An Integrated Model to Assess the Impacts of Dams in Transboundary River Basins

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Abstract. This extended abstract presents an integrated agent-based and hydrological model to explore the impacts of dams in transboundary river basins where riparian nations have competing water uses. The purpose of the model is to explore the effects of interactions between stakeholders from multiple levels and sectors on the management of dams, and its subsequent effects on the Water-Energy-Food-Environment (WEFE) nexus in river basins.

Keywords: Dams, Coupled Human-Natural Systems, Transboundary water management, Agent-based modelling, Hydrological modelling.

1 Introduction

Dams are a critical component of water resources management in river basins. There are over 800,000 dams across the world and 3,700 dams are currently being planned in developing nations [1, 2]. These engineered systems often serve multiple purposes such as energy production, irrigation, water supply for industrial and domestic uses, downstream navigation, recreation, etc. In doing so, dams embed infrastructure into the water, energy, food and environment nexus. On the other hand, by storing, diverting and controlling the flow of water, which in turn affects sediment and nutrient transport in rivers and alters water temperature and chemistry, dams pose limitations that could negatively impact natural ecosystems, biodiversity and the people whose livelihood depend on them [3]. Growing concerns about climate change and natural resources depletion have motivated decision-makers and authorities to prioritise the environmental and social impacts of dams.

The beneficial and negative impacts of a dam is governed by the interactions between dam structure (engineering dimension), its operation and management driven by multi-sectoral socio-economic needs and geo-political factors (human dimension), and the hydrology (interaction of water with the physical and biological environment through processes such as precipitation, evaporation, infiltration, etc.) of watercourses (natural dimension). The impacts of dams vary across sites based on the nature and characteristics of the engineered, human and natural systems unique to each site [3]. Understanding these relationships, which impose profound, complex and multiple societal and ecosystems impacts, is essential for stakeholders and decision-makers to plan the management of water resources in an integrated and sustainable way.

Computational modelling offers one way to plan the management of environmental resources, especially in the context of being useful for informing policy making [4].

2 Modelling Water Resources Management: A short review

The common approach of modelling water resources as scarce goods and ascribing economic value to them has been widely used to quantitatively inform and assess water management policies, e.g., hydro-economic modelling [5]. However, although monetising in this way is often useful to convert a multi-objective management problem into a single objective problem (e.g., profit maximisation), it does not allow assessing the qualitative or hard-to-quantify aspects of water demands, management methods and institutions, e.g., issues related to environmental and ecological values and benefits, social equity, and the interdependencies between ecological, hydrological and social systems [3, 5, 6]. A purely economic assessment also does not consider the inherent complexity of integrated human-environment systems such as dams.

On the other hand, agent-based modelling (ABM) is a method useful for representing and simulating the inherent complexity of coupled socio-ecological systems, which have interdependent natural and social components. It does so by defining and implementing complexity mechanisms such as nonlinearity, feedback, uncertainty, causality and heterogeneity [4, 7]. These capabilities have contributed to the continued popularity of ABM as a viable approach to investigate the effect of decisions and strategies for managing coupled socio-ecological systems (also referred to as coupled human-natural systems or coupled human-environment systems), or more specifically socio-hydrological systems (coupled human-water systems) [7–9].

There are two main ways in which ABM has been used in the context of modelling human-water interactions. Firstly, agent-based models are intended as a form of *science-policy/modeller-expert interface tools* that modellers (e.g., academics), decision makers (e.g., policy makers), stakeholders (e.g., actors in the river basin), system experts and domain experts can develop and validate collaboratively, making sure everyone develops a shared understanding of the system and the issues being examined [10, 11]. Secondly, in an *integrated model* that includes other modules (e.g., hydrological, economic, engineering, etc.) and techniques (e.g., optimisation, Bayesian belief networks, etc.), agent-based models are used to: (1) model bottom-up decision-making, learning and adaptation of actors, (2) consider non-linear relationships between system components, (3) model spatially explicit representations of systems and their evolution over time, (4) represent self-organisation of systems, and (5) model emergence of macro-level phenomena from micro-level behaviour. It is also possible to combine the two applications, whereby an agent-based model is developed in a participatory context involving the relevant stakeholders, and is integrated with other social science (e.g., economic) and/or physical science (e.g., hydrological) modules to emulate specific real-world applications [6, 12, 13].

In the following section, we present an integrated model to explore the effects of stakeholder interactions on the management of dams and its subsequent effects on the Water-Energy-Food-Environment (WEFE) nexus in the Volta River Basin (VRB) in

West Africa. The novel aspect is the focus on the human dimension, which complicates the management of dams owing to the many layers of social, political and economic institutions involved in river basin management and manifold end-users even at the sub-basin level, e.g., small-scale farmers, large-scale farmers, hydro-electric power companies, industrial users, tourism and recreation users, and municipal water users [14–16]. As conflicts in river basins mostly arise at regional or local levels, which could then escalate into national conflicts, it is important to involve stakeholders from multiple levels and sectors when formulating water management decisions [17]. Decision-making should result from the lateral interactions between riparian nations and the vertical interactions starting from grassroots stakeholders (e.g., farmers, herders, village chief, etc.) through to national agencies (e.g., water resource commissions) and international agencies (e.g., river basin authorities) [18]. Another novel aspect of the model is the implementation described in the following section.

3 An integrated model to explore the impacts of dams

The resources of the VRB, which has a transboundary watershed of approximately 400,000 km^2, are shared by six riparian countries: Côte d'Ivoire, Ghana, Togo, Benin, Burkina Faso and Mali. A major part of the watershed lies in the coastal Ghana and land-locked Burkina Faso (around 42% each) while a minor part lies in the remaining four countries [19]. The differing economic priorities of the riparian countries in the VRB have an important role in the water management of the basin, e.g., Burkina Faso is less developed and relies heavily on irrigation for farming whereas Ghana's increasing electricity demand has made hydropower generation a priority. At the basin level, domestic water supply and irrigation for farming are the priorities for water use in all six nations except Ghana where hydropower generation is the priority [20]. The Volta Basin Authority (VBA) water charter was signed by the VRB riparian nations in 2006 as a means to support collaborative water management, enable coordination to resolve transboundary water conflicts and tensions, influence joint development, and achieve policy harmonisation. However, the VBA is yet to become fully functional in terms of achieving its mandates and objectives [18, 21].

The differing economic priorities of the riparian nations and the lack of adequate governance mechanisms are both critical issues affecting transboundary water management in the VRB. Therefore, we conceptualise an integrated model to explore the possibilities of coordination among stakeholders in making water management decisions by considering their competing sectoral priorities and preferences. We consider the following sectoral priorities relevant in the context of the VRB: irrigation, hydropower generation, domestic water supply and ecosystem health. In terms of preferences, we consider stakeholders' willingness to cooperate with the requests of other stakeholders in the system and contribute to capacity building in the basin, which are both important to avoid water conflicts [22]. The element of capacity building we consider is knowledge exchange between stakeholders which has been shown to improve the confidence of stakeholders, overcome mistrust and enable cooperative action [17].

The integrated model illustrated in figure 1 has a hydrological model and an agent-based model. The former simulates the impact of stakeholders' dam operation decisions on the quality and quantity of water in the river basin. The latter consists of two layers: a network layer and a decision layer. The network layer defines the relationship between a diverse set of local, regional, national and international stakeholder agents. The decision layer simulates the decision-making of individual stakeholders using a rule-based system. Below is a high-level description of each of these components.

The agent-based modelling component controls stakeholders' decisions associated with dam operations on a monthly time step which is a reasonable timescale for water management decisions [13]. First, a prespecified network configuration is used to model the interactions between a diverse group of stakeholders with regards to willingness to cooperate on dam operations and knowledge exchange on water management issues. The VRB is divided into geographically and politically similar sub-regions, each of which is influenced or governed by a local stakeholder agent. Local stakeholders who have common water use needs are grouped under a regional stakeholder agent. The main water allocation and management bodies in each of the six riparian nations are the national stakeholders. The VBA and other relevant actors (e.g., financial institutions and NGOs) are the international stakeholders [18, 21].

Based on the interactions with other connected stakeholders in the system, each stakeholder agent makes a dam operation decision (or a decision that influences a dam operation decision of a higher-level stakeholder in its network). Decisions are derived using a rule-based system, developed by organising real-world stakeholder inputs within the modelling framework, which in turn improves the effectiveness of the participatory approach used to develop and refine the model. A rule-based system includes: (1) a working memory initialised with a set of facts relevant to the beginning state of each agent, (2) a rule set describing the actions to be performed under different conditions, (3) a matching scheme to decide which rules are applicable, and (4) a conflict resolution scheme to choose the most applicable condition-action rule among alternatives. The rule-based system enables each stakeholder agent to make appropriate dam operation decisions for different sectoral priorities (irrigation, hydropower generation, domestic water supply and ecosystem health) based on individual targets (set based on historical data) and interactions with other stakeholders in the system.

The dam operation decisions of stakeholders are subsequently fed into a hydrological model developed using the Soil and Water Assessment Tool (SWAT[1]), free software used to explore and quantify the effects of human intervention (in our case, dam operation decisions) on the quality and quantity of water resources in a river basin. The outputs of the hydrological model (discharge, nutrient data, sediment data, crop yields at the sub-basin level, etc.) are fed into the agent-based model, which in turn affects the priorities and thereby the dam operation decisions of stakeholders at the next time step. In the last time step of a model run, a summary is generated describing the performance of the different sectoral priorities and instances of successful cooperation and knowledge exchange among stakeholders at different levels of governance. The model can be applied to different scenarios of stakeholder interaction (with regards to cooperation and knowledge exchange) and decision-making (with regards to dam operations

[1] https://swat.tamu.edu/

based on individual water use needs and interactions with connected stakeholders) to assess the impact of dam operations on the WEFE nexus in VRB.

The inputs required for the integrated model are as follows. (1) The configuration of the VRB stakeholder network and data about the nature of the interactions between stakeholders are obtained from existing literature in the first instance. (2) The rule sets and priorities for the rule-based system specified are based on available data (e.g., the Transboundary Waters Assessment Programme database[2], the Global Reservoir and Dam database[3], the AQUASTAT database[4]) and stakeholder inputs. (3) The SWAT hydrological model requires input data on weather, soil properties, topography, vegetation, etc., most of which are commonly available as open source datasets (e.g., the WaterBase dataset[5]).

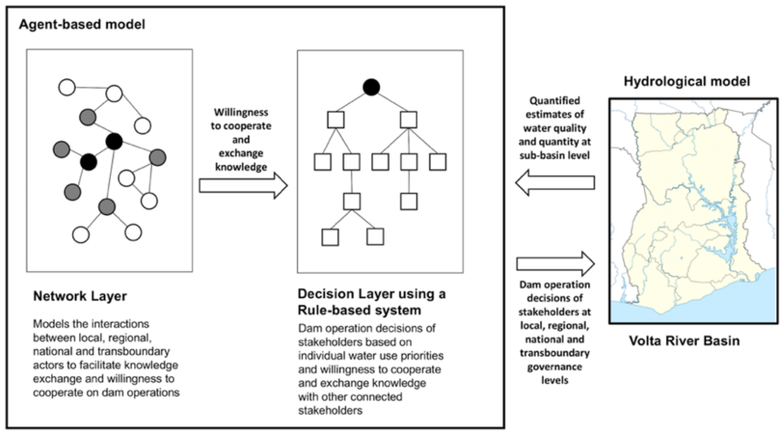

Fig. 1. An Integrated Model to Assess the Impact of the Management of Dams in the VRB

4 Discussion

This paper presented an integrated model to be useful for exploring the impacts of multi-level stakeholder interactions and decision-making related to dam operations on the WEFE nexus in the Volta River Basin. We will implement the integrated model by linking a hydrological model developed using SWAT and an agent-based model developed using NetLogo[6]. We will use the JESS rule engine[7] to implement the rule-based system governing the decisions of stakeholders. Although the proposed implementation is specific to the VRB, the integrated model can be easily adapted to other river basins.

[2] http://twap-rivers.org/
[3] http://www.gwsp.org/products/grand-database.html
[4] http://www.fao.org/nr/water/aquastat/main/index.stm
[5] http://www.waterbase.org/download.html
[6] https://ccl.northwestern.edu/netlogo/
[7] www.jessrules.com/jess/

References

1. Kennedy TA, Muehlbauer JD, Yackulic CB, et al (2016) Flow Management for Hydropower Extirpates Aquatic Insects, Undermining River Food Webs. BioScience 66:561–575
2. Poff NL, Schmidt JC (2016) How dams can go with the flow. Science 353:1099–1100
3. Bergkamp G, McCartney M, Dugan P, et al (2000) Dams, ecosystem functions and environmental restoration. Thematic review II 1:1–187
4. Zellner ML (2008) Embracing Complexity and Uncertainty: The Potential of Agent-Based Modeling for Environmental Planning and Policy. Planning Theory & Practice 9:437–457
5. Harou J, Pulido-Velazquez M, Rosenberg DE, et al (2009) Hydro-economic models: Concepts, design, applications, and future prospects. Journal of Hydrology 375:627–643
6. Pope AJ, Gimblett R (2015) Linking Bayesian and agent-based models to simulate complex social-ecological systems in semi-arid regions. Front Environ Sci 3:
7. An L (2012) Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecological Modelling 229:25–36
8. Sivapalan M, Savenije HHG, Blöschl G (2012) Socio-hydrology: A new science of people and water. Hydrol Process 26:1270–1276
9. Blair P, Buytaert W (2016) Socio-hydrological modelling: a review asking "why, what and how?" Hydrol Earth Syst Sci 20:443–478
10. Barreteau O, Bousquet F, Attonaty J-M (2001) Role-playing games for opening the black box of multi-agent systems: method and lessons of its application to Senegal River Valley irrigated systems. Journal of artificial societies and social simulation 4:5
11. Barreteau O, Antona M, D'Aquino P, et al (2003) Our companion modelling approach. Journal of Artificial Societies and Social Simulation 6:
12. Smajgl A, Toan T, Nhan D, et al (2015) Responding to rising sea levels in the Mekong Delta. Nature Climate Change 5:167
13. Khan HF, Yang YE, Xie H, Ringler C (2017) A coupled modeling framework for sustainable watershed management in transboundary river basins. Hydrology and Earth System Sciences 21:6275
14. Le Bars M, Attonaty J-M, Pinson S (2002) An agent-based simulation for water sharing between different users. ACM, pp 211–212
15. Berger T, Birner R, Díaz J, et al (2006) Capturing the complexity of water uses and water users within a multi-agent framework. In: Integrated Assessment of Water Resources and Global Change. Springer, Dordrecht, pp 129–148
16. Barthel R, Janisch S, Nickel D, et al (2010) Using the Multiactor-Approach in G lowa-Danube to Simulate Decisions for the Water Supply Sector Under Conditions of Global Climate Change. Water Resources Management 24:239
17. Dabelko D, Aaron T (2004) Water, conflict, and cooperation. Environmental Change and Security Project Report 10:60–66
18. Gao Y, Margolies A (2009) Transboundary water governance in the Volta River Basin
19. de Condappa D, Chaponnière A, Lemoalle J (2009) A decision-support tool for water allocation in the Volta Basin. Water International 34:71–87
20. UNEP-GEF Volta Project (2013) Volta Basin Transboundary Diagnostic Analysis. UNEP/GEF/Volta/RR 4/2013
21. Kim K, Glaumann K (2012) Transboundary water management: who does what, where. Analysing the Data in SIWI's Transboundary Water Management Database Swedish Water House, Stockholm
22. Petersen-Perlman JD, Veilleux JC, Wolf AT (2017) International water conflict and cooperation: challenges and opportunities. Water International 42:105–120