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# An agent-based platform for the study of watersheds as coupled natural and human systems

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ABSTRACT

This study describes the architecture and capabilities of an open source agent-based Java platform that permits the systematic study of interactions among hydrology, climate, and strategic human decision-making in a watershed over time. To demonstrate the platform's use and capabilities, an application is presented in accordance with ODD protocol requirements that captures, in simplified form, the structural attributes of the Squaw Creek watershed in central Iowa. Illustrative findings are reported for the sensitivity of farmer and city social welfare outcomes to changes in three key treatment factors: farmer land-allocation decision method, farmer targeted savings, and levee quality effectiveness for the mitigation of city flood damage.



## 1. Introduction: study scope and organization

Sustainable access to adequate water ranks among the most serious challenges facing the world in the 21st century. Finding solutions requires coordinated efforts by natural and social scientists, engineers, water managers, policy-makers, and stakeholders from the broader community. These groups have diverse interests, values, histories, and disciplinary perspectives. Changing climate, demographics, and economic demands add to the challenge by presenting a moving target. Complicating matters further are the complex and seemingly contradictory messages the public receives about expected changes, especially concerning climate (Barsugli et al., 2013; Hewitson et al., 2014). This poor communication allows parties to focus on messages that align best with their views, ignoring other viewpoints (Sarewitz, 2004).

Cohesive planning for sustained water resources with community support will thus require continual co-development of knowledge and problem solutions (Rosenzweig et al., 2014). Software frameworks permitting water sustainability issues to be studied from multiple viewpoints by means of systematic computational experimentation can potentially enhance this co-development.

This paper describes the development of the *W*ater *A*nd *C*limate *C*hange Water*shed (WACCShed)* Platform, an agent-based Java framework permitting the systematic study of watersheds as coupled natural and human systems (Liu et al., 2007). A distinctive feature of the platform is that it permits a careful modeling of the physical and institutional environment that shapes and channels the actions of human watershed participants. In turn, as advocated by An (2012), it permits a watershed environment to be affected by the actions and interactions of its human participants. WACCShed has been released as open source software under the GNU General Public License (GPL) at a code and data repository site (Jie et al., 2016).

A watershed application is presented in order to demonstrate, in concrete terms, the capabilities and use of the WACCShed platform. For clarity of exposition, the presentation adheres to the ODD (**O**verview, **D**esign concepts, and **D**etails) protocol developed by Grimm et al. (2006, 2010a, 2010b). The watershed application captures, in highly simplified form, the structural attributes of the

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Squaw Creek watershed in central Iowa (Wendt, 2007). The application restricts attention to two types of decision makers, a representative farmer and a city manager, in order to identify with care the manner in which their strategic interactions and risk-management practices result in an intrinsic dynamic coupling of natural and human systems. Illustrative findings are reported showing the sensitivity of farmer and city social welfare outcomes to changes in three key treatment factors: farmer land-allocation decision method, farmer targeted savings level, and levee quality effectiveness for the mitigation of city flood damage.

Section 2 clarifies the relationship of this study to previous related studies. Section 3 discusses key features of the WACCShed platform architecture. The watershed application is presented in Sections 4–6 in accordance with the three ODD protocol categories (overview, design concepts, and details). A welfare sensitivity study for the watershed application is developed in Section 7, and illustrative findings from this study are reported in Section 8. Section 9 provides concluding discussion.

## 2. Relationship to existing literature

In traditional water resource management studies, human activities such as land use, construction, and policy determination were typically modeled as externally imposed interventions. In contrast, the emerging field of socio-hydrology treats environments and human inhabitants as co-evolving factors (Sivapalan et al., 2012). In this way, socio-hydrological models can account for two-way feedback between human and environmental systems (Gordon et al., 2008) and address not only physical processes but also social, political, cultural, economic, and ethical issues within integrated system frameworks.

One approach enabling the integrated dynamic modeling of human and environmental systems is agent-based modeling (ABM), the representation of real-world systems as open-ended dynamic systems of interacting "agents" (Axelrod and Tesfatsion, 2006; Borrill and Tesfatsion, 2011; Tesfatsion, 2011; Chen, 2016; Tesfatsion, 2016). An agent is an entity capable of acting over time within its modeled world on the basis of its own internal data, attributes, and methods. Agents can represent a broad spectrum of entities ranging from passive physical features to sophisticated human decision makers.

As noted by many previous researchers, ABM is well suited for the study of dynamic coupled natural and human systems (An, 2012; Heckbert et al., 2010; Müller et al., 2014; Filatova et al., 2013; Tesfatsion, 2015). ABM permits models to be tailored to real-world systems rather than forcing researchers to simplify system representations purely for analytical tractability. It enables researchers to develop empirically-based frameworks that capture the salient physical, biological, and institutional aspects of a real-world system and then pose the following types of questions: Given these environmental characteristics, what do the human participants do? What could they do? What should they do, given their various purposes?

Researchers are increasingly using ABM to study coupled interactions among human decisions and hydrological processes (Blair and Buytaert, 2016). Topics from studies with agricultural components have included: the crop-yield effects of coordination among farmer associations (Lansing and Kremer, 1993); the connection between upstream water management and the viability of downstream farming (Becu et al., 2003); the effects of subsistence farming on deforestation (Bithell and Brasington, 2009); and the impacts of farming input costs, crop prices, carbon allowances, and biofuel adoption on farmer behavior and stream nitrate loads (Ng et al., 2011). Nikolic et al. (2013) note the importance of standardized communication among agents to facilitate including agents from different sources.

Although the modeling of hydrological processes is difficult, the modeling of human decisions and behaviors is arguably even more difficult. Spurred by the work of Di Baldassarre et al. (2015), a recent debate (Montanari, 2015) identifies several key issues that arise when attempts are made to incorporate human decisions in socio-hydrological models. Citing several case studies, Loucks (2015) highlights factors that greatly complicate the prediction of human behavior, including an inability to formulate a set of fundamental principles governing behavior, and the ever-present influence of media, political entities, and cultural and social pressures. Fortunately, as reviewed by An (2012), some of these issues are being addressed in ABM studies, including participatory ABM studies in which stakeholders interact directly with modelers in an ongoing development of an ABM.

The WACCShed platform contributes to socio-hydrological modeling in two principal ways. First, it complements previous work on human decisions and behaviors by allowing strategic game-theory interactions among humans to be modeled within socio-hydrological environments. Although game theory has been used in socio-ecological and water resource management studies (Diekert, 2012; Madani and Hooshyar, 2014), it has not yet been included in the study of socio-hydrological problems (Blair and Buytaert, 2016).

Second, WACCShed is a flexible, extensible, open source platform that others can readily adapt to their own purposes. Noting that most ABMs designed for environmental problems have been used only by their developers (Papajorgji et al., 2004), Hu et al. (2015) implement their previously developed ABM (Ng et al., 2011) as a web-based application in a cloud computing environment to ensure its accessibility and scalability. In a similar way, as detailed in the following section, we simplify and adapt the OpenDanubia framework developed by Barthel et al. (2008) to increase its general usability for socio-hydrological studies.

## 3. WACCShed platform architecture

### 3.1. Software overview

This section provides an overview of the WACCShed platform architecture. Covered aspects include relationship to existing software, platform components, and application components. Detailed WACCShed design and implementation aspects can be found in the documentation provided at the WACCShed code and data repository site (Jie et al., 2016).

### 3.2. Adaptation from existing software

WACCShed is a Java software library that facilitates the systematic study of coupled interactions among hydrological, climate and human decision-making processes over time. The core of the platform builds upon OpenDanubia, an open source software framework released by GLOWA-Danube (Barthel et al., 2008; GLOWA-Danube Project, 2014). OpenDanubia was developed to study the impacts of climate change on the Upper Danube watershed in Germany. However, its core system was designed with a great degree of decoupling from application components, which allows for the implementation of customized models.

In the process of adapting OpenDanubia to the specific demands of WACCShed, we substantially reduced the number of Java packages while including additional features. We next describe the main