People and water: understanding integrated systems needs integrated approaches

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ABSTRACT

As we rapidly modify the environment around us, researchers have a critical role to play in raising our understanding of the interactions between people and the world in which they live. Knowledge and understanding of these interactions are essential for evidence based decision-making on resource use and risk management. In this paper, we explore three research case studies that illustrate co-evolution between people and water systems. In each case study, we highlight how different knowledge and understanding, stemming from different disciplines, can be integrated by complementing narratives with a quantitative modelling approach. We identify several important research practices that must be taken into account when modelling people-water systems: transparency, grounding the model in sound theory, supporting it with the most robust data possible, communicating uncertainty, recognising that there is no 'one true model' and diversity in the modelling team. To support interdisciplinary research endeavours, we propose a three-point plan: (1) demonstrating and emphasising that interdisciplinary collaboration can both address existing research questions and identify new, previously unknown questions at the interface between the disciplines; (2) supporting individual interdisciplinary learning at all career stages and (3) developing group practices and a culture of interdisciplinary collaboration.

Key words | interdisciplinary, socio-hydrology, water management

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HIGHLIGHTS

- Water systems involve water and people interacting together.
- We can model the dynamics between water and people, and this is a rapidly evolving research area with high potential.
- Several crucial research practices to support people-water model building are identified.
- Collaboration across different research fields, particularly between the social and natural sciences is vital.
- We propose a three-point plan to enhance interdisciplinary research collaborations.

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INTRODUCTION

There are few pristine environments remaining on Earth and we are considered to be living in the Anthropocene Epoch – where human activity has a notable impact on the global environment (Crutzen 2002; Lewis & Maslin 2015). This is particularly apparent in our water resources, where most rivers, lakes and groundwater aquifers have experienced changes in their quality or quantity due to humans (Wada *et al.* 2016; Strokal *et al.* 2019). As we rapidly modify the environment around us, researchers have a critical role to play in raising our understanding of the interactions between people and the world in which they live. Knowledge and understanding of these interactions are essential for evidence based decision-making on resource use and risk management.

Overarching research questions, on how people modify their environments, and how their environments modify them, present challenging, yet highly exciting topics of research. They are challenging because they require knowledge, understanding and synthesis from a great many different and traditionally separate scientific, engineering, social science and humanities research fields. Bringing together the diversity of knowledge, understandings, methodologies, priorities and world views spread between different individuals, institutions and departments, is typically perceived to be difficult (Carr *et al.* 2018). However, if the challenges can be overcome, research at the interface of different research fields holds many exciting opportunities for generating new knowledge and understanding (Blöschl 2006; Blöschl *et al.* 2012), particularly on how people and water interact with one another (Di Baldassarre *et al.* 2016).

In this paper, we explore the intense interactions, or co-evolution, between people and water systems. We first show how the concept of co-evolution has evolved in the water sciences. Then, using three case studies, we highlight how different knowledge and understanding, stemming from different fields of specialisation, can be integrated by complementing narratives with a quantitative modelling approach. We emphasise the exciting research opportunities and huge potential for a new understanding of people-water systems presented by collaborative and integrative research between natural and social scientists. We draw attention to several important research practices for such endeavours. Finally, we share a three-point plan for supporting interdisciplinary collaborative research that we hope will support diverse water professionals from engineering, natural sciences and social sciences to engage with each other with success.

WATER SYSTEMS INVOLVE PEOPLE AND WATER, INTERACTING TOGETHER

The dominant paradigm from the mid-19th century, up until around 1980, was of water as a resource, disconnected from its social, historical and even local conditions. Water management involved structural engineering for economic gains with little regard for the potential impacts of interventions on the environment and society (Linton 2014). This 'hydraulic paradigm' is supported by the classic conceptualisation of the water cycle, whereby water moves via precipitation, runoff and evaporation and the role played by ecology and human society are ignored (Linton 2014).

However, by 1980, clear failures in the approach had become apparent, as experiences of reservoirs running dry, flood reduction infrastructure being overtopped and water pollution rendering resources unsafe showed how the management approaches designed to buffer out the natural variability and unpredictability inherent in 'natural' water systems were actually introducing new risks and jeopardising economic growth and development. A re-evaluation followed that led to a move towards integrated water resources management (IWRM) and culminated in its formalisation through the Dublin Statement on Water for Sustainable Development in 1992 (WMO 1992; Benson *et al.* 2015). IWRM is now a widely accepted approach that emphasises that social, economic and environmental aspects of water resources should be acknowledged and addressed simultaneously in order to reach management decisions that are well balanced and equitable (Savenije *et al.* 2014).

People and ecosystems are now firmly embedded within (many) researchers' conceptualisations of water systems.

Many new approaches and ways of thinking that combine them have been developed in recent years. For example, in the nexus approach, water, food and energy are considered simultaneously, with the aim of promoting resource security and reducing mismatches in policymaking (e.g. policy that supports agricultural development, or bio-fuel crops at the cost of sustainable use of available water resources) (Benson *et al.* 2015; Figure 1).

In the hydrosocial cycle, proposed by Linton & Budds (2014), people, power, technology and water are all part of a single entity that is a product of itself (Figure 2). So while other approaches consider people as effecting water, or water effecting people, this approach internalises the

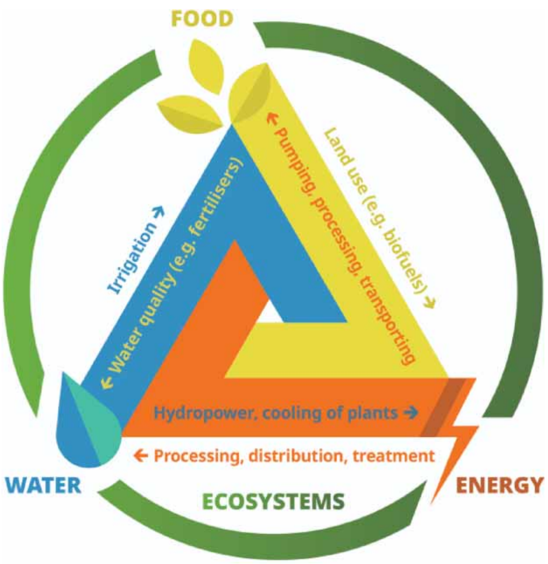

Figure 1 | The nexus approach (from Global Water Partnership (2019)).

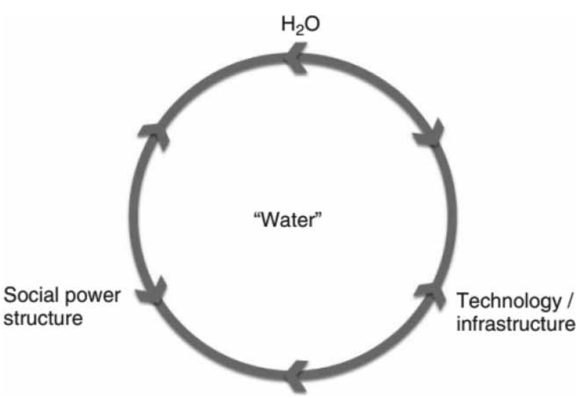

Figure 2 | The hydrosocial cycle (from Linton & Budds (2014)).

processes, meaning that 'water', as we perceive and experience it (e.g. how available it is, how clean it is, where it does and does not flow), is a product of the diverse and changing meanings, ideas, discourses and representations attached to it, at a given moment in time.

The hydrosocial cycle concept is important because it emphasises that 'water' itself is a product of everything it involves. In a similar way, numerous studies have observed that people and water continually feedback on one another resulting in an identifiable system behaviour or trajectory, a process referred to as co-evolution (Norgaard 1994; Sivapalan *et al.* 2012; Savenije *et al.* 2014; Sivapalan & Blöeschl 2015). Kallis (2010) illustrates people-water co-evolution for urban water supply in Athens, Greece, over the last 180 years. He shows how 'water supply and demand in fact coevolve, new supply generating higher demands, and in turn, higher demands favouring supply expansion over other alternatives'. Di Baldassarre *et al.* (2015) argue that co-evolution provides a new paradigm for generating future scenarios of risk because, while the traditional approach involves combining the probability of a flood with the likely damage at different time points, the co-evolution approach internalises, within the model, how a flood would change society itself (e.g. building flood defences) and how this would lead onto different impacts of subsequent floods (Figure 3).

A different co-evolutionary path has been documented for the Murray Darling Basin, Australia, by Wei *et al.* (2017). Here, a shift in societal value of water as being for economic development (1900–1962) to environmental sustainability (from 1963) is documented through newspaper analysis, policy analysis, environmental flow allocations and engineering projects. The shift is attributed to societal response to water pollution and rising environmental awareness. This feedback has been termed the 'pendulum swing' (Kandasamy *et al.* 2014; Liu *et al.* 2015; Mostert 2018; Di Baldassarre *et al.* 2019) or the 'impair then repair' mentality (Vörösmarty *et al.* 2015).

The advantage of conceptualising people and water systems as co-evolving is that it enables systematic analysis of the interplay between the different environmental and social processes that are occurring and interacting at different timescales, and so enables more informed projections into the future (Sivapalan & Blöschl 2015; Wei *et al.* 2017;

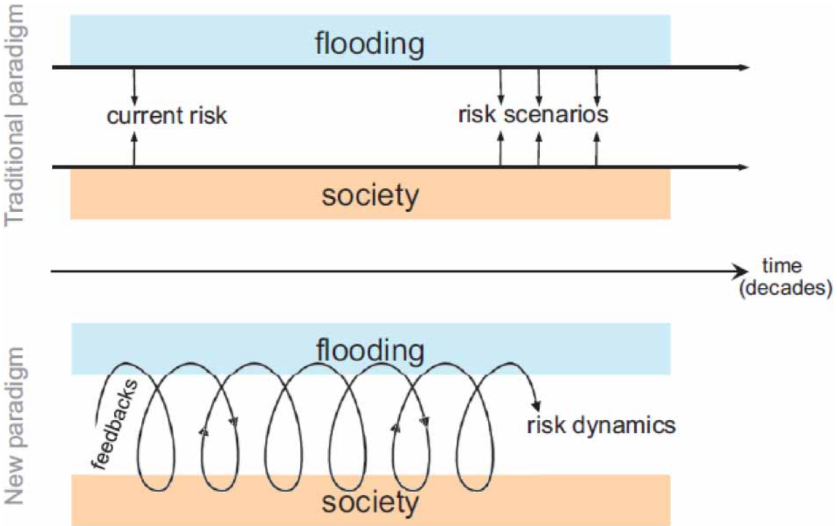

Figure 3 | Scenarios of future water resource systems, the traditional approach versus the co-evolution approach (from Di Baldassarre *et al.* (2015)).

Ward *et al.* 2019). For example, fast human processes such as water abstraction and evaporation via irrigation may lead to slow catchment changes, such as a reduction in biodiversity as river levels fall. Tipping points in the system from which recovery may become impossible can be encountered as the processes interact. By analysing these systems quantitatively, it is possible to explore them through modelling and to identify actual or potential tipping points. Additionally, the external drivers of the system (e.g. rainfall) can be changed through time to generate time series of different trajectories that may result from a change (e.g. in rainfall). The researcher can then explore why the model produces the scenarios that it does – potentially revealing unexpected and perhaps previously unknown phenomena to be explored in more detail (Troy *et al.* 2015; Blair & Buytaert 2016; Di Baldassarre *et al.* 2016; 2019). Such knowledge and understanding are essential to anticipate how the system may develop in the future, over a timescale of decades (the speed at which the slow processes change) rather than days and months.

PEOPLE AND WATER INTERACTIONS: FROM NARRATIVES TO MODELS

Three case studies are presented here to illustrate firstly, how a narrative approach can identify co-evolution in action (water reuse in Jordan). Secondly, how a narrative approach can then be developed into a quantitative, socio-hydrological model of system interactions and evolutions (water quality in South West Burkina Faso). Thirdly, how historical data can be used to inform a quantitative socio-hydrological model and explore how a people-water system may have evolved and may respond in the future (flood risk management in Dresden). The case studies draw attention to several important research practices that should be taken into account when modelling people-water systems.

Water reuse in Jordan

Domestic and industrial wastewater collection and treatment is a critical public health and environmental protection strategy. In the Middle East, and many other arid areas, treated wastewater is increasingly being acknowledged as a valuable water resource. In Jordan, 95% of treated water is reused, mainly for irrigated agriculture, through an effective system of direct reuse (surrounding wastewater treatment plants), and indirect reuse via natural waterways.

Drinking water for Amman, the capital city, and its surrounding areas, with a population of 2.2 million inhabitants, is sourced via a canal from Lake Tiberias (Sea of Galilee) in Israel, and more recently from a non-renewable deep aquifer (Disi aquifer) that is piped from the south of the country (Figure 4). Wastewater is then transferred from the city to

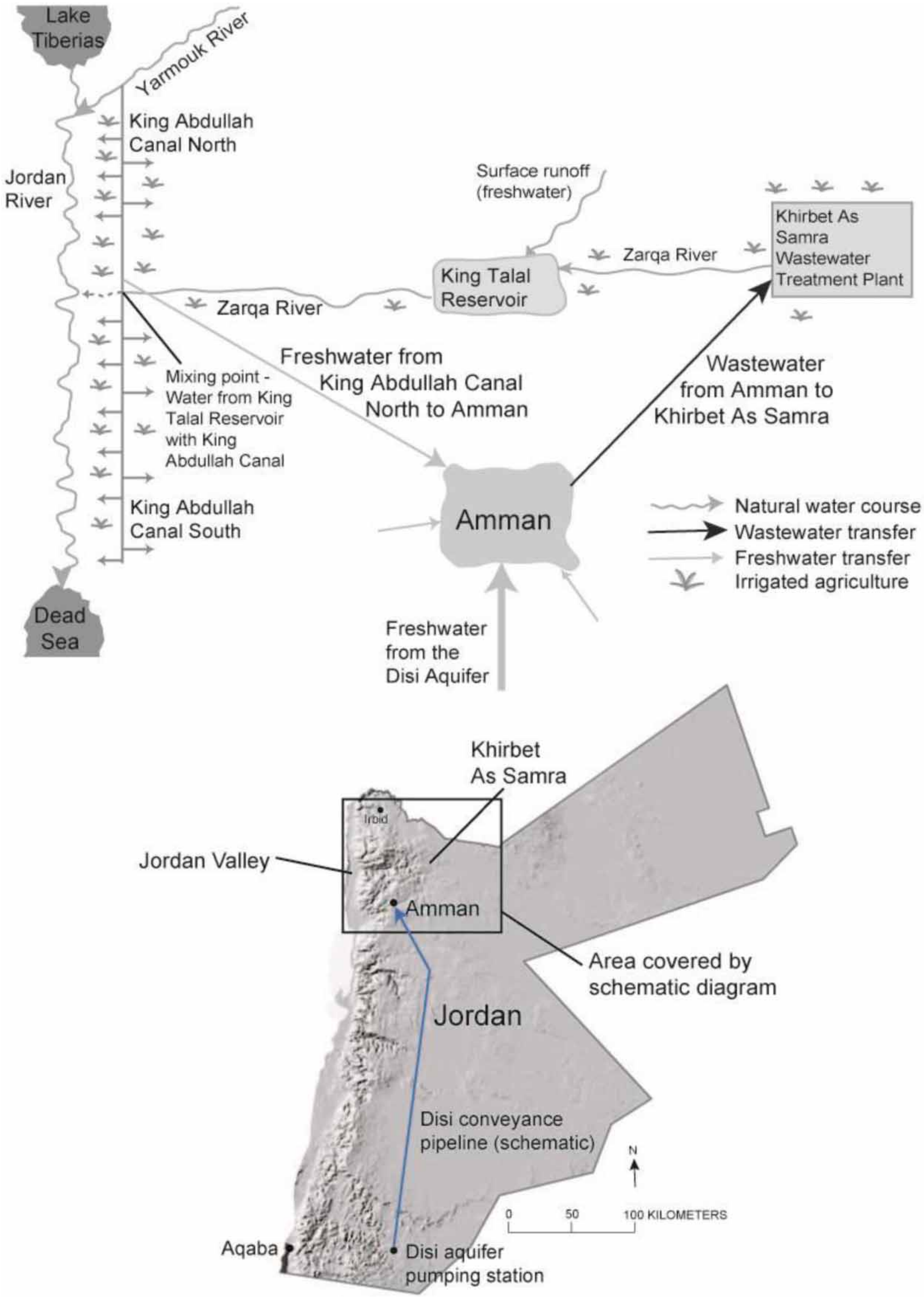

Figure 4 | Water movement in Jordan (based on Carr *et al.* (2011)).

Khirbet As Samra Wastewater Treatment plan (https://www.water-technology.net/projects/as-samra-wastewater-treatment-plant-jordan/, May 2020). After the treatment process, this water is released into the Zarqa River, where it flows 42 km to the King Talal reservoir before it is gradually released, to flow a further 23 km to the Jordan Valley. In the Jordan Valley, it is used for the irrigation of high-value fruit and vegetable crops (Shatanawi & Fayyad 1996; Carr et al. 2011; Mustafa et al. 2016).

The volumes of water in the system have increased over the last decades, driven by an increase in Amman's population (affected by refugees from neighbouring Iraq and Syria), and development of new (non-renewable) resources (the Disi Conveyance) to meet the growing demand. This is coupled with the prioritisation (and funding) of wastewater collection and treatment for public health reasons, along with a demand for water in the Jordan Valley for high-value agriculture. The water treatment capacity at the Khirbet As Samra wastewater treatment plant continues to be enlarged and upgraded to cope with the increasing volumes of water entering Amman, and to produce higher-quality treated wastewater suitable for release into the environment and subsequent use in agriculture.

Recent years have seen a shift to high investment (and high water demanding) date palm cultivation in the Jordan Valley (Jordan Times 2016; Figure 5). While this may be linked to market limits to vegetable cultivation due to ongoing instability in the region (Mustafa et al. 2016), it could also be a direct response to the growth in the urban population and the subsequent increase in steady, reliable water reaching the Jordan Valley – co-evolution in action.

Figure 5 | Date palms in Jordan (from http://jodates.org/).

This observable co-evolution between urban grown, water supply, wastewater treatment, reuse and agriculture is interesting. However, in order to anticipate future risks and challenges, we need to think about how this system might continue to evolve. The establishment of high water demanding crops increases water demand, perhaps beyond that which can be met by the future water availability. Date palm is also sensitive to soil salinity (Tripler et al. 2011), meaning that water quality is equally important for their cultivation as water availability. Importantly, sodium chloride and boron are introduced into wastewater via domestic cleaning products and washing powders and are not removed through the biological wastewater treatment process. The long-term strategy for urban water supply is also an open question, with expensive mega-projects such as the Red-Sea Dead-Sea desalination scheme being planned.

If we were to develop a numerical model to describe the relationships we have identified, and we brought together sufficient data on the volumes of water available, the volumes being used, and the crop yields, we could start to test, analytically, our hypothesis that an increase in date palms are due to an increase in available irrigation water. We could explore the role of farmers' decision-making processes as a response to water availability on crop choices (see Kuil et al. 2018). Furthermore, if we knew the quality of the water and the impact on soil salinity, we could estimate the long-term fertility of date palm cultivation in this setting. Beyond this, if we could estimate parameters for an increase (or decrease) in urban water demand, parameters for wastewater treatment, and parameters for changes in wastewater quality (e.g. due to different treatment technologies or policies to reduce boron in washing powder), we could then develop trajectories for possible agricultural futures in the Jordan Valley.

We could add in a parameter for the societal value of reclaimed water that is activated in the model when a certain level of urban water stress is experienced, and we could explore what might happen to the system if the urban population chose to retain their reclaimed water for their own purposes (such as domestic use or urban landscaping). We could explore where the tipping points might be. Such as when the soil structure may break down and become less productive due to salinity, or at which point water shortage leads to the abandonment of date palm plantations. We may even be able to speculate on possible socio-economic implications and policies that might result (such as water transfers from low-value agriculture to high-value agriculture) to offset some of the water shortage experienced by high investment agriculture.

We could explore the risk and vulnerability in the system. For example, the system may seem robust because urban water demand remains constant, but if for any reason, the supply of urban water is reduced (such as through power shortage for pumping or damage to the conveyance pipeline (Jordan Times 2020a, 2020b)), the economic damage to farmers due to water shortage would be very large. If we are able to develop a calibrated model, it would even be possible to put numbers on these gains and potential losses caused by an unlikely but possible event. We could 'map future possibility spaces' or multiple trajectories of how the system may evolve in the future, that could inform governments and individuals on the vulnerability of their systems (Sivapalan & Blöschl 2015).

Water quality management in South West Burkina Faso

In South West Burkina Faso, the rivers, reservoirs and riparian areas are intensively used for fishing, rainfed and irrigated agriculture, drinking water and domestic uses, for watering livestock and for recreation. Cultivation of riparian areas close to the water bodies, intensive application of agrochemicals (pesticides and fertilizers), uncontrolled cattle grazing and lack of designated watering points for animal drinking, and commercial and traditional gold mining activities have been identified as the major causes of pollution, soil erosion and subsequent sediment transfer to water bodies (Balana *et al.* 2019). This directly impacts on the health of the ecosystem and the health of the people dependent on the water. To reduce pollution and sediment transfer from the riparian zone to the rivers and reservoirs, a 100-m-wide riparian buffer zone in which cultivation is forbidden has been established along all waterways. There are also attempts in some catchments to encourage farmers to replace the crops grown in the 100 m zone from those requiring much soil disturbance, such as vegetables, with those that stabilize soil and sediment such as tree crops, and to reduce pollution from fertiliser and pesticide use.

Strategies to encourage farmers to take measures include support to cease cultivation in the riparian zone, plant trees or reduce pollution; fines for cultivating in the riparian zone; and awareness raising on the links between agriculture and water quality. To explore how organisations, farmers and the water system are driving and responding to these strategies, a conceptual model was developed based on interviews with stakeholders and field observations (Figure 6). The basic conceptualisation of the model is based on 'pendulum swing' or 'impair then repair' theory, in that as water quality decreases, people become more aware of water problems and are more willing to take action to address them. Farmer willingness to take action results from institutional support that either incentivises them or punishes them (see Carr *et al.* 2019 for a description of the model). A series of differential equations was developed to describe the relationships between the variables. Constants derived from the literature were used to define how the variables interact with one another, e.g. ceasing agriculture in the 100 m zone was estimated to reduce pollution by 75%. For simplicity, a constant river flow rate was used as input data. Parameters were estimated using observational and interview data (e.g. influence of actual water quality on organisation and farmers awareness to quality problems, decline in awareness through time, and amount of support provided to farmers to take action). Model simulations of water quality response through time with support for different management strategies are generated (Figure 7).

This model is an initial attempt to capture the dynamics between actual water quality and farmers' willingness and capacity to take action to improve water quality. The trajectories shown in Figure 7 indicate that, based on this model run, support for ceasing cultivation in the 100 m zone is most effective at reducing pollution, while support for tree planting is least effective. The addition of fines appears to have only a sight impact on the system. This exercise indicates the potential that such models may have for exploring policy options and supporting decision-making. However, it is important to communicate the uncertainty in the estimates and relationships included in the model.

The model is a highly simplified version of a complex socio-hydrological system, and it may not be capturing all the most important hydrological and social processes. For example, its lumped nature, means that it does not capture the varying relationships and power differences between the individuals and organizations, spatially and

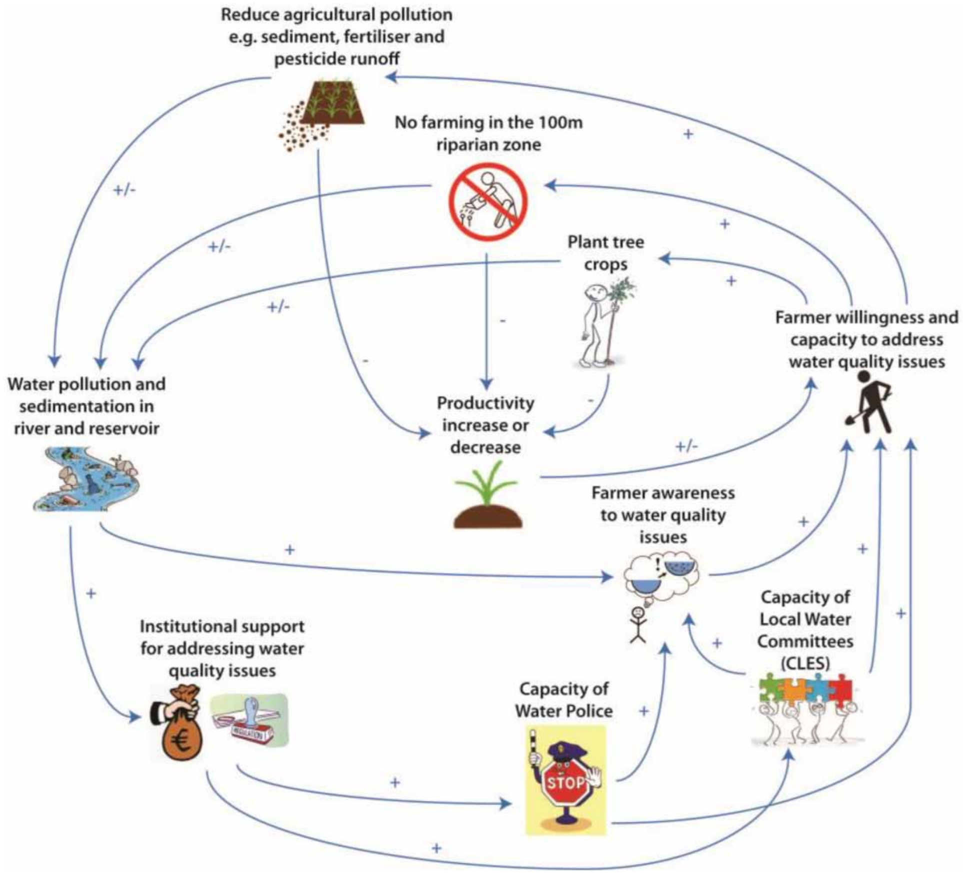

Figure 6 | Conceptual model of co-evolution of water quality, based on interviews and observations in Burkina Faso.

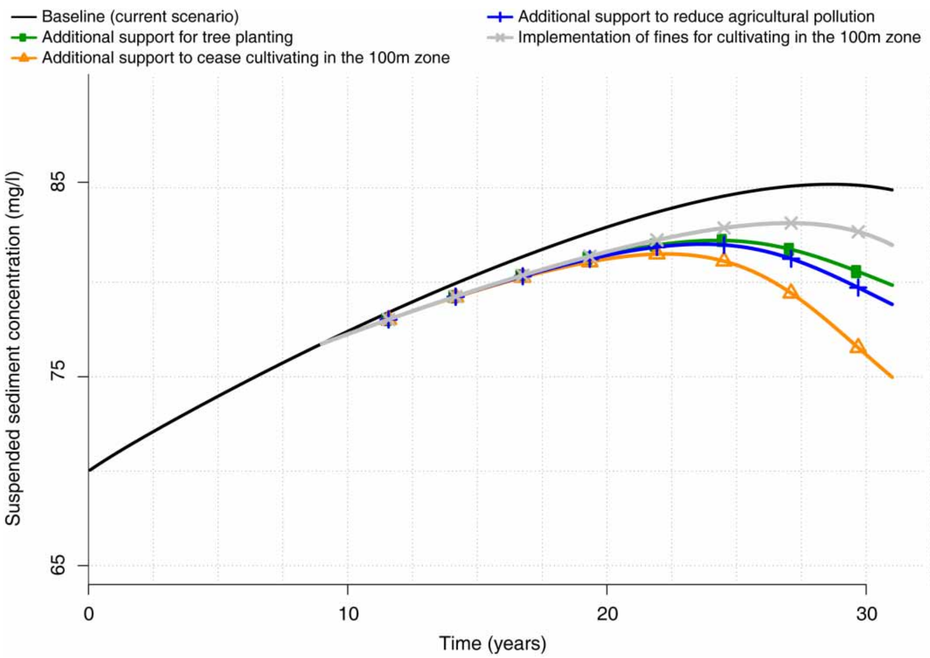

Figure 7 | Example of model scenarios generated over 30 years showing the impact of different management strategies on the water quality in the river.

hierarchically, e.g. in which locations and on which issues the water police receive more institutional support and have more influence. However, by working as an interdisciplinary team (including a geographer, hydrologist, economist and anthropologist), we have grounded the model in strong theory (supported by the literature) supported by robust (qualitative) data. We went through a stakeholder consultation process on the models' validity and use and we clearly describe the context (the social, political and economic situation) in which the model is embedded. Different modelling approaches might better address the spatial and hierarchical differences (e.g. agent-based models, companion modelling (Étienne 2014)), and by including a wider range of different stakeholders in the conceptual model building more of the diversity would be captured (see Walker et al. 2015). However, this type of model can facilitate stakeholder participation and mediate trade-offs between different interest groups. It can identify gaps in our understanding and highlight where more social science/qualitative data, analysis and ground-truthing are needed. It can also provide policy support, not for making predictions, but for visioning the shared water future desired, and exploring the pathways by which it can be achieved.

Flood risk management in Dresden

As shown in the Burkina Faso case, there is a great degree of uncertainty in the modelled outputs, partly because the parameters on which the model is based are not well-constrained. Parameter estimation in socio-hydrology is particularly challenging because of the non-linear nature of the processes involved (Sivapalan & Blöschl 2015). Improving parameter estimation is, therefore, a priority research area for socio-hydrological modellers. To address this, Barendrecht et al. (2019) use Bayesian Inference to improve their estimates of the parameters for a socio-hydrological model that describes the interactions between floods, settlement density, damage, awareness and preparedness using limited empirical data.

The narrative of the model is that flooding occurs when river flow (discharge) is higher than the design flow capacity of the flood protection. This leads to losses, but only when the river flow is higher than the level of the flood protection and when there is a settlement on the floodplain. The losses may be lower if the populations' awareness to floods is high (e.g. because they have already experienced them) and their preparedness is high, meaning that they take precautionary measures to reduce flood damage (e.g. moving their expensive possessions upstairs, installing flood-proof closures on their basement windows). Awareness is reinforced when floods occur and reduce as floods become distant memories. High awareness will also reduce development in the flood plain and therefore reduce settlement density. Hence, the system co-evolves, as peoples' actions increase or reduce the likelihood of devastating floods being experienced.

Through interdisciplinary collaboration, Barendrecht et al. (2019) bring together a diverse collection of empirical data on flood magnitude, losses, settlement density, awareness and preparedness from floods between 1798 and 2013. As well as flow rates, this includes urban growth data, historical data on flood losses and survey data on awareness and preparedness to flood risk are included. The parameters are estimated using Bayesian Inference that identifies the possible range of the parameters by taking into account the measured values and the uncertainty associated with them. They use their model to show that as expected, the inhabitants of Dresden became aware of flood risk following the 2002 flood and implemented (more) precautionary measures in 2013 than in 2002, thus increasing their preparedness and reducing flood loss in 2013 (Figure 8).

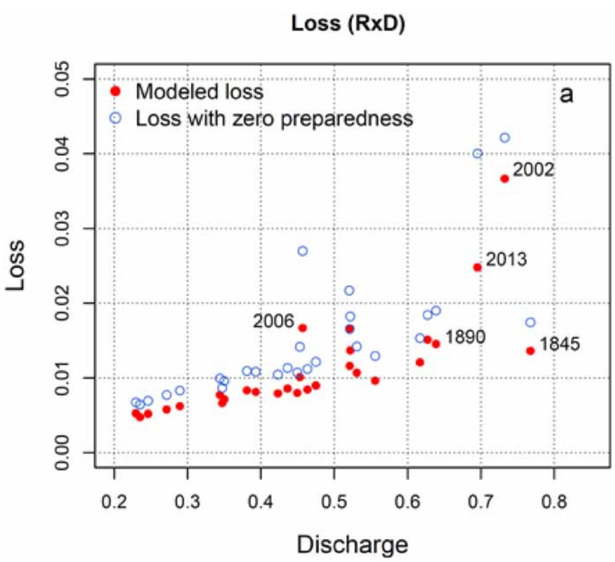

Figure 8 | Flood loss modelling that shows the impact of preparedness for reducing flood losses for the Elbe at Dresden. Both axes have been non-dimensionalised with respect to reference values (from Barendrecht et al. (2019)).

The model shows that preparedness is a key parameter determining flood losses and preparedness corresponds to prior experience of flooding and, therefore, awareness. The work suggests that examining how awareness raising could be achieved in the absence of flooding would be a worthwhile investment. The model could be used to show the possible damage that might occur at the next large flood with and without awareness. So rather than predicting the impacts of future floods, it can be used to explore a range of different 'possibility spaces' (Sivapalan & Blöschl 2015; Srinivasan *et al.* 2017).

The model for Dresden attempts to capture human behaviour and decision-making. This is naturally difficult to capture in rules and equations, as emphasised by this quote:

> '*if history shows anything, it is surely that human behaviour is not law-like. Human behaviour does change, and often we would have to say that this is a good thing*…. *One would have to argue that the more models include human behaviour, the more they are likely to break down*' (Oreskes 2015, p. 264).

Despite the clear challenges, much of the global response to COVID-19 has been (to varying degrees) informed by models, that map the possibility space, of how the virus (a natural hazard) may propagate through the population. In many countries, such models have played an important role in decision-making, despite the many uncertainties and challenges of modelling how people will react, and how their reactions will impact the contagion (Squazzonia *et al.* 2020). This highlights (1) the urgency of developing methods for coupling people and natural systems through models, (2) its feasibility (yet need for improvements) and (3) the value of such models in a decision-making setting. In the water sciences, our models must engage with the social element, while acknowledging the uncertainty (Walker *et al.* 2015; Di Baldassarre *et al.* 2016).

Finally, it is very important to note that any model captures the modeller's or modelling team's view of the world. Models are shaped by the culture, personal experiences and priorities of the modeller. This is demonstrated by the Chicken Creek modelling experiment, which showed how researchers with different specialisations each model the water flow very differently for the same (fictitious) catchment based on their area of expertise (Holländer *et al.* 2009). Numerous studies have shown how men and women view the world differently, and how people from different cultures prioritise different relationships and interactions (Baker *et al.* 2015; Fanelli *et al.* 2017; Nielsen *et al.* 2018; Criado Perez 2019). There are multiple ways that a system can be modelled, especially when parameters for 'people' are included and there is no 'one true model'. However, if modelling teams can capture sufficient diversity, through a balance of specialisations, genders and cultures, and if they have the skills to bring the diversity together, they can build a model which reflects their collective perceptions of how the system is evolving.

SUPPORTING INTERDISCIPLINARY COLLABORATION

The case studies have illustrated several key research practices that must be taken into account when modelling people-water systems: transparency, grounding the model in sound theory, supporting it with the most robust data possible, communicating uncertainty, recognising that there is no 'one true model' and the ongoing pursuit of diversity in the modelling team (different specialisations, different backgrounds, different experiences, and, where possible, also including diverse stakeholders). Critical to all of these is collaboration between the different specialisations, particularly between the social and natural sciences, to bring together different narratives, data sets and analysis approaches that improve our understanding of the co-evolution of people and water.

Challenges to interdisciplinary collaboration

Realising collaborations is typically experienced as challenging for several reasons. Firstly, because different people have different priorities and approaches to the task being undertaken. Clarifications are continually needed to make sure that everyone understands each other. Basic concepts from one field need to be explained from the beginning to people from other fields, and then they might not agree with them or find them 'unscientific'. Therefore, individual specialists from different fields need to be able to understand enough of each others' fields in order to engage with each other and collaborate successfully (Carr *et al.* 2017).

Secondly, in academia, young researchers typically are assessed on the basis of their first author publications. Therefore, collaborations leading to a co-author publication are usually of less priority to those early in their careers, even though this group of researchers typically reports a high level of motivation for doing interdisciplinary work.

Thirdly, publications and proposals of interdisciplinary research are often judged on their actual or planned capacity to extend the state of the art in all areas of specialisation that they address. Reviewers and editors often fail to see the added value of integrating their own area of specialisation with another area of specialisation. Obtaining funding for interdisciplinary work is, therefore, notoriously difficult, even though funding agencies may recognise and emphasise the benefits of interdisciplinary work for science and practice.

Addressing the critical challenges to interdisciplinary collaboration

To address the challenges, we believe that a three-point programme is needed:

1. Emphasise even more strongly, how interdisciplinary collaborative work not only addresses existing (interdisciplinary) research challenges, but that it creates opportunities for generating new research questions to answer as yet, unknown research challenges. This is possible because there are both tangible and intangible outcomes and benefits from these collaborations (Carr *et al.* 2018). Tangible outcomes are the new models that are built, the new understanding that is developed and the papers that are published. Intangible outcomes are the learning that each individual achieves through the collaboration process and the group practices that are developed. Intangible outcomes are essential for any project or programme to achieve tangible outcomes. The development of individual capacity and group practices for collaboration enable future (as yet unidentified) questions to be found and addressed, leading to more new knowledge and understanding.
2. Support individual interdisciplinary learning. This means that time should be allocated, when needed, for individuals to learn about different fields or topics, and how they integrate with one's own field. Part of this will also include identifying and defending the research boundaries that have been chosen. This means explaining what has been included and why, and being open about the restrictions defining the boundaries, such as funds, skills, resources, time. Trade-offs will be necessary. Reviewers should be trained in reviewing interdisciplinary papers and proposals, with a specific emphasis on integrative review, i.e. different reviewers review different parts of the work reflective of their own specialisation, and the editor brings their opinions together to form a judgement.
3. Develop interdisciplinary group practices. Group practices include the way that differences between the research fields are handled within the collaboration process. For example, a culture of mutual respect for each other and the different fields, and involving people who are both personally motivated for the collaboration and have an open-minded nature and willingness to explore new topics. Group practices for working with differences include clear communication, clarification and negotiation, as shown by the following excerpt:

   '*… the authors of this paper have personal experiences of socio-hydrological modelling whereby social science is coupled with hydrology to build mathematical models that describe the interaction between floods and people. To do this, participants in a multi-disciplinary research team use questioning and clarification to uncover each other's assumptions and to capture as fairly as possible the different priorities of each researcher. They negotiate which theoretical processes must be included and which could be omitted in order to reach agreement on the boundaries of the research. Importantly, the practices employed for developing shared understanding take place throughout the entire research process, from developing the research question to submitting and revising the publication*' (Carr *et al.* 2018, p. 45).

CONCLUSIONS

This paper has aimed to rouse the motivation of water professionals from academia, industry and government to engage with their colleagues from other specialisations, particularly between those from the social and natural sciences with the purpose of better understanding people-water systems. It has aimed to show that water systems are both water and people – interacting together. These interactions are highly complex, and so, the modelling approach has been used to illustrate one way of exploring this interdisciplinary system that has, we believe, huge potential to generate new understanding and improve the management of water resource systems. In this short paper, we have provided a taste of the possibilities that modelling people-water systems offer. We have identified a few essential research practices that are needed when modelling people and water together. An interdisciplinary collaborative approach is a critical pathway to accommodating these research practices.

We have identified a three-point plan to support interdisciplinary collaboration: (1) demonstrating and emphasising that interdisciplinary collaboration can both address existing problems and identify new, previously unknown research questions at the interface between the specialisations; (2) supporting individual interdisciplinary learning at all career stages (learning about different specialisations and learning how to integrate); and (3) developing group practices and a culture of interdisciplinary collaboration.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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