata L.). *Scientia Horticulturae*, 125 (2), 103–109. doi:10.1016/j.scienta.2010.03.017

Swaninger, M. and Groesser, S., 2006. Systems dynamics modelling: validation for quality assurance. *In*, and R. A. Meyers, ed. *Encyclopaedia of complexity and systems science series*. Vol. 9. New York, NY: Springer, 9000–9014.

Tiessen, K.H.D., *et al.*, 2010. Conventional and conservation tillage: influence on seasonal runoff, sediment, and nutrient losses in the Canadian prairies. *Journal of Environmental Quality*, 39 (3), 964–980. doi:10.2134/jeq2009.0219

Torou, B.M., Debevec, L., and Da, D.E.C., 2018. La difficile territorialisation de la gestion de l'eau au Burkina Faso: une lecture au filtre de la théorie de la proximité. *Développement Durable Et Territoires*, Online Journal, 9, 1. Available from: http://journals.openedition.org/developpementdurable/12046

Troy, T.J., Pavao-Zuckerman, M., and Evans, T.P., 2015. Debates Perspectives on socio-hydrology: socio-hydrologic modeling: tradeoffs, hypothesis testing, and validation. *Water Resources Research*, 51 (6), 4806–4814. doi:10.1002/2015WR017046

Venot, J.P., Torou, B.M., and Daré, W., 2014. Territorialisation ou spatialisation: les agences et comités locaux de l'eau au Burkina Faso. *L'Espace Géographique, 2014/2 Tome*, 43, 148–163. doi:10.3917/eg.432.0148

Viglione, A., *et al.*, 2014. Insights from socio-hydrology modelling on dealing with flood risk – Roles of collective memory, risk-taking attitude and trust. *Journal of Hydrology*, 518(A), 71–82. doi:10.1016/j.jhydrol.2014.01.018

Vörösmarty, C.J., Meybeck, M., and Pastore, C.L., 2015. Impair-then repair: a brief history and global-scale hypothesis regarding human-water interactions in the anthropocene. *Dædalus*, 144, 94–109. doi:10.1162/DAED_a_00345

Walker, W.E., Loucks, D.P., and Carr, G., 2015. Social responses to water management decisions. *Environmental Processes*, 2 (3), 485–509. doi:10.1007/s40710-015-0083-5

Yu, D.J., *et al.*, 2017. Incorporating institutions and collective action into a sociohydrological model of flood resilience. *Water Resources Research*, 53 (2), 1336–1353. doi:10.1002/2016WR019746

Yu, D.J., *et al.*, 2020. Socio-hydrology: an interplay of design and self-organization in a multilevel world. *Ecology and Society*, 25 (4), 22. doi:10.5751/ES-11887-250422

Zikeli, S. and Gruber, S., 2017. Reduced tillage and no-till in organic farming systems, Germany—status quo, potentials and challenges. *Agriculture*, 7 (4), 35. doi:10.3390/agriculture7040035

Appendix

Coding scheme for interview data

Farmers

Farmers – awareness of pollution
    Farmers – not reducing agricultural area but can reduce pollutants, e.g. insecticides
    Farmers – have awareness that actions cause pollution but alternative strategies and funds needed
    Farmers – have awareness that actions cause pollution but don't care
    Farmers – costs of switching to mango trees
    Farmers – willing to change practices but need support/compensation
    Farmers – willing to move away from 100-m zone but need to be given means to make livelihood
    Farmers – willing to move but need compensation
    Farmers – make water points away from river for animals
    Farmers – exploit projects
    Farmers – a politically influential group

Policy

Policy – Regulations to stop water pollution
    Policy – regulations only work if farmers are also given support to farm outside 100-m zone

    Policy – need to provide alternative strategies/financial support/compensation to agriculture in 100-m zone
    Policy – awareness raising will lead to solutions for compensation being found
    Policy – awareness raising
    Policy – awareness raising about boundary of 100-m zone (putting up markers)
    Policy – awareness raising not effective
    Policy – enforcement of regulations
    Policy – de-siltation
    Policy – collecting used agricultural chemical containers
    Policy – compensation
    Policy – support for agroforestry

Institutions

Institutions – support for reducing water pollution
    Institutions – not enforcing laws
    Institutions – conflicting priorities between ministry of water and ministry of agriculture
    Institutions – water and agriculture sectors need good communication between them
    Institutions – management committee important for awareness raising
    Institutions – need financial support

Water quality

Pollution increasing
    Pollution – drinking water
    Pollution – from car washing
    Pollution – from human actions
    Pollution – from industry
    Pollution – fish contaminated
    Pollution – no fish
    Pollution – from fishing
    Pollution – from rubbish
    Pollution – from agriculture
    Pollution – invisible
    Siltation
    Siltation and water shortage
    Siltation from animals
    Flooding
    Groundwater reduction
    Water scarcity
    Water scarcity – no fish