

An Agent-Based Platform for the Study of Watersheds as Coupled Natural and Human Systems

Leigh Tesfatsion^{a,*}, Chris R. Rehmann^b, Diego S. Cardoso^a, Yu Jie^c,
William J. Gutowski^d

^a*Dept. of Economics, Iowa State University, Ames, IA 50011-1054*

^b*Dept. of Civil, Construction, and Environmental Engineering,
Iowa State University, Ames, IA 50011*

^c*Dept. of Electrical & Computer Engineering, Iowa State University, Ames, IA 50011*

^d*Dept. of Geological & Atmospheric Sciences, Iowa State University, Ames, IA 50011*

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.

Keywords: watershed, agent-based software, coupled natural and human system, strategic human decision-making, ODD protocol

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 coor-

*Corresponding author. L. Tesfatsion, Tel: +01 515-294-0138, Fax: +01 515-294-0221, Email: tesfatsi@iastate.edu, Web: <http://www2.econ.iastate.edu/tesfatsi/>

**Other email addresses: rehmann@iastate.edu (C. Rehmann), dcardoso@iastate.edu (D. Cardoso), jysarah@iastate.edu (Y. Jie), gutowski@iastate.edu (W. Gutowski).

minated 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 *Water And Climate Change Watershed (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,b). The watershed application captures, in highly simplified form, the structural attributes of the 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, 2016a). 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; Muller et al., 2014; Filatova et al., 2013; Tesfatsion, 2016b). 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 exclusions and extensions we made to OpenDanubia.

To ensure portability and an ability to execute in remote High-Performance Computing servers, WACCSHed was developed as a console-based application. To accomplish this, we detached the simulation from the data analysis part of the system. Consequently, we do not include within WACCSHed the original OpenDanubia packages for Graphical User Interface and Data Visualization tools.

Additionally, we extended OpenDanubia to allow for simulations to be run as stand-alone applications. This was performed by embedding HyperSQL, a Java-based Relational Database Management System (RDBMS), within the platform. In contrast, OpenDanubia relies on an externally configured MySQL for data management. One direct benefit of this embedding is the ability to hold simulation data in RAM, minimizing slow input-output access to hard disks. On the other hand, this embedding might be disadvantageous

for applications with very large data sets. For this reason, we designed the communication to RDBMS via an interface for which we provided HyperSQL and MySQL implementations.

Finally, OpenDanubia supports parallel processing by implementing agents as separate threads. However, there is no support for concurrent simulation runs with different sets of parameter values. For this reason, OpenDanubia cannot directly automate sensitivity analyses using its original packages. To overcome this limitation, we developed software-controlled simulation parameters for WACCShed, thus allowing simultaneous execution of multiple simulation configurations in separate threads under the same process.

3.3. WACCShed Platform Components

Platform components form the core of WACCShed and are responsible for the underlying structure of simulations. Each component contains a collection of classes that together encapsulate one or more features of the system. Specifically, these components implement simulation execution control, parameter setup, scheduling, and synchronization. They also provide the base classes for application components and their communication interfaces. In this subsection we briefly review the WACCShed platform components associated with the main tasks in a simulation.

Values for the simulation parameters subject to sensitivity analysis, i.e., the *treatment factors*, are entered by the user into a main class that runs the simulation. Each configuration of values for the treatment factors is stored separately, allowing for parallel execution of different simulation cases. User-entered values for the remaining parameters of the model are loaded into the simulation from a hierarchical configuration structure of simple text files. One root configuration file sets the data period and the geographic area for the simulation and lists the application components. A separate metadata file contains the parameter values related to the geographic area, such as the surface area and the number of sub-basins.

An application component is a representation of a specific domain of a model. Application components interact and synchronize with other parts of the system by implementing a common cycle with four basic methods - *get-Data*, *compute*, *provide*, and *store* - which change the state of the application component when called. The application components are treated in separate threads. However, they respect synchronization queues, and their execution only proceeds after all other application components are in the same state

of the cycle. Fig. 1 illustrates the states for a typical execution cycle of an application component.

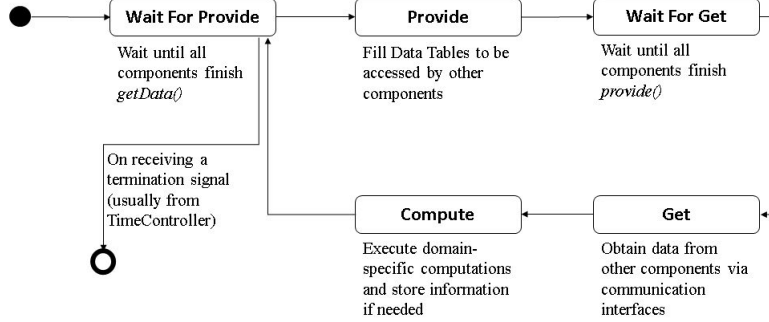


Figure 1: Typical WACCShed execution cycle implemented by an application component.

Application components do not have direct access to each other. Instead, each application component X that provides data to an application component Y has to implement an interface $XtoY$. This feature favors a low coupling design, allowing application components to be developed with a high degree of encapsulation.

Intermediate and final results of the simulation are communicated to a database through a generic interface; it defines basic operations such as connect, query, insert, and delete. The default and recommended implementation of the database interface is the *HSQLDataBaseManager*, which controls an embedded instance of the HyperSQL RDBMS. A configurable MySQL manager is also provided.

3.4. Illustration: Watershed Application Components

The watershed application, described in detail in Sections 4–6, is implemented by means of five WACCShed application components: Climate, Hydrology, Market, Farmland, and City. Figure 2 depicts the information flow among these five components. Below we briefly discuss technical aspects of this implementation.

The Climate component is responsible for providing precipitation data to Hydrology, Farmland, and City. The precipitation information comes from a fixed data set for three representative years indexed by level: low, moderate, or high. The Climate component is configured to operate in hourly steps

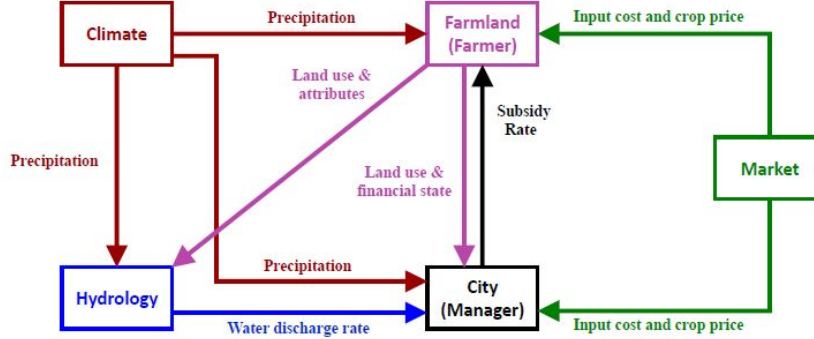


Figure 2: WACCSHed watershed application components and their information flows implemented via communication interfaces.

in simulation time. Hence, the precipitation data table is fed with new information for each simulated hour during each simulation run.

The Hydrology component is also set to hourly time steps. This component handles the calculations associated with hydrological processes. It communicates to City the water discharge rate into the city based on precipitation data and land attributes.

The Market component is based on a fixed data set for representative years. It provides information on input costs and crop prices to Farmland and City. It is configured to daily time steps, as are all remaining components.

The Farmland component encapsulates the decision-making activities of Farmer agents with respect to land allocation, consumption, and savings decisions. The Farmland component allows a user to implement multiple Farmer agents with heterogeneous data, attributes, and methods.¹ The Farmer agents compute decisions using information on precipitation, input costs, crop prices, and subsidy rates. The Farmland component then provides data on land use to Hydrology and City and data on Farmer financial states to City. The Farmland component also stores decisions, outcomes, and state changes in the database. Other processes associated with farming, such as harvest yield, are also included in the Farmland component.

The City component encapsulates the decision-making activities of a City Manager agent with respect to budget allocation decisions. It also encapsu-

¹For clarity of exposition, the particular watershed application reported in the current study implements a single representative Farmer agent.

lates the process determining the quality effectiveness attribute of a Levee agent, where quality effectiveness measures the ability to mitigate city flood damage. The City component processes information from all other application components, generates a budget allocation decision, and communicates the subsidy portion of this budget allocation decision to the Farmland component. The City component also stores decisions, outcomes, and state changes in the database.

The spatial structure for the watershed application is a watershed region partitioned into a user-specified number of sub-basins. Climate, Hydrology, and Farmland processes are specific to each sub-basin, while Market prices are common across all sub-basins. For the particular watershed application reported in the current study, the number of sub-basins is set to one.

4. Watershed Application: Overview

4.1. Purpose

The watershed application is a relatively simple test case that demonstrates, in concrete terms, the capabilities and use of the WACCSHed platform. The application highlights, in particular, how WACCSHed permits the study of watersheds as dynamic coupled natural and human systems with humans modeled as strategically interacting decision makers subject to physical and financial constraints.

4.2. Agents, State Variables, and Scales

The watershed application is an agent-based modeling of an agricultural watershed that operates over successive simulated years. The modeled watershed consists of the collection of hierarchically organized agents depicted in Fig. 3. Note that the Farmland, City, Market, Climate, and Hydrology agents depicted in Fig. 3 correspond to the five WACCSHed application components depicted in Fig. 2.

The base agent for the watershed application is the Watershed World populated by physical, institutional, and decision-making agents. Specifically, the Watershed World has a Basin (geographical area) divided between Farmland and a City. Farmland has a decision-making agent called a Farmer. City has a decision-making agent called a City Manager plus a physical Levee agent for protection against city flood damage. The Watershed World has two instances of a Market agent: namely, an intermediate-goods market for the inputs (seed and chemicals) needed for the production of corn as well as

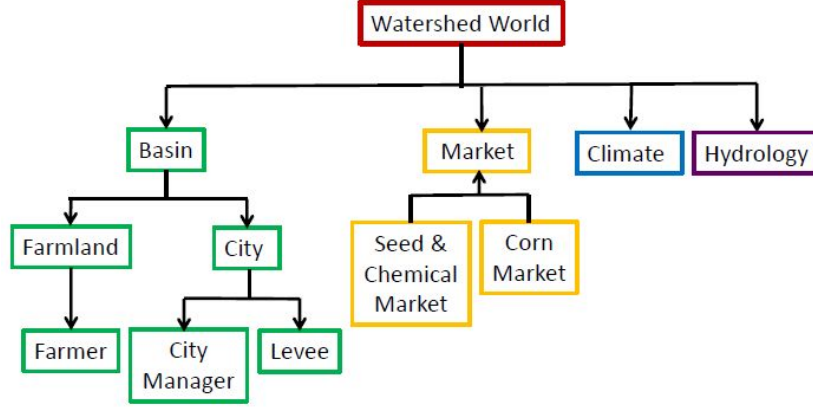


Figure 3: Agent hierarchy for the watershed application. Down-pointing arrows denote “has a” relationships, and up-pointing arrows denote “is a” relationships.

a final-goods market for the sale of corn. The Watershed World also has a Climate agent that encapsulates processes for the determination of annual precipitation patterns, and a Hydrology agent that encapsulates processes determining the relationship between water and land.

As detailed in Tesfatsion (2016a), the *state* of a modeled system at any given time is a characterization of all system aspects deemed by the modeler to be relevant for a specified purpose. For an agent-based model, such as the watershed application, the state of the modeled system at any given time consists of the states of its constituent agents. In turn, the state of an agent at any given time consists of the agent’s internal data, attributes, and methods (functions, subroutines,...). These state aspects further subdivide into aspects that remain fixed over time and aspects that can change over time, hereafter referred to as *fixed* and *variable* aspects respectively. In the watershed application the variable state aspects of agents are updated (as appropriate) every time a decision or event is realized.

The fixed and variable state aspects of the Watershed World and Basin agents in Fig. 3 consist of the fixed and variable state aspects of their constituent agents as identified by “has a” relationships. Summary descriptions of the fixed and variable state aspects for each other agent in the watershed application are listed in Table 1. Nomenclature tables providing lists of symbols, abbreviated definitions, and units for these fixed and variable state aspects are provided in Appendix A.

Four aspects of Table 1 warrant clarification. First, a *curve number (CN)*

Table 1: Fixed and variable state aspects for watershed application agents

Agent	Fixed State Aspects	Variable State Aspects
Farmland	Land area; planting density; curve numbers for bare soil, retention-land, & cropland at different growth stages; harvest yield function; Farmer inhabitant	
Farmer	Preferences; decision method for land allocation, consumption, & savings	Information; money holdings
City	Land area; levee; curve number; city flood damage function; city inhabitants; City Manager inhabitant	
City Manager	Annual budget; budget allocation method	Information
Levee	Levee quality update method	Levee quality
Market	Market type; possible prices & probabilities	
Seed/Chem Market	Market type (corn-production inputs); possible input prices & probabilities	
Corn Market	Market type (corn); possible corn prices & probabilities	
Climate	Possible precipitation patterns & probabilities	
Hydrology	HEC-HMS (Hydrologic Modeling System) mapping land area, land usage, curve numbers, & precipitation patterns into city peak water discharge rates	

is a hydrological measure expressing relative water runoff for land with different types of cover. Second, in this study, *water retention land* is defined to be land for which management practices result in higher water retention (lower water runoff), hence a lower CN , than bare soil, fallow land, or cropland with a mature crop cover. Third, as detailed more carefully in Appendix D, the CN for cropland decreases over the growing season as the cropland varies from no coverage (bare soil) to coverage by a mature crop. Fourth, information is included as a variable state aspect of the Farmer and City Manager because their information is continually updated to include all past decisions and environmental event realizations.

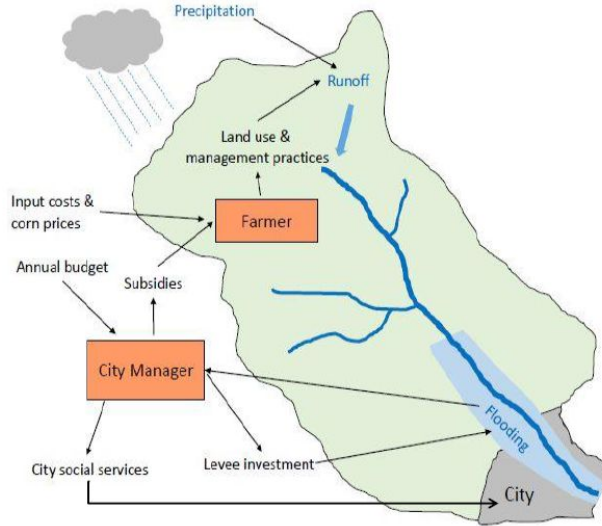


Figure 4: Interactions among the agents in the Watershed World

4.3. Process Overview and Scheduling

The interactions among the agents populating the Watershed World are depicted in Fig. 4. During each simulated year the Watershed World experiences a randomly determined amount of precipitation that affects farmland and city runoff as well as cropland yield. In addition, during each simulated year a randomly determined input cost is determined in the market for seed and chemicals and a randomly determined corn price is realized in the corn market. These input costs and prices affect the profitability of corn production within the Watershed World.

The Farmer seeks to achieve and sustain a high level of personal welfare over time through appropriate annual allocations of her farmland among cropland, water-retention land, and fallow land. The City Manager attempts to maintain and increase city social welfare over time through appropriate annual allocations of the city budget among city social services, levee investment, and water-retention land subsidy payments to the Farmer.

Each simulated year $t = 1, 2, \dots$ in the Watershed World is divided into seasonal subperiods $t_1, \dots, t_7$ during which either a decision is taken or an environmental event is realized; see Table 2. The variable state aspects of each agent are updated (as appropriate) after each decision or event realization. Subperiod t_k denotes the time interval $[t:k, t:(k+1))$, with $t:1 = t$ and

$t:8 = t + 1$. Thus, year t covers the time interval $[t:1, t:8) = [t, t + 1)$.

Table 2: Timeline for year- t decisions and events

Jan	Feb	March	April-Sept	Oct	Nov	Dec
t_1	t_2	t_3	t_4	t_5	t_6	t_7

In subperiod t_1 (January) of year t , an input cost (\$/acre) for corn planting is realized for the year. In subperiod t_2 (February) the City Manager allocates the annual city budget among three portions to enhance city social welfare, expressed as a weighted combination of city social services and the mitigation of city flood damage. The three budget portions are for city social-services, retention land subsidies, and levee investment. The City Manager then sets the subsidy rate for retention land for the current year. In making these decisions, the City Manager takes into account their likely effect on the Farmer's subsequent land-allocation decision in subperiod t_3 .

In subperiod t_3 (March), given the input cost realized in t_1 and the retention-land subsidy rate set in t_2 , the Farmer allocates her farmland among cropland, retention land, and fallow land in pursuit of consumption and savings goals. The Farmer immediately receives a subsidy payment from the City Manager for her retention-land portion. In subperiod t_4 (April–September) the Farmer uses her money holdings to purchase the inputs needed to plant her cropland. She then plants seeds and tends to her cropland.

In subperiod t_5 (October) the Farmer's yield (bushels/acre) from her harvested crop is determined by the precipitation pattern, i.e., by the rainfall realized from January 1 through October 15. The precipitation pattern, together with the Farmer's land allocation, also determines the peak water discharge rate into the city. This discharge rate, together with the quality of the city's levee, determines city flood damage. The City Manager then calculates the amount of city flood damage mitigated by his expenditures on retention-land subsidies and levee investment, which in turn permits him to calculate city social welfare for year t .

At the beginning of subperiod t_6 (November) a corn price is realized in the corn market. During subperiods t_6 – t_7 (November–December) the Farmer sells corn in the corn market and retains (and/or buys) corn for her own consumption, conditional on a savings target. The Farmer calculates her year- t welfare by the utility (benefit) she obtains from her own consumption.

At the end of subperiod t_7 (December 31st), the Farmer and City Manager take stock of all that has occurred during year t and update their states accordingly. A new year $t + 1$ then commences.

5. Watershed Application: Design Concepts

5.1. Design concept overview

The design concept category for the ODD protocol lists eleven elements (Grimm et al., 2010a, Table 1). The first-listed element is basic principles, characterized as general concepts, theories, hypotheses, or modeling approaches that underly a model’s design. The ten remaining elements concern the specific manner in which processes are modeled.

The basic principles underlying the watershed application are explained in Section 5.2, and the ten remaining design-concept elements for the watershed application are explained in Section 5.3.

5.2. First ODD Design Concept: Basic Principles

WACCSHed is an agent-based computational platform, and the watershed application—implemented by means of this platform—is an agent-based model. Specifically, the watershed application is an instance of *agent-based computational economics (ACE)* modeling, the computational modeling of economic processes as open-ended dynamic systems of interacting agents. Although the precise meaning of “agent-based modeling” continues to be debated in the literature, seven basic modeling principles have been developed for ACE that carefully distinguish it from other types of modeling and that highlight its particular relevance for the study of watersheds as dynamic coupled natural and human systems.

The seven basic modeling principles underlying ACE model design are presented and explained in Table 3 as BMP1 through BMP7. Taken together, these seven principles express the fundamental goal of many agent-based modelers: namely, to be able to study real-world systems as historical processes unfolding through time, driven solely by their own internal dynamics (Tsfatsion, 2016a, Sections 8-11).

Three additional basic modeling principles specific to the watershed application are listed in Table 3 as BMP8 through BMP10. These three principles reflect a concern that physical and financial feasibility constraints be carefully modeled to provide a proper scaffolding for the study of human decision-making processes.

Table 3: Basic modeling principles (BMPs) underlying the watershed application

BMP	BMP Aspect	BMP Description
BMP1	<i>Agent Definition</i>	An agent is a software entity within a computational world able to act over time on the basis of its own state, i.e., its own internal data, attributes, and methods.
BMP2	<i>Agent Scope</i>	Agents can represent individuals, social groupings institutions, biological entities, and/or physical entities.
BMP3	<i>Agent Local Constructivity</i>	The decision-making process undertaken by a decision-making agent at any given time must be entirely expressible as a function of the agent's state at that time.
BMP4	<i>Agent Autonomy</i>	Coordination of agent interactions cannot be externally imposed by means of free-floating restrictions; that is, by means of modeler-imposed restrictions not embodied within agent states.
BMP5	<i>System Constructivity</i>	The state of the modeled system at any given time consists of the collection of agent states at that time.
BMP6	<i>System Historicity</i>	Given initial agent states, all subsequent events in the modeled system are determined solely by agent interactions.
BMP7	<i>Modeler as Culture-Dish Experimenter</i>	The role of the modeler is limited to the setting of initial agent states and to the non-pertubational observation of model outcomes.
BMP8	<i>Empirically-Based Hydrological Modeling</i>	The HEC-HMS is used to model relationships among precipitation, land curve numbers, and water runoff.
BMP9	<i>Stock-Flow Consistency</i>	Stocks (physical/financial assets) are carefully modeled as accumulations of flows (net investment/savings).
BMP10	<i>Balance-Sheet Accounting</i>	Budget constraints are fully respected; every purchase is backed by actual purchasing power at the time the purchase is made.

The HEC-HMS referred to in BMP8 is the U.S. Army Corps of Engineers Hydrologic Modeling System, a well-tested and widely applied system within hydrology and engineering communities (Feldman, 2000; Scharffenberg, 2013). A more detailed discussion of the HEC-HMS can be found in Tesfatsion et al. (2016, Section 3.2).

5.3. Ten Additional ODD Design Concepts

The ten remaining ODD design concepts concern the specific modeling of agent interaction and decision-making processes and the outcomes that result from these modeled processes. Since these aspects of the watershed application are covered at length in subsequent sections, only brief summaries are provided here. Closely related concepts are grouped together for clarity.

Emergence: Farmer and city social welfare outcomes arise over time from the state-conditioned decisions and interactions of the agents populating the modeled watershed. A key concern for effective local governance is whether these welfare outcomes are *aligned*, in the sense that they move up and down together in response to changing conditions, or are *in conflict* in the sense that a gain for one is a loss for the other.

Sensing and Adaptation: The Farmer and City Manager are goal-directed agents that attempt to adapt their behavior optimally in response to changed state conditions, including changes to information, physical conditions, and financial conditions.

Stochasticity: Input costs, precipitation, and corn prices are modeled as random variables whose annual realizations are drawn from stationary empirically-based probability distributions. Also, the decision methods used by the Farmer and the City Manager include the use of pseudo-random number generators to select randomly among decisions perceived to be equally desirable.

Objectives: The long-term objective of the Farmer is to achieve and sustain an optimal consumption level over time. The long-term objective of the City Manager is to maximize social welfare for his city’s inhabitants over time.

Learning and Prediction: Due to computational constraints, the Farmer and City Manager attempt to achieve their long-term objectives by

solving successive decision problems that only require the expected net benefits associated with alternative decisions to be calculated over short planning horizons.

Interaction: Coupled interactions occur among human decision making, environment, and market processes during each simulated year. The budget allocation decision of the City Manager affects the income earning opportunities available to the Farmer, which in turn influence the Farmer’s land allocation decision; and it also determines levee quality and the amount of expenditure on city social services. The subsequent realization of a precipitation pattern then determines city flooding and hence city social welfare; and the subsequent realization of a corn price (given earlier realizations for input costs and precipitation) determines the Farmer’s corn consumption (welfare) as well as her money holdings for the start of the subsequent year.

Collectives: The City Manager is a collective only in the following fiduciary sense: he acts on behalf of his city’s inhabitants in an attempt to ensure their social welfare.

Observation/Output Data: Three treatment factors are tested: Farmer decision method, Farmer savings target, and levee quality effectiveness. For each tested configuration of these three treatment factors, annual Farmer and city social welfare outcomes are reported for twenty simulated years under thirty-one different environmental scenarios. Additional outcomes (e.g., time series for City Manager and Farmer allocation decisions) are reported in Tesfatsion et al. (2016).

6. Watershed Application: Details

6.1. Initialization

Apart from treatment factors and random event realizations, all exogenous (externally determined) variables for the watershed application are maintained at fixed values for all of the sensitivity findings reported in this study. These fixed values are provided in Table A.5 in Appendix A.

The fixed state aspects of the Farmer and City Manager, set at the initial time 1:1, include complete structural information about the physical and economic aspects of the Watershed World relevant for their decision making.

This information includes knowledge of the probability distributions governing random environmental event realizations. In addition, the City Manager at time 1:1 knows the Farmer’s decision method and initial money holdings.

6.2. Input Data

Annual environmental events (input costs, precipitation, corn prices) in the watershed application are modeled as realizations drawn from independent, stationary, empirically-based probability distributions. These distributions are specified as follows:²

- *Input Cost Distribution:* Three possible realizations (low, mod, high) for annual corn-production input costs, with probabilities 25%, 50%, and 25%, respectively, are estimated based on 2005-2013 data for seed and chemical costs assuming corn-following-corn (ISU, 2015a).
- *Precipitation Distribution:* Three possible realizations (low, mod, high) for annual precipitation (hourly rainfall depth in inches), with probabilities 25%, 50%, and 25%, respectively, are estimated based on 1997-2013 rainfall data for Ames, Iowa (IEM, 2015).
- *Corn Price Distribution:* Three possible realizations (low, mod, high) for the annual corn price, with probabilities 25%, 50%, and 25%, respectively, are estimated based on 1997-2013 corn price data (ISU, 2015b).

Making use of these independent stationary probability distributions for annual input costs, precipitation, and corn prices, we constructed an ensemble $\mathcal{S}$ consisting of thirty-one potential environmental scenarios s , each covering twenty simulated years, for use in all reported sensitivity studies for the watershed application. Each scenario s takes the form

$$\text{scenario } s = ((x_1^s, y_1^s, z_1^s), (x_2^s, y_2^s, z_2^s), \dots, (x_{20}^s, y_{20}^s, z_{20}^s)) \quad (1)$$

where:

$$\begin{aligned} x_j^s &= \text{input cost (low, mod, or high) in year } j \text{ under scenario } s \\ y_j^s &= \text{precipitation (low, mod, or high) in year } j \text{ under scenario } s \\ z_j^s &= \text{corn price (low, mod, or high) in year } j \text{ under scenario } s \end{aligned}$$

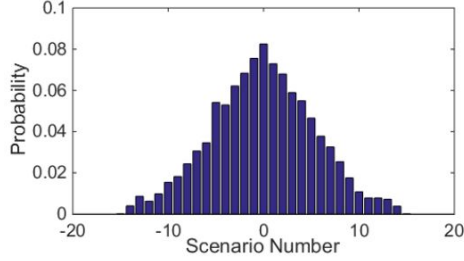


Figure 5: Probability distribution for environmental scenarios in the watershed application

As detailed in Appendix B, the thirty-one scenarios in the ensemble $\mathcal{S}$ have unique scenario numbers ranging from -15 to +15. A scenario's assigned number represents its Hamming-measure distance from the *normal scenario 0* characterized by moderate input costs, moderate precipitation, and moderate corn prices in each of the twenty simulated years. Scenarios with negative scenario numbers tend to deviate from scenario 0 on the low side, and scenarios with positive scenario numbers tend to deviate from scenario 0 on the high side. The bell-shaped probability distribution function calculated for these thirty-one scenarios is depicted in Fig. 5.

6.3. Submodels: Process Details

The Watershed World is a discrete-time state space model in initial value form (Teshfatsion, 2016a). Starting from initial conditions, set by the modeler, all dynamic outcomes in the Watershed World are driven solely by the actions and interactions of its constituent physical, institutional, and decision-making agents.

More precisely, recall from Section 4.3 that each simulated year t in the watershed application is divided into seasonal subperiods t_k , $k = 1, \dots, 7$, where t_k denotes the time interval $[t:k, t:(k+1))$. Let $x_{t:k}$ denote the state of the Watershed World at the beginning subperiod t_k . Let $\omega_{t:k}$ denote the realizations for all random events occurring during subperiod t_k , which could include an input cost, a precipitation pattern, a corn price, and/or outcomes from pseudo-random number devices employed by decision-making agents to resolve choice among equally-preferred decision options. Let $d_{t:k} = d(x_{t:k}, \omega_{t:k})$ denote all decisions made by the Farmer and City Manager

²See Table A.5 for the low, moderate, and high values set for each random variable.

during subperiod $t:k$, which are dependent in part or in whole on $x_{t:k}$ and $\omega_{t:k}$; and let $y_{t:k} = y(x_{t:k}, \omega_{t:k}, d_{t:k})$ denote all other outcomes during subperiod $t:k$, which are dependent in part or in whole on $x_{t:k}$, $\omega_{t:k}$, and $d_{t:k}$: e.g., harvest yield.

Then, making use of the functional forms for $d_{t:k}$ and $y_{t:k}$, the motion over time of the Watershed World state can be expressed as follows. For any subperiod t_k :

$$x_{t:(k+1)} = S(x_{t:k}, \omega_{t:k}, d_{t:k}, y_{t:k}) \equiv F(x_{t:k}, \omega_{t:k}, d(x_{t:k}, \omega_{t:k})) ; \quad (2)$$

$$x_{1:1} = x_{1:1}^o \quad (\text{exogenously given}) \quad (3)$$

This form indicates that the driving forces determining the Watershed World state $x_{t:(k+1)}$ at time $t:(k+1)$ are the previous state $x_{t:k}$, the random event realizations $\omega_{t:k}$, and the manner in which the Farmer and City Manager determine their decisions $d_{t:k}$ as a function $d(x_{t:k}, \omega_{t:k})$ of $x_{t:k}$ and $\omega_{t:k}$.

This section provides detailed descriptions of the processes determining $\omega_{t:k}$, $y_{t:k}$, and $x_{t:(k+1)}$ for each subperiod t_k , conditional on $d_{t:k}$, for $k = 1, \dots, 7$ and for any simulated year $t \geq 1$. Nomenclature tables giving symbols, verbal definitions, units, and values (where appropriate) for all variables appearing in these descriptions can be found in Appendix A. Some technical aspects of these descriptions are relegated to Appendix B through Appendix F.

The physical and financial feasibility conditions constraining the Farmer and City Manager decisions $d_{t:k}$ are taken into account in these process descriptions. However, since the decision methods $d(x_{t:k}, \omega_{t:k})$ used by the Farmer and City Manager to select their decisions $d_{t:k}$ are key treatment factors for the ensuing sensitivity study, the precise formulation of these decision methods is deferred until the presentation of the sensitivity study design in Section 7.

Subperiod t_1 (January): An input cost per acre is realized.

At the beginning of subperiod $t_1 = [t:1, t:2)$ the Farmer and City Manager are

in states $X_{t:1}^F$ and $X_{t:1}^{CM}$.³ An input cost per acre is then realized, as follows:

$$\begin{aligned} \text{InputCost}_{t:1} &= \text{Input cost (\$/acre)} \\ &= \text{Per-acre cost of seed and chemicals} \\ &\quad \text{needed to plant cropland} \end{aligned} \tag{4}$$

This modeling of input costs assumes a fixed planting density (seeds/acre). Thus, the Farmer does not attempt to modify her input costs (\$/acre) by varying her planting density.

Subperiod t_2 (February): City Manager allocates city budget.

At the beginning of subperiod $t_2 = [t:2, t:3)$ the City Manager allocates the city budget $B_{t:1}$ into a city social service expenditure portion, a subsidy portion, and a levee investment portion. This budget allocation is determined by the values the City Manager selects for the subsidy and levee investment percentages $(s_{t:2}, \ell_{t:2})$, which must lie in the following decision domain:

$$D^{CM} = \{(s, \ell) \mid 0 \leq s, 0 \leq \ell, s + \ell \leq 1\} \tag{5}$$

The percentages $(s_{t:2}, \ell_{t:2})$ determine the city budget allocation as follows:

$$\begin{aligned} \text{RetSub}^{poss}(s_{t:2}) &= s_{t:2}B_{t:1} \\ &= \text{Dollars set aside for retention-land subsidy spending} \end{aligned} \tag{6}$$

$$\begin{aligned} \tau_{t:2} = \tau(s_{t:2}) &= [\text{RetSub}^{poss}(s_{t:2})] / [r^{max} A^F] \\ &= \text{Retention-land subsidy rate (\$/acre) set for year } t \end{aligned} \tag{7}$$

$$\begin{aligned} \text{LevInv}(\ell_{t:2}) &= \ell_{t:2}B_{t:1} \\ &= \text{Dollars set aside for levee repair and improvement} \end{aligned} \tag{8}$$

³The decision processes undertaken by the Farmer and City Manager at any time $t:k$ during year t depend on their updated time- $(t:k)$ states $X_{t:k}^F$ and $X_{t:k}^{CM}$; recall from Section 4.2 that the information included in these states is continuously updated to include all past decisions and environmental event realizations. However, for clarity of exposition, this dependence is not explicitly indicated in the notation used below to describe decision processes.

$$\begin{aligned}\text{SocServ}^{poss}(s_{t:2}, \ell_{t:2}) &= [1 - s_{t:2} - \ell_{t:2}]B_{t:1} \\ &= \text{Dollars set aside for city social service spending}\end{aligned}\quad (9)$$

In (7), A^F denotes the total amount of farmland in the watershed, and $r^{max} \in [0, 1]$ is a watershed policy parameter giving the maximum percentage of A^F that the Farmer is allowed to allocate as retention land.

The City Manager's budget allocation in turn determines levee quality for year t , as follows:

$$\begin{aligned}LQ_{t:2} = LQ(\ell_{t:2}) &= [1 - \delta]LQ_{(t-1):2} + g\text{LevInv}(\ell_{t:2}) \\ &= \text{Levee quality for year } t\end{aligned}\quad (10)$$

In (10), g (ft/\$) maps dollars of levee investment into levee quality (height), δ is a depreciation rate, and the levee quality $LQ_{(t-1):2}$ determined at time $(t-1):2$ for year $t-1$ is known to the City Manager from inclusion in his state $X_{t:1}^{CM}$.

Subperiod t_3 (March): The Farmer allocates her farmland.

At the beginning of subperiod $t_3 = [t:3, t:4)$ the Farmer allocates her farmland A^F among cropland, retention land, and fallow land. This allocation is determined by the values the Farmer selects for the cropland and retention-land percentages $(c_{t:3}, r_{t:3})$, which must lie in the following decision domain:

$$D^F(r^{max}) = \{(c, r) \mid 0 \leq c, 0 \leq r \leq r^{max}, c + r \leq 1\} \quad (11)$$

The percentages $(c_{t:3}, r_{t:3})$ determine the Farmer's land allocation as follows:

$$A^{crop}(c_{t:3}) = c_{t:3}A^F = \text{Farmer's cropland for year } t \quad (12)$$

$$A^{ret}(r_{t:3}) = r_{t:3}A^F = \text{Farmer's retention land for year } t \quad (13)$$

$$\begin{aligned}A^{fal}(c_{t:3}, r_{t:3}) &= [1 - c_{t:3} - r_{t:3}]A^F \\ &= \text{Farmer's fallow land for year } t\end{aligned}\quad (14)$$

The percentages $(c_{t:3}, r_{t:3})$ also determine the following additional outcomes at time $t:3$:

$$\begin{aligned}\text{RetSub}^{act}(\tau_{t:2}r_{t:3}) &= \tau_{t:2}r_{t:3}A^F \\ &= \text{F's actual retention-land subsidy receipts (\$) for year } t\end{aligned}\quad (15)$$

$$\begin{aligned}\text{SocServ}^{act}(\tau_{t:2}r_{t:3}, \ell_{t:2}) &= B_{t:1} - \text{RetSub}^{act}(\tau_{t:2}r_{t:3}) - \text{LevInv}(\ell_{t:2}) \\ &= \text{CM's actual city social service spending (\$) for year } t\end{aligned}\quad (16)$$

The Farmer's money holdings at time $t:3$ are thus given by

$$M_{t:3}(\tau_{t:2}r_{t:3}) = M_{t:1} + \text{RetSub}^{act}(\tau_{t:2}r_{t:3}) \geq 0 \quad (17)$$

The Farmer does not want to waste resources by designating more farmland as cropland than she can afford to plant. Since a realization $\text{InputCost}_{t:1}$ (\$/acre) for year- t input costs has already been observed at time $t:1$, the Farmer can ensure non-wastage of cropland by imposing the following additional constraint on her choice of the percentages $(c_{t:3}, r_{t:3})$ at time $t:3$:

$$\begin{aligned} \text{InputCost}_{t:1} \cdot c_{t:3} A^F &= \text{InputCost}_{t:1} \cdot A^{crop}(c_{t:3}) \\ &\leq M_{t:3}(\tau_{t:2}r_{t:3}) \end{aligned} \quad (18)$$

Condition (18) and the requirement $c_{t:3} \leq 1$ impose the following upper bound on $c_{t:3}$:

$$c_{t:3} \leq c^{max}(\tau_{t:2}r_{t:3}) \equiv \min\left\{1, \frac{M_{t:3}(\tau_{t:2}r_{t:3})}{\text{InputCost}_{t:1} \cdot A^F}\right\} \quad (19)$$

Subperiod t_4 (April-September): The Farmer buys inputs, plants seed, and tends her cropland.

At the beginning of subperiod $t_4 = [t:4, t:5)$ the Farmer uses her money holdings $M_{t:3}(\tau_{t:2}r_{t:3})$ to purchase all inputs needed to plant $A^{crop}(c_{t:3})$. The Farmer's money holdings at time $t:4$, after all input purchases have been made, are given by

$$M_{t:4}(c_{t:3}, \tau_{t:2}r_{t:3}) = M_{t:3}(\tau_{t:2}r_{t:3}) - \text{InputCost}_{t:1} A^{crop}(c_{t:3}) \geq 0 \quad (20)$$

Subperiod t_5 (October): A precipitation pattern is fully realized, determining city social welfare and the Farmer's mature corn crop

A precipitation pattern $\text{Precip}_{t:5}$ is fully realized during subperiod $t_5 = [t:5, t:6)$ consisting of the hourly rainfall depth occurring from January 1 through October 15 of year t . This precipitation pattern determines the

following outcomes:

$$H_{t:5} = H(\text{Precip}_{t:5}) = \text{Harvest yield (bushels/acre) for year } t \quad (21)$$

$$\text{CCrop}_{t:5}(c_{t:3}) = H_{t:5} \cdot A^{crop}(c_{t:3}) = \text{Corn crop (bushels) for year } t \quad (22)$$

$$\begin{aligned} Q_{p,t:5}(c_{t:3}, r_{t:3}) &= Q_p(\text{Precip}_{t:5}, A^{crop}(c_{t:3}), A^{ret}(r_{t:3}), A^{fal}(c_{t:3}, r_{t:3})) \\ &= \text{Peak water discharge rate into the city (ft}^3/\text{s} \equiv \text{cfs}) \end{aligned} \quad (23)$$

$$\begin{aligned} FD_{t:5}(\ell_{t:2}, c_{t:3}, r_{t:3}) &= FD(LQ(\ell_{t:2}), Q_{p,t:5}(c_{t:3}, r_{t:3})) \\ &= \text{City flood damage (\$) during year } t \end{aligned} \quad (24)$$

$$\begin{aligned} \text{CSW}_{t:5}(\tau_{t:2}, \ell_{t:2}, c_{t:3}, r_{t:3}) \\ &= \text{CSW}(\text{SocServ}^{act}(\tau_{t:2}r_{t:3}, \ell_{t:2}), FD_{t:5}(\ell_{t:2}, c_{t:3}, r_{t:3})) \\ &= \text{City social welfare (\$) for year } t \end{aligned} \quad (25)$$

More precisely, $\text{CSW}_{t:5}$ is a weighted average of city social services (\$) and city flood-damage mitigation (\$) given by

$$\text{CSW}_{t:5} = \text{SocServ}_{t:3}^{act} + \psi \cdot [FD^{max} - FD_{t:5}] \quad (26)$$

In (26), ψ is a trade-off parameter, FD^{max} is a parameter in the city flood damage function (24) that denotes maximum avoidable city flood damage, $FD_{t:5}$ denotes actual city flood damage, and $[FD^{max} - FD_{t:5}]$ measures avoided city flood damage. Detailed specifications for the harvest yield function (21) and the city flood-damage function (24) are provided in Appendix C and Appendix D, respectively.

Subperiod t_6 (November): A corn price is realized.

At the beginning of subperiod $t_6 = [t:6, t:7)$ a corn price, $\text{CPrice}_{t:6}$ (\$/bushel), is realized in the corn market. This corn price in turn determines

$$\begin{aligned} \text{Value}_{t:6}^{crop}(c_{t:3}) &= \text{CPrice}_{t:6} \cdot \text{CCrop}_{t:5}(c_{t:3}) \\ &= \text{Market value (\$) of the Farmer's corn crop} \end{aligned} \quad (27)$$

Subperiod t_7 (December): Farmer welfare is determined.

At the beginning of subperiod $t_7 = [t:7, t:8)$, the Farmer's possible money holdings if she sells all of her crop in the corn market are

$$M_{t:7}^{poss}(c_{t:3}, \tau_{t:2}r_{t:3}) = M_{t:4}(c_{t:3}, \tau_{t:2}r_{t:3}) + \text{Value}_{t:6}^{crop}(c_{t:3}) \quad (28)$$

The Farmer sells corn in the corn market at price $\text{CPrice}_{t:6}$ and retains (and/or buys) corn in amount $\text{Cons}_{t:7}^F$ to consume for herself. This determines her year- t welfare, measured by the utility (benefit) she obtains from the consumption of $\text{Cons}_{t:7}^F$. This utility-of-consumption is measured by:

$$\text{UOC}_{t:7} = u(\text{Cons}_{t:7}^F) = \ln(\text{Cons}_{t:7}^F - \bar{C}^F + D) \quad (29)$$

where the Farmer's subsistence consumption level $\bar{C}^F$ is set at 125 bushels and the Farmer's risk tolerance parameter D is set at 126 bushels.⁴ The Farmer's consumption level $\text{Cons}_{t:7}^F$ is determined as follows:

- If the Farmer is unable to attain at least her subsistence consumption level $\bar{C}^F$, i.e., if $\text{CPrice}_{t:6} \cdot \bar{C}^F > M_{t:7}^{\text{poss}}(c_{t:3}, \tau_{t:2}r_{t:3})$, she then consumes

$$\text{Cons}_{t:7}^F = \frac{M_{t:7}^{\text{poss}}(c_{t:3}, \tau_{t:2}r_{t:3})}{\text{CPrice}_{t:6}} < \bar{C}^F \quad (30)$$

Unable to remain in the farming business, she exits the watershed at the end of subperiod t_7 and all of her farmland reverts to fallow land.

- If $\text{CPrice}_{t:6} \cdot \bar{C}^F \leq M_{t:7}^{\text{poss}}(c_{t:3}, \tau_{t:2}r_{t:3})$, then the Farmer selects a savings level $S_{t:7}^F$ and a consumption level $\text{Cons}_{t:7}^F$ subject to the following budget, subsistence, and savings-target constraints:

$$S_{t:7}^F + \text{CPrice}_{t:6} \cdot \text{Cons}_{t:7}^F = M_{t:7}^{\text{poss}}(c_{t:3}, \tau_{t:2}r_{t:3}) \quad (31)$$

$$\text{Cons}_{t:7}^F \geq \bar{C}^F \quad (32)$$

$$S_{t:7}^F \geq S^{Fo} \quad (33)$$

where, if necessary, the Farmer ratchets down her initial savings target $S^{Fo} \geq 0$ until all three constraints can be satisfied.⁵ Thus, the Farmer's money holdings for the start of year $t + 1$ are

$$M_{(t+1):1} = S_{t:7}^F \quad (34)$$

⁴These settings for $\bar{C}^F$ and D ensure that (29) is well-defined even when $\text{Cons}_{t:7}^F = 0$. Note that $D = -u'(\bar{C}^F)/u''(\bar{C}^F)$. As detailed in Tesfatsion et al. (2016, Section 7.3), within economics the inverse expression, $-u''(C)/u'(C)$, is known as the Arrow-Pratt Measure of Risk Aversion; it provides a proxy measure for the *aversion* to risk displayed by an (expected) utility maximizing consumer at a particular consumption level C .

⁵This ratcheting process is detailed in Appendix E.

At the end of subperiod t_7 , the Farmer (if still present in the watershed) is in state $X_{(t+1):1}^F$. This updated state includes her previous state $X_{t:1}^F$, a record of all decisions and environmental event realizations she observed during year t , and her money holdings (34) for the start of year $t + 1$.

At the end of subperiod t_7 the City Manager is in state $X_{(t+1):1}^{CM}$. This updated state includes his previous state $X_{t:1}^{CM}$, a record of all decisions and environmental event realizations he observed during year t , and the city budget $B_{(t+1):1}$ for year $t + 1$.

7. Sensitivity Design for the Watershed Application

7.1. Sensitivity Design Overview

The sensitivity design for the watershed application focuses on welfare outcomes. Simulation experiments are conducted to explore how Farmer welfare and city social welfare vary in response to changes in three treatment factors pertaining to the risk management practices of the Farmer and the City Manager.

Farming is a risky business. Cropland is a risky asset because positive net earnings are not assured. Poor precipitation conditions (too much or too little rain) can diminish harvest yield, and poor market conditions (input costs too high and/or corn prices too low) can lead to small or even negative profit margins. In contrast, water-retention land and fallow land are sure-thing assets: the Farmer is guaranteed to receive a non-negative subsidy rate on each retention acre and a zero return rate on each fallow acre. However, the Farmer has no safe harbor; she must secure a sufficient return on her farmland to meet her annual consumption needs $\bar{C}^F$ in order to sustain her farming business in the watershed over time.

Consequently, the Farmer's land allocation decision is an important reflection of her stance towards risk. A key treatment factor considered in the sensitivity design, called the *Decision Treatment*, determines the decision method annually used by the Farmer to determine her land allocation as well as her consumption and savings levels. The first tested decision method is annual maximization of expected consumption; the Farmer acts as if normal (average) market and precipitation conditions will prevail each year, ignoring the risk that adverse events could bankrupt her farm and force her exit from the watershed. The second tested decision method is annual maximization of

expected utility-of-consumption (UOC), where the concave curvature of the UOC function induces risk-averse consideration of possible adverse events.

The second considered treatment factor is the *savings-target scale factor* θ^o . This scale factor determines the magnitude of the Farmer’s initial savings target $S^{Fo} = S^F(\theta^o)$, i.e., her planned annual precautionary savings against *future* risks. The magnitude of this scale factor thus reflects the extent to which the Farmer recognizes the approximate nature of her short-term decision problems in relation to her longer-term goal: to survive and prosper as a watershed farmer over multiple years.

The third considered treatment factor is *Levee Quality Effectiveness (LQE)*. The LQE parameter measures the effectiveness of city levee investments as a means for mitigating city flood damage. All else equal, a larger LQE setting implies a smaller need for the City Manager to make subsidy payments to the Farmer for retention-land set-aside, which reduces Farmer income and increases Farmer bankruptcy risk.

For each treatment-factor configuration, thirty-one simulation runs are conducted, one for each of the thirty-one environmental scenarios s whose construction is explained in Section 6.2. Since each scenario s spans twenty simulated years, each run also spans twenty simulated years. All other exogenous (externally determined) aspects of the watershed application are maintained at fixed values for all of the sensitivity findings reported in this study; see Table A.5.

7.2. Decision Treatments

Two decision methods are considered for the Farmer: F-OFF (expected consumption maximization) and F-ON (expected utility-of-consumption maximization). Only one decision method is considered for the City Manager: CM-ON (expected city social welfare maximization). Each decision method includes the use of a pseudo-random number generator to select randomly among equally-preferred decision options.

More precisely, as detailed in Appendix E and Appendix F, the following two decision treatments are tested:

Decision Treatment 1: (F-OFF, CM-ON)

- The Farmer at time $t:3$, during each successive year t , selects a land allocation $(c_{t:3}, r_{t:3})$ from her decision domain (11) that maximizes her state-conditioned expected money holdings $\mathbb{E}[M_{t:7}^{poss}(c, \tau_{t:2}r) \mid X_{t:3}^F]$ for the start of time $t:7$. The Farmer at time $t:7$ then consumes as much

as possible, conditional on the budget, subsistence, and savings-target constraints (31) through (33).

- The City Manager at time $t:2$, during each successive year t , selects a budget allocation $(s_{t:2}, \ell_{t:2})$ from his decision domain (5) that maximizes state-conditioned expected city social welfare $\mathbb{E}[\text{CSW}_{t:5} \mid X_{t:2}^{CM}]$ for year t . This maximization takes into account how the retention-land subsidy rate $\tau_{t:2} = \tau(s_{t:2})$ resulting from the selected budget allocation will affect the Farmer's land allocation at time $t:3$.

Decision Treatment 2: (F-ON, CM-ON)

- The Farmer at time $t:3$, during each successive year t , selects a land allocation $(c_{t:3}, r_{t:3})$ from her decision domain (11), as well as consumption and savings levels $\text{Cons}_{t:7}^F$ and $\text{Sav}_{t:7}^F$, to maximize her state-conditioned expected utility-of-consumption $\mathbb{E}[u(\text{Cons}_{t:7}^F) \mid X_{t:3}^F]$ for year t conditional on the budget, subsistence, and savings-target constraints (31) through (33).
- The City Manager behaves the same as in Decision Treatment 1.

7.3. Farmer Savings-Target Treatments

Under each tested Farmer decision method, F-OFF or F-ON, the Farmer's initial savings target S^{Fo} appearing in her savings-target constraint (33) is given by

$$S^{Fo} = S^F(\theta^o) = \theta^o \cdot \mathbb{E}[\text{CPrice}] \cdot \bar{C}^F \quad (35)$$

In (35), the *savings-target scale factor* θ^o is a unit-free non-negative scalar that affects the magnitude of S^{Fo} , $\mathbb{E}[\text{CPrice}]$ is the stationary expectation for the annual corn price, and $\bar{C}^F$ is the Farmer's annual subsistence corn consumption level. Thus, the initial savings target (35) is anchored by an estimate of the money holdings the Farmer would need to ensure her subsistence consumption for the next year in the absence of any new income.

The value for θ^o is systematically varied across computational experiments as a treatment factor. Results for the following three θ^o settings are reported in this study:

Low Savings-Target Scale Factor: $\theta^o = 100$

Moderate Savings-Target Scale Factor: $\theta^o = 5,000$

High Savings-Target Scale Factor: $\theta^o = 20,000$

7.4. Levee Quality Effectiveness Treatments

As detailed in Appendix D, the city flood damage function $FD(LQ, Q_p)$ determines city flood damage as a function of city levee quality LQ and the peak water discharge rate Q_p into the city. Among the parameters characterizing this function is a shift factor LQE representing levee quality effectiveness: For any given LQ , a higher setting for LQE shifts the flood damage function to the right, increasing the range of Q_p values for which city flood damage remains low. Results for the following two LQE settings are reported in this study:

Low Levee Quality Effectiveness: LQE = 51.5 cfs/ft

High Levee Quality Effectiveness: LQE = 98.2 cfs/ft

8. Illustrative Welfare Outcomes for the Watershed Application

8.1. Welfare outcome overview

The welfare outcomes reported in this section for the watershed application are for illustrative purposes only. Consequently, discussions of these outcomes are kept brief. A more comprehensive report of findings for the watershed application is provided in Tesfatsion et al. (2016, Sections 6-7).

8.2. Welfare Metrics

Farmer welfare (utility-of-consumption) is measured by total UOC (29) attained over twenty simulated years, and city social welfare is measured by total CSW (26) attained over twenty simulated years. Outcomes for total UOC and total CSW are reported in two forms: (i) in expected form, as a probability-weighted average across the thirty-one possible environmental scenarios, together with dispersion ranges; and (ii) differentiated by environmental scenario.

Regarding form (i), bar charts are used to report overall expected values and dispersion ranges for total UOC and total CSW under various treatments. Bar height indicates expected value, and the vertical line centered at each bar height depicts the dispersion range for the expected value, determined as plus or minus one standard deviation around the expected value.

Regarding form (ii), each scenario represents low, moderate, or high annual realizations over twenty simulated years for three environmental factors: namely, input cost, precipitation, and corn price. As explained in Section 6.2,

the thirty-one scenarios (identified by scenario number) are dispersed around the normal scenario 0 for which all environmental factors take on moderate values.

In interpreting the welfare outcomes reported below, it is helpful to keep three points in mind. First, these outcomes are conditioned on a fixed value of 125 bushels for the Farmer's subsistence consumption level $\bar{C}^F$. If the Farmer is at a subsistence consumption level $\bar{C}^F$ in each of the twenty simulated years, then the total UOC she attains is 96.7. Second, if the Farmer goes bankrupt and is forced to leave farming, her annual UOC thereafter drops to 0. Third, welfare outcomes do not necessarily peak at the normal scenario 0. For example, all else equal, city social welfare is highest when precipitation is low, since this minimizes the risk of city flood damage.

8.3. Welfare Outcomes

Figures 6 and 7 report Farmer and city social welfare outcomes as measured by expected total UOC and expected total CSW, respectively, for six tested treatments with low (ℓ), moderate (m), and high (h) treatment values. These figures also report dispersion ranges around expected outcomes.

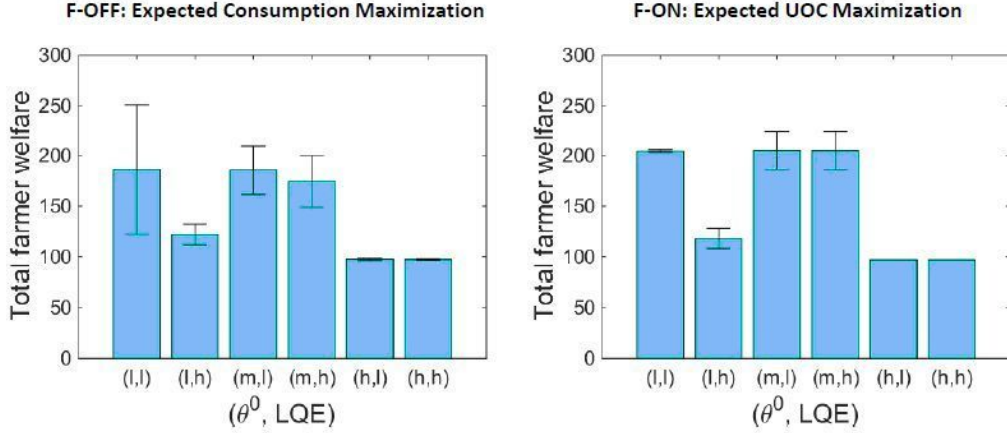


Figure 6: Expected total UOC outcomes (with dispersion ranges) for Farmer decision methods F-OFF and F-ON under six tested (θ^0, LQE) settings.

Four interesting regularities are apparent in Figs. 6 and 7. First, all else equal, expected total CSW increases and expected total UOC stays the same or decreases as LQE is increased from low to high. This occurs because the increase in LQE implies that a higher CSW outcome can be obtained for the

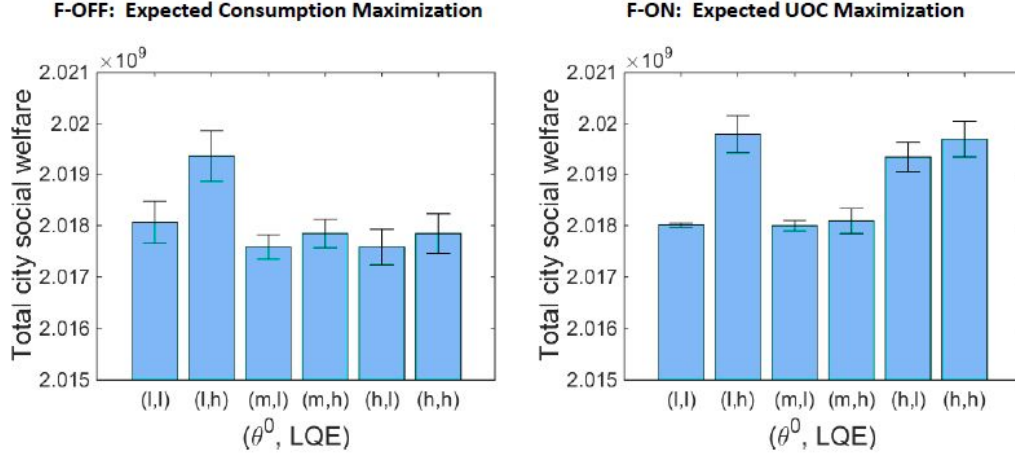


Figure 7: Expected total CSW outcomes (with dispersion ranges) for Farmer decision methods F-OFF and F-ON under six tested (θ^0, LQE) settings.

same overall budget spending level, either by maintaining current spending portions, or by shifting monies away from levee investment and towards city social services and/or subsidy payments.

Second, Farmer and city social welfare are well-aligned with regard to the Farmer's decision method. All else equal, expected total UOC and expected total CSW both tend to be higher for F-ON than for F-OFF. The F-OFF Farmer tends to select riskier land allocations with higher percentages of cropland, which in turn tends to increase runoff (hence city flood damage) as well as the chance of Farmer bankruptcy.

Third, Farmer and city social welfare outcomes are *not* well-aligned with regard to Farmer savings behavior. All else equal, expected total UOC is at or very near its highest level when the Farmer saves a reasonably high amount ($\theta^0 = \text{moderate}$). On the other hand, expected total CSW tends to be highest when the Farmer saves too little ($\theta^0 = \text{low}$), because this forces the Farmer to allocate at least some of her land to retention land in order to secure income for the purchase of inputs for crop production.

Fourth, the dispersion ranges around expected welfare outcomes tend to be larger (and in some cases substantially larger) for the F-OFF treatments relative to the F-ON treatments. These dispersion ranges reflect, in aggregate form, how welfare outcomes vary across environmental scenarios.

To provide a better understanding of the dispersion ranges depicted in

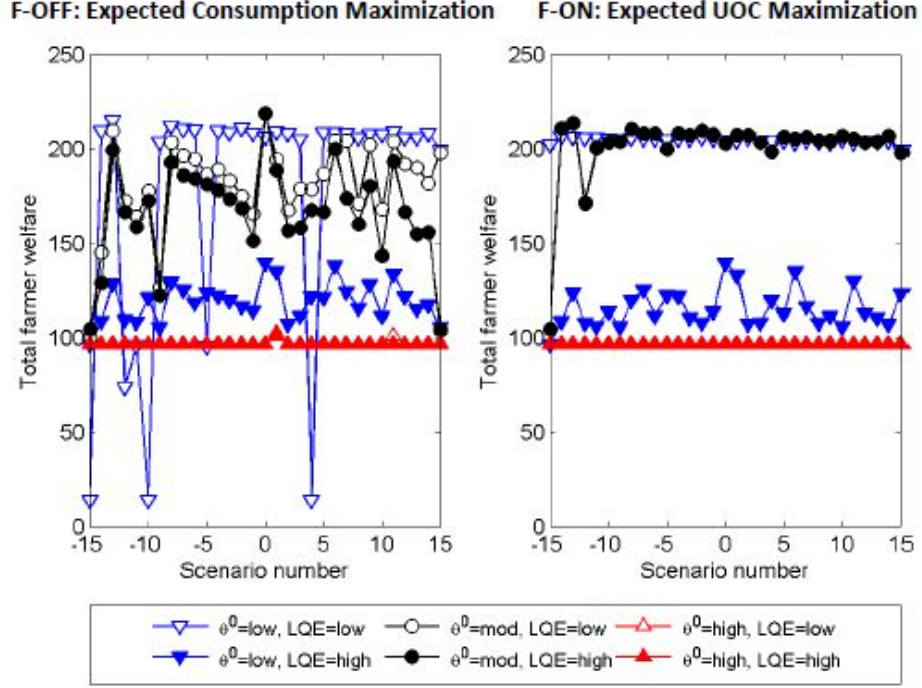


Figure 8: Total UOC outcomes for Farmer decision methods F-OFF and F-ON under six tested (θ^0 , LQE) settings, differentiated by environmental scenario. Scenario data points corresponding to the same treatment are connected by lines for visual clarity.

Figs. 6 and 7, Farmer and city social welfare outcomes are reported in Figs. 8 and 9 for the same set of treatments depicted in Figs. 6 and 7, only now differentiated by environmental scenario.⁶ Specifically, these figures report total UOC and total CSW for each of the thirty-one environmental scenarios constructed in Section 6.2, where the identification numbers for these thirty-one scenarios range from -15 to +15.

Figures 8 and 9 reveal, in stark terms, that total UOC and total CSW both exhibit much greater dispersion across scenarios in the F-OFF treat-

⁶Some types of symbols in Figs. 8 and 9 are obscured beneath other types of symbols for cases in which outcomes are not sensitive to changes in a treatment factor setting. For example, for the F-ON case depicted in Fig. 8 the black-bordered open circles lie completely beneath the black-filled circles because total UOC is not affected by a change from LQE=high to LQE=low, given $\theta^0=\text{mod}$.

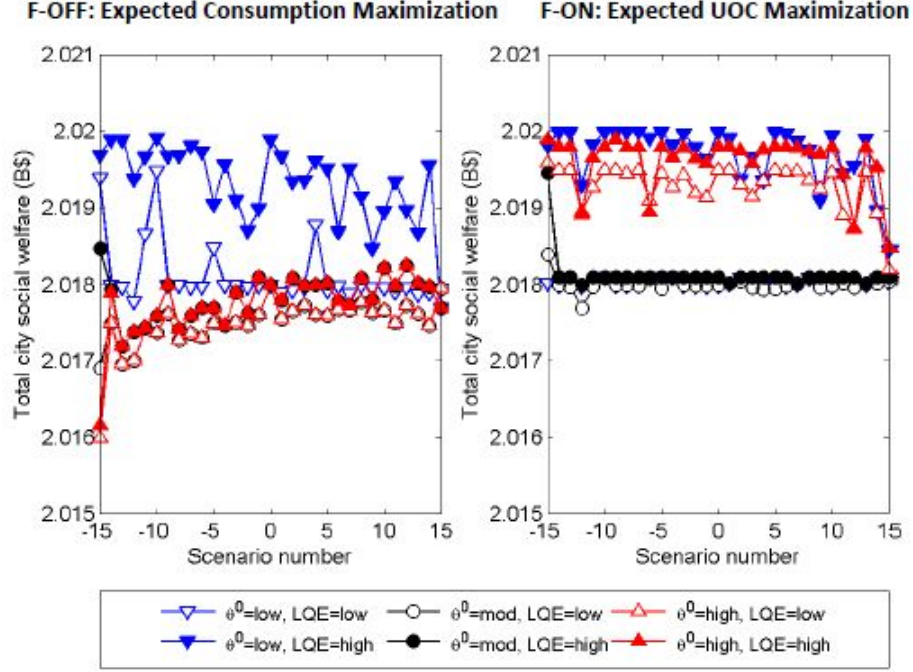


Figure 9: Total CSW outcomes for Farmer decision methods F-OFF and F-ON under six tested (θ^o , LQE) settings, differentiated by environmental scenario. Scenario data points corresponding to the same treatment are connected by lines for visual clarity.

ments than in the corresponding F-ON treatments. This greater dispersion reflects the F-OFF Farmer's singular focus on the *expected* net earnings associated with different land uses, ignoring production risks arising from uncertain precipitation and corn prices.

Consider, for example, the welfare outcomes in Figs. 8 and 9 corresponding to the treatment with θ^o =moderate and LQE=low, depicted by black-bordered open circles.⁷ Given θ^o =moderate, the Farmer annually plans to put aside a moderately large amount of money for future contingencies. Given LQE=low, levee investment is not a very effective use of city budget monies for city flood-damage mitigation; hence, if additional mitigation is desired, the City Manager has to offer the Farmer a sufficiently high sub-

⁷A detailed discussion of this treatment is provided in Tesfatsion et al. (2016, Section 6) for the normal scenario 0.

sidy rate to induce her to allocate part of her farmland to retention land rather than to cropland.

Thus, at least during the first few years (bolstered by her initial money holdings), the F-OFF Farmer has sufficient funds to purchase inputs for crop production through her own savings and/or through subsidy payments for retention land. The primary determinant of her annual cropland allocation at time $t:3$ during each year t is the input cost realized at time $t:1$; a low input cost induces a high cropland allocation, and vice versa. The F-OFF Farmer pays no attention to the risk of a bad crop yield arising from adverse weather (too much or too little precipitation) or to the risk of low net earnings arising from a low corn price. Rather, she essentially assumes that moderate precipitation and a moderate corn price will prevail.

In contrast, the F-ON Farmer selects a land allocation at each time $t:3$ in each year t that is conditional on the input cost realized at time $t:1$ but that also takes into account the full range of possible precipitation and corn price outcomes. The result is that the F-ON Farmer tends each year to allocate less of her land to cropland (and more of her land to retention-land) than the F-OFF Farmer, all else equal. Consequently, although the F-OFF Farmer does better than the F-ON Farmer in good farming years, the F-OFF Farmer does worse than the F-ON Farmer in bad farming years and is more likely to go bankrupt before the end of the twenty years. If the Farmer goes bankrupt, all of her land reverts to fallow land with a relatively high curve number (runoff potential) and her utility-of-consumption (UOC) drops to 0.

The land allocation decisions and welfare outcomes for the F-OFF Farmer are thus more volatile over time than those for the F-ON Farmer. This, in turn, induces more volatility in city social welfare outcomes.

9. Discussion

This study reports on the development of the WACCS_{hed} platform, an open source agent-based Java framework that permits watersheds to be studied as coupled natural and human systems. A key feature of this platform is its ability to model *strategic* decision-making among multiple types of human participants seeking to survive and prosper over time within watershed environments affected by climate and market events and constrained by institutional arrangements.

A watershed application is presented in accordance with the ODD protocol template (Grimm et al., 2010b) in order to provide a concrete demon-

stration of the capabilities and use of the WACCSHed platform. Given its purpose, the application is deliberately kept simple. The application reflects, in highly stylized form, the basic structural aspects of the Squaw Creek watershed in central Iowa: namely, an agricultural watershed with upstream farmland and a downstream city overseen by a city manager.

The watershed application demonstrates the platform’s ability to model policy interventions; the city manager sets an annual subsidy rate (\$/acre) for water-retention land as a mitigation device for city flood damage. The application also illustrates the platform’s ability to model strategic human decision-making by focusing on strategic interactions between the city manager, concerned solely with city social welfare, and an upstream farmer whose objective is to ensure the prosperity of her farming business over time. The city manager chooses his annual budget allocation taking into account how the resulting retention-land subsidy rate will affect the farmer’s land allocation, with subsequent implications for city flood damage. The findings reported in Section 8 confirm that this strategic interaction substantially affects farmer and city social welfare outcomes over time.

Moreover, although the application is primarily a qualitative rendering of a watershed, it indicates the platform’s ability to implement more empirically-based watershed models. Empirical data from Iowa are used to construct climate and market scenarios for the application, and the harvest yield function and city flood damage function used in the application are informed by actual harvest yield and curve number data from Iowa.

An important capability of the WACCSHed platform that is not explored in the current study is its suitability for use in Iterative Participatory Modeling (IPM) studies. As detailed in Barreteau et al. (2012) and Giuliani and Castelletti (2013), IPM envisions multidisciplinary researchers and stakeholders engaging together over time in the modeling and study of real-world systems of common interest. The intent is to help researchers and stakeholders manage complex systems through an ongoing collaborative learning process rather than through the attempted discovery of definitive problem solutions.

During 2016 the watershed application was used as the initial model for an IPM process whose purpose was improved local governance for the Squaw Creek watershed in central Iowa. Interactions with stakeholders led the modeling team to consider how the WACCSHed platform could be used to develop extended versions of this application to address issues of particular concern to these stakeholders. For example, how would the introduction of different

types of crop insurance programs affect farmer and city social welfare outcomes over time relative to the no-insurance base-case application reported in the current study? Future studies will report on this IPM-inspired work.

Acknowledgements

This study is an abbreviated revised version of Tesfatsion et al. (2016). It has been supported in part by a seed grant awarded under Iowa State University's Liberal Arts and Sciences Signature Research Initiative on Sustainability. The authors are grateful for helpful comments received from the editor, three anonymous referees, ISU LAS Dean Beate Schmittmann, ISU LAS Associate Dean Martin Spalding, Volker Grimm, Gary Polhill, and our other seed-grant participants: namely, David Dziubanski, Kristie Franz, Jean Goodwin, William W. Simpkins, and Alan Wanamaker. We are particularly grateful to David Dziubanski and Kristie Franz for their coding of the hydrology application component for our watershed application.

References

- AGDM, 2015. Historical Corn Yields by County, Ag Decision Maker, File A1-12, March. <http://www.extension.iastate.edu/agdm/crops/pdf/a1-12.pdf>
- An, L., 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models, *Ecological Modelling* 229(March), 25-36.
- Axelrod, R., Tesfatsion, L., 2006. A Guide for Newcomers to Agent-Based Modeling in the Social Sciences, pp. 1647-1659 in *Handbook of Computational Econ. Vol. 2: Agent-Based Computational Economics*, edited by L. Tesfatsion and K. L. Judd, Elsevier, Amsterdam, the Netherlands. <http://www2.econ.iastate.edu/tesfatsi/abmread.htm>
- Barreteau, O., Abrami, G., Daré, W., Du Toit, D., Ferrand, N., Garin, P., Souchère, V., Popova, A., Wery, C., 2012. Collaborative modelling as a boundary institution to handle institutional complexities in water management, Chapter 6 (pp. 109-127) in H.S. Karl et al. (eds.), *Restoring Lands-Coordinating Science, Politics, and Action: Complexities of Climate and Governance*, Springer, 2012.

- Barsugli, J.J., Guentchev, G., Horton, R.M., Wood, A., Mearns, L.O., Liang, X.-Z., Winkler, J.A., Dixon, K., Hayhoe, K., Rood, R.B., Goddard, L., Ray, A., Buja, L., Ammann, C., 2013. The practitioner's dilemma: How to assess the credibility of down-scaled climate projections. *EOS Transactions American Geophysical Union* 94, 424-425.
- Barthel, R., Janisch, S., Schwarz, N., Trifkovic, A., Nickel, D., Schulz, C., Mauser, W., 2008. An integrated modelling framework for simulating regional-scale actor responses to global change in the water domain, *Environmental Modelling & Software* 23, 1095-1121.
- Becu, N., Perez, P., Walker, A., Barreteau, O., Le Page, C., 2003. Agent based simulation of a small catchment water management in northern Thailand description of the CATCHSCAPE model, *Ecological Modelling* 170(2-3), 319-331.
- Bithell, M., Brasington, J., 2009. Coupling agent-based models of subsistence farming with individual-based forest models and dynamic models of water distribution, *Environmental Modelling & Software* 24(2), 173-190.
- Blair, P., Buytaert, W., 2016. Socio-hydrological modelling: A review asking why, what and how?, *Hydrology and Earth System Sciences* 20(1), 443-478.
- Borrill, P., Tesfatsion, L., 2011. Agent-Based Modeling: The right mathematics for the social sciences?, in *Elgar Companion to Recent Economic Methodology*, edited by J. B. Davis and D. W. Hands, pp. 228-258, Edward Elgar, New York, NY.
<http://www2.econ.iastate.edu/tesfatsi/ABMRightMath.PBLTWP.pdf>
- Chen, S.H., 2016. *Agent-Based Computational Economics*, Routledge, New York, 507pp.
- Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., Blösch, G., 2015. Debates–Perspectives on socio-hydrology: Capturing feedbacks between physical and social processes, *Water Resources Research* 51(6), 4770-4781.
- Diekert, F. K., 2012. The tragedy of the commons from a game-theoretic perspective, *Sustainability* 4(8), 1776-1786.

- Feldman, A.D., 2000. Hydrologic Modeling System HEC-HMS Technical Reference Manual, U.S. Army Corps of Engineers, Davis, CA, 155 pp.
- Filatova, T., Verburg, P.H., Parker, D.C., Stannard, C.A., 2013. Spatial agent-based models for socio-ecological systems: Challenges and prospects, *Environmental Modelling and Software* 45, 1-7.
- Giuliani, M., Castelletti, A., 2013. Assessing the value of cooperation and information exchange in large water resources systems by agent-based optimization, *Water Resources Research* 49, 3912-3926.
- GLOWA-Danube Project, 2014. German Ministry of Education and Research, <http://www.glowa-danube.de/de/opendanubia/allgemein.php>
- Gordon, L. J., Peterson, G. D., Bennett, E. M., 2008. Agricultural modifications of hydrological flows create ecological surprises, *Trends in Ecology & Evolution* 23(4), 211-219.
- Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F., 2010a. The ODD protocol: A review and first update. *Ecological Modelling* 221, 2760-2768.
- Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F., 2010b. ODD protocol template. <http://www2.econ.iastate.edu/tesfatsi/ODDTemplate.GrimmEtAl2010.pdf>
- Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S., Huse, G., Huth, A., Jepsen, J.U., Jrgensen, C., Mooij, W.M., Müller, B., Peer, G., Piou, C., Railsback, S.F., Robbins, A.M., Robbins, M.M., Rossmanith, E., Rger, N., Strand, E., Souissi, S., Stillman, R.A., Vabo, R., Visser, U., DeAngelis, D.L., 2006. A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* 198, 115126.
- Heckbert, S., Baynes, T., Reeson, R., 2010. Agent-based modeling in ecological economics, *Annals of the New York Acad. of Sci.* 1185, 39-53.
- Hewitson, B.C., Daron, J., Crane, R.G., Zermoglio, M.F., Jack, C., 2014. Interrogating empirical statistical downs-scaling, *Climatic Change* 122(4), 539-554.

- Hu, Y., Cai, X., DuPont, B., 2015. Design of a web-based application of the coupled multi-agent system model and environmental model for watershed management analysis using Hadoop, *Environmental Modelling & Software* 71(August), 149-162.
- IEM, 2015. Automated Surface Observing System (ASOS) Station AMW, Iowa Environmental Mesonet. Precipitation data: <https://mesonet.agron.iastate.edu/ASOS/>
- ISU, 2015a. Input-cost data (2005-20013), Extension, Iowa State University, Ames, IA. <http://www.extension.iastate.edu/agdm/crops/pdf/a1-20.pdf>
- ISU, 2015b. Corn-price data (1997-2013), Extension, Iowa State University, Ames, IA. <http://www.extension.iastate.edu/agdm/crops/pdf/a2-11.pdf>
- Jie, Y., Cardoso, D., Tesfatsion, L., Rehmann, C.R., Gutowski, W.J., 2016. WACCShed: Code and Data Repository Site. Available at: <https://bitbucket.org/waccproject/waccshedsoftwareplatform>
- Lansing, J.S., Kremer, J.N., 1993. Emergent properties of Balinese water temple networks - Co-adaptation on a rugged fitness landscape, *American Anthropology* 95(1), 97-114.
- Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Schneider, C., Taylor, W.W., 2007. Complexity of coupled human and natural systems, *Science* 317, 1513-1516.
- Loucks, D. P., 2015. Debates—perspectives on socio-hydrology: Simulating hydrologic-human interactions, *Water Resour. Res.* 51(6), 4789-4794.
- Madani, K., Hooshyar, M., 2014. A game theory-reinforcement learning (GT-RL) method to develop optimal operation policies for multi-operator reservoir systems., *J. Hydrol.* 519, 732-742.
- Montanari, A., 2015. Debates—Perspectives on socio-hydrology: Introduction, *Water Resour. Res.* 51(6), 4768-4769.
- Müller, B., et al., 2014. Standardised and transparent model descriptions for agent-based models: Current status and prospects, *Environmental Modelling & Software* 55(February), 156-163.

- Ng, T.L., Eheart, J.W., Cai, X.M., Braden, J.B., 2011. An agent-based model of farmer decision-making and water quality impacts at the watershed scale under markets for carbon allowances and a second-generation biofuel crop, *Water Resources Research* 47(9).
- Nikolic, V.V., Simonovic, S.P., Milicevic, D.B., 2013. Analytical support for integrated water resources management: A new method for addressing spatial and temporal variability, *Water Res. Management* 27(2), 401-417.
- Papajorgji, P., Beck, H. W., Braga, J. L., 2004. An architecture for developing service-oriented and component-based environmental models, *Ecological Modelling* 179(1), 61-76.
- Rosenzweig, B., Vörösmarty, C., Gutowski, W., Steiner, A.L., 2014. Joining scientists and stakeholders in regional earth system modeling, *EOS, Transactions American Geophysical Union*, 95(27), 247-248.
- Sarewitz, D., 2004. How science makes environmental controversies worse, *Environmental Science & Policy* 7, 385-403.
- Scharffenberg, W.A., 2013. Hydrological Modeling System User's Manual. United States Army Corps of Engineers, Davis, CA, 426 pp.
- Sivapalan, M., Savenije, H. H. G., Bloeschl, G., 2012. Socio-hydrology: A new science of people and water, *Hydrol. Process.* 26(8), 1270-1276.
- Tesfatsion, L., 2011. Agent-based modeling and institutional design, *Eastern Economic Journal* 37(1), 13-19.
- Tesfatsion, L., 2016a. Elements of dynamic economic modeling: Presentation and analysis, *Eastern Economic Journal*, to appear. DOI: <http://dx.doi.org/10.1057/eej.2016.2>
- Tesfatsion, L., 2016b. Agent-Based Modeling of Coupled Natural and Human Systems, <http://www2.econ.iastate.edu/tesfatsi/aagric.htm>.
- Tesfatsion, L., Jie, Y., Rehmann, C.R., Gutowski, W.J., 2016. WACC-Shed: A platform for the study of watersheds as dynamic coupled natural and human systems, Working Paper No. 15022, ISU Economics Department. Last updated: February 2016. Paper site: <http://www2.econ.iastate.edu/tesfatsi/WACCShedPaper.WPVersion.pdf>

Wendt, A.A., 2007. Watershed planning in central Iowa: An integrated assessment of the Squaw Creek watershed for prioritization of conservation practice establishment, M.S. Thesis, Environmental Science, ISU.

APPENDICES

Appendix A. Nomenclature Tables for the Watershed Application

A variable appearing within a model is classified as *endogenous* if its value is determined within the model. A variable appearing within a model is classified as *exogenous* if its value is set as an external input to the model.

Table A.4 provides a list of symbols, units of measurement, and abbreviated definitions for the *endogenous* variables appearing in the watershed application. Table A.5 provides a list of symbols, values, and abbreviated definitions for the *exogenous* variables appearing in the watershed application. In both tables, “F” designates the Farmer and “CM” designates the City Manager.

An exogenous variable in Table A.5 is labeled “Random” if it is randomly determined and “TF” if it is a treatment factor whose value is systematically varied across sensitivity study treatments. The possible realizations for the random variables are given in Section 6.2, and the ranges of tested values for the treatment factors are given in Section 7.

Table A.4: Endogenous variables for the watershed application

Symbol	Unit	Description
$A_{t:3}^{crop}$	acres	Cropland selected by F at $t:3$
$A_{t:3}^{ret}$	acres	Retention land selected by F at $t:3$
$A_{t:3}^{fal}$	acres	Fallow land selected by F at $t:3$
$c_{t:3}$	decimal %	F's cropland allocation percentage at $t:3$
$CCrop_{t:5}$	bushels	F's corn crop realized at $t:5$
$Cons_{t:7}^F$	bushels	F's actual corn consumption at $t:7$
$CSW_{t:5}$	\$	City social welfare for year t , determined at $t:5$
$FD_{t:5}$	\$	City flood damage realized during subperiod t_5
$H_{t:5}$	bushels/acre	Harvest yield realized during subperiod t_5
$\ell_{t:2}$	decimal %	CM's budget allocation percentage for levee investment at $t:2$
$LevInv_{t:2}$	\$	CM's levee investment at $t:2$
$LQ_{t:2}$	height in feet	Levee quality for year t determined at $t:2$
$M_{t:k}$	\$	F's money holdings at time $t:k \neq 1:1$
$M_{t:7}^{poss}$	\$	F's money holdings at $t:7$ if she sells her total crop
$Q_{p,t:5}$	ft ³ /s $\equiv$ cfs	Peak water discharge rate into city during subperiods t_1 - t_5
$r_{t:3}$	decimal %	F's retention-land allocation percentage at $t:3$
$RetSub_{t:2}^{poss}$	\$	CM's planned subsidy payment expenditures at $t:2$
$RetSub_{t:3}^{act}$	\$	CM's actual subsidy payment expenditures at $t:3$
$s_{t:2}$	decimal %	CM's budget allocation percentage for subsidy payments at $t:2$
$S_{t:7}^F$	\$	F's actual savings level determined at $t:7$
$SocServ_{t:2}^{poss}$	\$	CM's planned social service expenditures at $t:2$
$SocServ_{t:3}^{act}$	\$	CM's actual social service expenditures at $t:3$
$\tau_{t:2}$	\$/acre	Retention-land subsidy rate set by CM at $t:2$
$UOC_{t:7}$	utils	F's utility-of-consumption for year t , determined at $t:7$
$Value_{t:6}^{crop}$	\$	Market value of F's corn crop at $t:6$
$X_{t:k}^{CM}$	state	CM's state at time $t:k \neq 1:1$
$X_{t:k}^F$	state	F's state at time $t:k \neq 1:1$

Table A.5: Exogenous variables for the watershed application

Symbol	Value	Description
α_H	0.8 scalar	Scale parameter (harvest yield function)
A^F	4,000 acres	Farmland owned and managed by F
A^W	444 acres	City land area managed by CM
$B_{t:1}$	1M \$	City budget at time $t:1$ for each year t
$\bar{C}^F$	125 bushels	F's subsistence corn-consumption for each year t
CM	agent	City Manager residing in urban watershed area
CN^{bare}	86 scalar	Curve number for bare soil
CN^{mcrop}	78 scalar	Curve number for cropland with mature crop
CN^{fal}	70 scalar	Curve number for fallow land
CN^{ret}	10 scalar	Curve number for water-retention land
$CPrice_{t:6}$	Random, \$/bushel	Corn price realized at $t:6$
$CPrice^{low}$	3.66 \$/bushel	Low corn price realization (25% probability)
$CPrice^{mod}$	4.40 \$/bushel	Moderate corn price realization (50% probability)
$CPrice^{high}$	5.68 \$/bushel	High corn price realization (25% probability)
D	126 bushels	Farmer risk-tolerance parameter (utility-of-consumption function)
DCM	set	CM's decision domain for budget allocation percentages
$D^F(r^{max})$	set	F's decision domain for land allocation percentages
D^{opt}	26.72 in	Optimal rainfall parameter (harvest yield function)
δ	0.02 (2%)	Levee quality depreciation rate for each year t
F	agent	Farmer who owns the farmland
FD^{max}	$100B_{t:1}$ \$	Max possible flood damage parameter (flood damage function)
g	10^{-5} ft/\$	Parameter (levee quality update function)
H^{max}	168 bushels/acre	Maximum yield parameter (harvest yield function)
$InputCost_{t:1}$	Random, \$/acre	Per-acre corn planting input cost realized at $t:1$
$InputCost^{low}$	604.20 \$/acre	Low input cost realization (25% prob)
$InputCost^{mod}$	698.00 \$/acre	Moderate input cost realization (50% prob)
$InputCost^{high}$	815.50 \$/acre	High input cost realization (25% prob)
$LQ_{0:2}$	3 ft	Levee quality for year 0 determined at time 0:2
LQE	TF, scalar	Levee quality effectiveness
LScenario	20 yrs	Length of each environmental scenario in simulated years
$M_{1:1}$	4M \$	F's initial money holdings at time 1:1
NScenarios	31	Number of scenarios tested for each treatment
$Precip_{t:5}$	Random, inches	Precipitation pattern (hourly rainfall depth) from January 1 through October 15 of year t
ψ	1.0 scalar	Trade-off parameter (city social welfare function)
Q_{1n}	369.8 cfs	Ordinate parameter for 1% flood damage (flood damage function)
Q_{99n}	756.7 cfs	Ordinate parameter for 99% flood damage (flood damage function)
r^{max}	0.25 (25%)	F's maximum permitted retention land percentage
s	Random, array	Environmental scenario (input cost, precipitation pattern, and corn price for twenty successive simulated years)
$S^{Fo}=S^F(\theta^o)$	TF, \$	F's initial savings target (desired end-of-year money holdings)
σ_D	5 in	Width parameter (harvest yield function)
t	year index	$t = 1, 2, \dots$, with year $t \equiv$ time interval $[t, t+1)$
$t:k$	time point	$k = 1, \dots, 8$, with $t:1 \equiv t$ and $t:8 \equiv t+1$
t_k	time subperiod	$t_k = [t:k, t:k+1)$, $k = 1, \dots, 7$
θ^o	TF, scalar	Parameter determining the scale of S^{Fo}
$X_{1:1}^{CM}$	state	CM's state at the initial time 1:1
$X_{1:1}^F$	state	F's state at the initial time 1:1

Appendix B. Watershed Application Scenario Construction

As explained in Section 6.2, realizations for annual input costs, precipitation patterns, and corn prices in the watershed application are governed by independent stationary probability distributions. Based on these distributions, we constructed an ensemble $\mathcal{S}$ consisting of thirty-one possible environmental scenarios s using the following nine steps.

1. Three Java pseudo-random number generators initialized with 5000 distinct seeds were used to generate three groups of 5000 sequences of length twenty for input costs x , precipitation y , and corn price z , respectively, in accordance with the independent stationary probability distributions specified in Section 6.2.
2. The sequences from these three groups were then matched (in their order of generation) to form 5000 scenarios $\hat{s}$, each twenty simulated years in length, as illustrated below:

$$\hat{s} = ((x_1^{\hat{s}}, y_1^{\hat{s}}, z_1^{\hat{s}}), (x_2^{\hat{s}}, y_2^{\hat{s}}, z_2^{\hat{s}}), \dots, (x_{20}^{\hat{s}}, y_{20}^{\hat{s}}, z_{20}^{\hat{s}})) \quad (\text{B.1})$$

3. Without loss of generality, the numerical x , y , and z values in each scenario $\hat{s}$ were then replaced by indicator values equal to 0 for a low value, 1 for a moderate value, and 2 for a high value.
4. The resulting collection $\hat{\mathcal{S}}$ of 5000 scenarios $\hat{s}$ was then enlarged to 5003 scenarios by the addition of (i) the *extreme-low scenario* s^{low} consisting of all 0 values; (ii) the *normal scenario* s^{norm} consisting of all 1 values; and (iii) the *extreme-high scenario* s^{high} consisting of all 2 values. Let this augmented scenario set be denoted by $\hat{\mathcal{S}}^A$.
5. The distance $d(\hat{s}, s^{norm})$ of each scenario $\hat{s}$ in $\hat{\mathcal{S}}^A$ from the normal scenario s^{norm} was then calculated using a Hamming signed-distance measure that calculates the accumulated differences in successive scenario values. For example, given two-year scenarios

$$\hat{s} = ((0, 1, 1), (2, 1, 0)) \text{ and } s^{norm} = ((1, 1, 1), (1, 1, 1)) \quad (\text{B.2})$$

one has

$$\begin{aligned} d(\hat{s}, s^{norm}) &= (0 - 1) + (1 - 1) + (1 - 1) + (2 - 1) + (1 - 1) + (0 - 1) \\ &= -1. \end{aligned} \quad (\text{B.3})$$

6. Each scenario $\hat{s}$ in $\hat{\mathcal{S}}^A$ was then assigned to one and only one of the following thirty-one scenario clusters S_d in accordance with its signed distance $d = d(\hat{s}, s^{norm})$:

$$\begin{aligned} & -60, [-59, -15], [-14, -13], -12, -11, -10, \dots, -1 \\ & 0, 1, \dots, 10, 11, 12, [13, 14], [15, 59], 60 \end{aligned} \quad (\text{B.4})$$

7. For each scenario cluster S_d , a single representative scenario s_d was then selected from among those scenarios in S_d having the highest assigned probability. The resulting set $\mathcal{S}$ of thirty-one selected scenarios s_d was then taken to be the scenario ensemble for the watershed application.
8. The original probability assigned to each s_d in $\mathcal{S}$ was then re-normalized by setting this probability equal to the number of scenarios in cluster S_d , divided by 5003, so that the summation of the re-normalized probabilities attached to the thirty-one scenarios in $\mathcal{S}$ exactly equaled 1.0.
9. Each of the thirty-one scenarios s_d in $\mathcal{S}$ was then assigned a *scenario number* equal to its signed distance from the normal scenario s^{norm} . Note that the scenario number for s^{norm} is 0.

The resulting probability distribution for the thirty-one environmental scenarios in $\mathcal{S}$ is depicted in Fig. 5.

Appendix C. Harvest Yield in the Watershed Application

In the watershed application, the planting density (seeds/acre) is assumed to be constant over time. The harvest yield $H_{t:5}$ (bushels/acre) realized at time $t:5$ during each year t is therefore assumed to depend only on the precipitation pattern $\text{Precip}_{t:5}$:

$$H_{t:5} = H(\text{Precip}_{t:5}) \quad (\text{C.1})$$

The specification of the harvest yield function (C.1) will now be explained in greater detail. This specification is not an empirically-derived expression. Rather, it is a general qualitative depiction of key relationships.

As depicted in Fig. C.10, the harvest yield $H_{t:5}$ depends on the rainfall depth D_t during the growing season (May 1 through October 15), where D_t in turn is a function of the precipitation pattern $\text{Precip}_{t:5}$. The rainfall depth D_t is measured as the total accumulated rainfall during the growing season, measured in inches. The harvest yield attains its maximum value

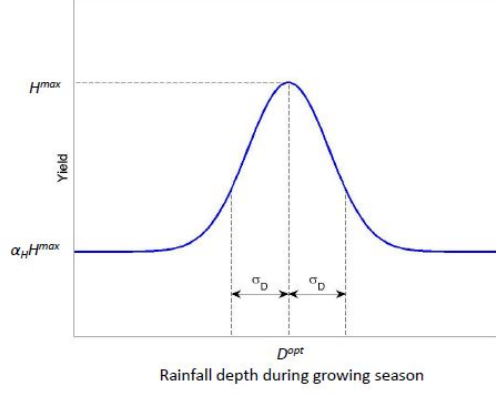


Figure C.10: Harvest yield $H(D)$ as a function of rainfall depth D , conditional on a constant planting density (seeds/acre)

H^{max} for a certain optimal amount of rainfall, D^{opt} . Below this optimal amount, harvest yield is reduced because the crops need more water. Above this optimal amount, harvest yield is reduced because the soil is too wet. For either low rainfall or high rainfall, harvest yield is a fraction α_H of H^{max} .

More precisely, the harvest yield (C.1) is calculated using the following Gaussian functional form:

$$H_{t:5} = H^{max} \cdot \left[\alpha_H + (1 - \alpha_H) \exp \left(- \frac{(D_t - D^{opt})^2}{\sigma_D^2} \right) \right] \quad (C.2)$$

The parameter σ_D in (C.2) controls the width of the bell curve.

The values for all of the parameters appearing in (C.2) are given in Table A.5. The value for H^{max} , 168 bushels/acre, is the Northwest Iowa district average corn yield from 2005-2014, as reported in AGDM (2015, Table 1).

Appendix D. City Flood Damage in the Watershed Application

In the watershed application, city flood damage $FD_{t:5}$ at time $t:5$ during each year t is determined as a function of the city's levee quality $LQ_{t:2}$ and the peak water discharge rate $Q_{p,t:5}$ into the city:

$$FD_{t:5} = FD(LQ_{t:2}, Q_{p,t:5}) \quad (D.1)$$

The precise manner in which the flood damage (D.1) is calculated will now be explained. This specification is not an empirically-derived expression. Rather, it is a general qualitative depiction of key relationships.

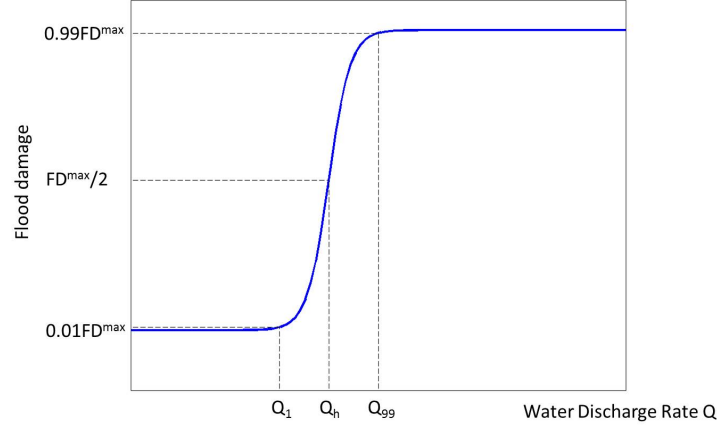


Figure D.11: City flood damage function FD as a function of the water discharge rate Q , conditional on a given levee quality LQ .

As illustrated in Fig. D.11, for any given levee quality, flood damage FD is assumed to be small until the water discharge rate Q reaches a point where the water flow begins to overtop the levee. As Q increases further, flood damage increases sharply. However, for large Q , the entire city is flooded and flood damage approaches the *maximum avoidable flood damage*, FD^{max} .

More precisely, the city flood damage function is specified as a logistic function:

$$FD(LQ, Q) = \frac{FD^{max}}{1 + \exp\left(-\frac{Q - Q_h(LQ)}{\Delta Q(LQ)}\right)} \quad (D.2)$$

where

$$Q_h(LQ) = \frac{Q_1(LQ) + Q_{99}(LQ)}{2} \quad (D.3)$$

and

$$\Delta Q(LQ) = \frac{Q_{99}(LQ) - Q_1(LQ)}{9.2} \quad (D.4)$$

and Q_1 and Q_{99} are the discharges at which the flood damage is 1% and 99%, respectively, of the maximum value. The discharge rates $Q_1(LQ)$ and $Q_{99}(LQ)$ are assumed to increase linearly with levee quality:

$$Q_1(LQ) = Q_{1n} + a_1 LQ \quad (D.5)$$

$$Q_{99}(LQ) = Q_{99n} + a_{99} LQ \quad (D.6)$$

where Q_{1n} and Q_{99n} are the values of Q_1 and Q_{99} with no levee, and a_1 and a_{99} are coefficients.

As detailed in Section 7.4, a common “levee quality effectiveness” value, $LQE = a_1 = a_{99}$, is set for the parameters a_1 and a_{99} in (D.5) and (D.6). This LQE value is systematically varied as a treatment factor across sensitivity experiments. The initializations maintained for all other parameters in the flood damage function (D.2) are provided in Table A.5.

Finally, the peak water discharge rate $Q_{p,t:5}$ in (D.1) for subperiod t_5 (October) is calculated as follows. Recall that the growing season for each year t is May 1 through October 15. The Hydrology application component for the watershed application is based on the HEC-HMS Hydrologic Modeling System (Feldman, 2000; Scharffenberg, 2013). Since the Hydrology application component runs on hourly time-steps, it calculates a water discharge rate for each simulated hour from January 1 through October 15. This hourly water discharge rate depends on the following factors: the hourly realized rainfall depth as determined by the realized precipitation pattern $\text{Precip}_{t:5}$ (low, mod, or high); the Farmer’s land allocation at time $t:3$; the *curve numbers (CNs)* for bare soil and fallow land; and the time-varying *CN* for cropland.⁸ The peak water discharge rate $Q_{p,t:5}$ is then calculated as the maximum hourly water discharge recorded from January 1 through October 15.

Appendix E. Farmer’s F-OFF and F-ON Decision Methods

Appendix E.1. F-OFF: Expected Consumption Maximization

The F-OFF Farmer solves two successive optimization problems in each year t , as follows:

- *First-Stage Optimization Problem:* At time $t:3$, conditional on state $X_{t:3}^F$, choose a land allocation $(c_{t:3}, r_{t:3}) \in D^F$ to maximize expected possible money holdings $\mathbb{E}[M_{t:7}^{\text{poss}}(c, \tau_{t:2}r) | X_{t:3}^F]$ for time $t:7$.
- *Second-Stage Optimization Problem:* At time $t:7$, conditional on state $X_{t:7}^F$, choose the maximum possible consumption level $\text{Cons}_{t:7}^F$ subject to the budget, subsistence, and savings-target constraints (31)–(33).

⁸The *CN* for cropland is set equal to the bare soil *CN* (86) on May 1 and is then decreased by 1 every ten simulated days until it reaches the mature crop *CN* (78) on July 20th. This mature crop *CN* is maintained for the cropland until harvest day, October 15, after which the *CN* for cropland reverts back to the bare soil *CN* (86).

An if-then decision rule will next be given that constructively solves the Farmer's first-stage optimization problem at time $t:3$.⁹ The statement of this if-then decision rule makes use of the following three calculations for *net earnings*, defined to be revenues minus costs.

The net earnings obtained by the Farmer from the sale of her corn crop at time $t:7$, per acre of her planted cropland, is given by

$$\text{NetEarn}_{t:7} = \text{CPrice}_{t:6} \cdot H(\text{Precip}_{t:5}) - \text{InputCost}_{t:1} \quad (\$/\text{acre}) \quad (\text{E.1})$$

Given the ensemble of possible environmental scenarios specified in Appendix B, the net earnings (E.1) can be either positive or negative. At time $t:3$ the Farmer calculates her *expected* net earnings per acre of planted cropland, conditional on her time $t:3$ state, as

$$\begin{aligned} E_{t:3}\pi^{crop} &= \mathbb{E} [\text{NetEarn}_{t:7} | X_{t:3}^F] \\ &= \mathbb{E} \text{CPrice} \cdot \mathbb{E} H(\text{Precip}) - \text{InputCost}_{t:1} \end{aligned} \quad (\text{E.2})$$

In addition, the Farmer knows that her expected net earnings per acre of retention land is given by the subsidy rate $\tau_{t:2}$ announced by the City Manager at time $t:2$, as determined in (7); i.e.,

$$E_{t:3}\pi^{ret} = \tau_{t:2} \quad (\text{E.3})$$

Finally, the Farmer knows that her expected net earnings per acre of fallow land is zero; i.e.,

$$E_{t:3}\pi^{fal} = 0 \quad (\text{E.4})$$

In addition, the statement of this if-then decision rule makes use of r^L , defined to be the largest value of r in $[0, r^{max}]$ that maximizes $c^{max}(\tau_{t:2}r)$ subject to $c^{max}(\tau_{t:2}r) + r \leq 1$, where $c^{max}(\tau_{t:2}r)$ is given in (19).¹⁰

Solution to Farmer's First-Stage Optimization Problem at Time $t:3$

Case 1: If $E_{t:3}\pi^{crop} > E_{t:3}\pi^{ret} > E_{t:3}\pi^{fal}$, plant the largest feasible portion of farmland as cropland, allocate the portion r^L to retention, and leave the remaining portion fallow; i.e., set

$$(c_{t:3}, r_{t:3}) = (c^{max}(\tau_{t:2}r^L), r^L) \quad (\text{E.5})$$

⁹A proof of this claim is provided in Tesfatsion et al. (2016, Appendix E.2).

¹⁰A constructive proof for determining the value of r^L is provided in Tesfatsion et al. (2016, Appendix E.2).

Case 2: If $E_{t:3}\pi^{crop} > E_{t:3}\pi^{ret} = E_{t:3}\pi^{fal}$, implying $\tau_{t:2} = 0$, plant the largest feasible portion of farmland as cropland and, with prob 1/2-1/2, allocate the rest to retention or fallow land; i.e., with prob 1/2-1/2 set

$$(c_{t:3}, r_{t:3}) = (c^{max}(0), \min\{1 - c^{max}(0), r^{max}\}) \\ \text{or } (c_{t:3}, r_{t:3}) = (c^{max}(0), 0) \quad (\text{E.6})$$

Case 3: If $E_{t:3}\pi^{ret} > E_{t:3}\pi^{fal} \geq E_{t:3}\pi^{crop}$, allocate the largest feasible portion of farmland to retention and leave the remainder fallow; i.e., set

$$(c_{t:3}, r_{t:3}) = (0, r^{max}) \quad (\text{E.7})$$

Case 4: If $E_{t:3}\pi^{ret} = E_{t:3}\pi^{fal} \geq E_{t:3}\pi^{crop}$, then with prob 1/2-1/2 allocate the largest feasible portion of farmland to retention and the remainder to fallow, or allocate all farmland to fallow; i.e., with prob 1/2-1/2 set

$$(c_{t:3}, r_{t:3}) = (0, r^{max}) \text{ or } (c_{t:3}, r_{t:3}) = (0, 0) \quad (\text{E.8})$$

Case 5: If $E_{t:3}\pi^{ret} \geq E_{t:3}\pi^{crop} > E_{t:3}\pi^{fal}$, allocate the largest feasible portion of farmland to retention, allocate the largest feasible portion of the remainder to cropland, and leave the rest fallow; i.e., set

$$(c_{t:3}, r_{t:3}) = (\min\{c^{max}(\tau_{t:2}r^{max}), 1 - r^{max}\}, r^{max}) \quad (\text{E.9})$$

Consider, now, the Farmer's second-stage optimization problem at time $t:7$. The Farmer's initial savings target for her money holdings at the end of year t takes form (35), where θ^o determines the scale of this target, $\mathbb{E}[\text{CPrice}]$ is the stationary expectation for the annual corn price, and $\bar{C}^F$ is the Farmer's annual subsistence need for corn.

Solution to Farmer's Second-Stage Optimization Problem at Time $t:7$

- If the Farmer's money holdings are insufficient to attain her subsistence consumption $\bar{C}^F$, i.e., if $M_{t:7}^{poss}(c_{t:3}, \tau_{t:2}r_{t:3}) < \text{CPrice}_{t:6} \cdot \bar{C}^F$, then

$$\text{Cons}_{t:7}^F = \frac{M_{t:7}^{poss}(c_{t:3}, \tau_{t:2}r_{t:3})}{\text{CPrice}_{t:6}} < \bar{C}^F \quad (\text{E.10})$$

and the Farmer exits the watershed at the end of subperiod t_7 .

- If the Farmer's money holdings are sufficient to attain $\bar{C}^F$ but not to attain $S^F(\theta^o)$, i.e., if $\text{CPrice}_{t:6} \cdot \bar{C}^F \leq M_{t:7}^{poss}(c_{t:3}, \tau_{t:2}r_{t:3}) < S^F(\theta^o) + \text{CPrice}_{t:6} \cdot \bar{C}^F$, then

$$\text{Cons}_{t:7}^F = \bar{C}^F \text{ and } S_{t:7}^F = M_{t:7}^{poss}(c_{t:3}, \tau_{t:2}r_{t:3}) - \text{CPrice}_{t:6} \cdot \bar{C}^F \quad (\text{E.11})$$

- If the Farmer's money holdings are sufficient to attain $\bar{C}^F$ and $S^F(\theta^o)$, i.e., if $M_{t:7}^{poss}(c_{t:3}, \tau_{t:2}r_{t:3}) \geq S^F(\theta^o) + \text{CPrice}_{t:6} \cdot \bar{C}^F$, then

$$\text{Cons}_{t:7}^F = \frac{[M_{t:7}^{poss}(c_{t:3}, \tau_{t:2}r_{t:3}) - S^F(\theta^o)]}{\text{CPrice}_{t:6}} \text{ and } S_{t:7}^F = S^F(\theta^o) \quad (\text{E.12})$$

Appendix E.2. F-ON: Expected Utility-of-Consumption Maximization

Without loss of generality, the Farmer's implementation of the F-ON decision method will be carefully explained for time 1:3 during the initial year 1. This problem formulation can easily be generalized to apply to time $t:3$ for an arbitrary year $t \geq 1$.

Suppose the Farmer at time 1:3 in year 1 is considering the selection of her land allocation, consumption, and savings decisions for year 1, denoted as follows:

$$d^F = (c_{1:3}, r_{1:3}, \text{Cons}_{1:7}^F, S_{1:7}^F) \quad (\text{E.13})$$

However, the Farmer realizes that, between her choice of land allocation percentages at time 1:3 and her choice of consumption and savings decisions at time 1:7, she will acquire additional information: namely, she will observe the realization of a precipitation pattern $\text{Precip}_{1:5}$ and a corn price $\text{CPrice}_{1:6}$. Consequently, in order to make efficient use of her information, she should choose the decisions in (E.13) as functions of her available information.

The Farmer's state $X_{1:3}^F$ at time 1:3 includes her state $X_{1:1}^F$ at time 1:1, her input-cost observation $\text{InputCost}_{1:1}$ at time 1:1, and the City Manager's subsidy-rate $\tau_{1:2}$ for year 1 as announced at time 1:2. That is,

$$X_{1:3}^F = \{X_{1:1}^F, \text{InputCost}_{1:1}, \tau_{1:2}\} \quad (\text{E.14})$$

The Farmer's state $X_{1:1}^F$ at time 1:1 includes all structural aspects of her decision environment, including the value of θ^o that affects the scale of her initial savings target (35) for the end of year 1.

At time 1:3 the Farmer selects $(c_{1:3}, r_{1:3})$ from her decision domain $D^F(r^{max})$ in (11) as functions $(c(X_{1:3}^F), r(X_{1:3}^F))$ of her time-1:3 state $X_{1:3}^F$. However, the

Farmer also understands that her state $X_{1:7}^F$ at time 1:7 will be larger than her state $X_{1:3}^F$ at time 1:3, as follows:

$$X_{1:7}^F = \{X_{1:3}^F, \text{Precip}_{1:5}, \text{CPrice}_{1:6}\} \quad (\text{E.15})$$

Consequently, to determine an optimal solution for her expected utility-of-consumption (UOC) maximization problem at time 1:3, the Farmer must consider state-contingent decision *functions* of the following form:

$$d^F(\mathbf{X}_1) = (c(X_{1:3}^F), r(X_{1:3}^F), \text{Cons}^F(X_{1:7}^F), S^F(X_{1:7}^F)) \quad (\text{E.16})$$

The F-ON Farmer's expected UOC maximization problem at time 1:3 thus takes the following form:

$$\max \mathbb{E}[u(\text{Cons}_{1:7}^F) \mid X_{1:3}^F] \quad (\text{E.17})$$

with respect to choice of d^F subject to the constraints

$$d^F = d^F(\mathbf{X}_1) \quad (\text{E.18})$$

$$0 \leq c_{1:3} \quad (\text{E.19})$$

$$0 \leq r_{1:3} \leq r^{max} \quad (\text{E.20})$$

$$c_{1:3} + r_{1:3} \leq 1 \quad (\text{E.21})$$

$$M_{1:3} = M_{1:1} + \tau_{1:2} \cdot r_{1:3} \cdot A^F \quad (\text{E.22})$$

$$M_{1:4} = M_{1:3} - \text{InputCost}_{1:1} \cdot c_{1:3} \cdot A^F \quad (\text{E.23})$$

$$M_{1:4} \geq 0 \quad (\text{E.24})$$

$$M_{1:7}^{poss} = M_{1:4} + \text{CPrice}_{1:6} \cdot H_{1:5} \cdot c_{1:3} \cdot A^F \quad (\text{E.25})$$

$$\text{Cons}_{1:7}^F \geq \bar{C}^F \quad (\text{E.26})$$

$$\text{CPrice}_{1:6} \cdot \text{Cons}_{1:7}^F = M_{1:7}^{poss} - S_{1:7}^F \quad (\text{E.27})$$

$$S_{1:7}^F = \theta_{1:7} \cdot \mathbb{E}[\text{CPrice}] \cdot \bar{C}^F \quad (\text{E.28})$$

$$\theta_{1:7} = \max_{0 \leq \rho \leq 1} \{\rho \cdot \theta^o \mid \text{F's problem has a solution}\} \quad (\text{E.29})$$

Detailed explanations for constraints (E.19) through (E.28) are provided in Section 6.3. However, constraint (E.29) needs further explanation. Suppose the Farmer's savings target is fixed at the initial savings target level $S^F(\theta^o)$ by setting $\theta_{1:7} = \theta^o$ in (E.28) and by omitting the ratcheting constraint (E.29). Then the above expected UOC maximization problem will

fail to have a solution if there exists a feasible state $X_{1:7}$ in which the Farmer is unable to attain both her initial savings target and her subsistence consumption level. Consequently, it is instead assumed that the F-ON Farmer is able to ratchet down her savings target towards zero in any state $X_{1:7}$ in which she is unable to attain both her initial savings target and her subsistence consumption level. This state-contingent downward ratcheting is captured in constraint (E.29).

It could happen for some feasible time-1:7 state $X_{1:7}$ that the F-ON Farmer is unable to attain her subsistence consumption level even if she ratchets her savings target all the way down to zero. For any such state, the Farmer at time 1:3 plans to consume as much as she can at time 1:7 followed immediately by a permanent departure from the watershed.

For analytical tractability, the F-ON Farmer's decision domain $D^F(r^{max})$ in (11) – represented by constraints (E.19) through (E.21) in the above expected UOC maximization problem – is approximated by a finite subset $AD^F(r^{max})$, constructed as follows. First, the range of possible values for the F-ON Farmer's cropland portion c and retention land portion r are restricted to the following subsets:

$$c \in \mathbb{C} = \{0.0, 0.1, \dots, 0.9, 1.0\} \quad (\text{E.30})$$

$$r \in \mathbb{R}(r^{max}) = \{0.0, 0.2, \dots, 0.8, 1.0\} \cdot r^{max} \quad (\text{E.31})$$

Second, $AD^F(r^{max})$ is constructed as

$$AD^F(r^{max}) = \{(c, r) \mid c \in \mathbb{C}, r \in \mathbb{R}(r^{max}), c + r \leq 1\} \quad (\text{E.32})$$

Finally, if the expected UOC maximization problem (E.17) for any year t has multiple possible solutions, the Farmer uses a pseudo-random number generator to select one of the solutions at random.

Appendix F. City Manager's CM-ON Decision Method

At time $t:2$ in each year t , conditional on state $X_{t:2}^{CM}$, the City Manager selects a budget allocation $(s_{t:2}, \ell_{t:2}) \in D^{CM}$ to maximize expected city social welfare $\mathbb{E}[\text{CSW}_{t:5} \mid X_{t:2}^{CM}]$ subject to system constraints,¹¹ where D^{CM} is given by (5) and $\text{CSW}_{t:5}$ is given by (26).

¹¹Levee investment at time $t:2$ is a physical capital investment that could yield a stream of returns over both current and future years in the form of increased flood-damage miti-

The CM-ON City Manager knows that city flood damage $FD_{t:5}$ at time $t:5$ depends in part on his budget allocation decision $(s_{t:2}, \ell_{t:2})$ at time $t:2$. Specifically, he knows that flood damage is determined by the functional relationship (24), reproduced here for ease of reference:

$$FD_{t:5}(\ell_{t:2}, c_{t:3}, r_{t:3}) = FD(LQ(\ell_{t:2}), Q_{p,t:5}(c_{t:3}, r_{t:3})) \quad (F.1)$$

where the peak water discharge rate Q_p is given by

$$Q_{p,t:5}(c_{t:3}, r_{t:3}) = Q_p(\text{Precip}_{t:5}, A^{crop}(c_{t:3}), A^{ret}(r_{t:3}), A^{fal}(c_{t:3}, r_{t:3})) \quad (F.2)$$

Thus, $FD_{t:5}$ depends through $Q_{p,t:5}$ on the Farmer's land allocation decision at $t:3$, which in turn depends on the City Manager's retention subsidy decision $s_{t:2}$; and $FD_{t:5}$ depends on the levee quality $LQ(\ell_{t:2})$, which in turn depends on the City Manager's levee investment decision $\ell_{t:2}$.

The CM-ON City Manager's state $X_{t:2}^{CM}$ at time $t:2$ includes the Farmer's initial state, $X_{t:1}^F$, and the input cost realization $\text{InputCost}_{t:1}$. In addition, however, it also includes all structural aspects of the CM's decision environment, including in particular the independent stationary probability distributions governing the realizations of the precipitation pattern $\text{Precip}_{t:5}$ and the corn price $\text{CPrice}_{t:6}$. Thus, the CM-ON City Manager at time $t:2$ is able to calculate the Farmer's *response functions* $c(X_{t:3}^F)$ and $r(X_{t:3}^F)$ for $c_{t:3}$ and $r_{t:3}$ at time $t:3$ as functions of the Farmer's time- $t:3$ state, given by¹²

$$X_{t:3}^F = \{X_{t:1}^F, \text{InputCost}_{t:1}, s_{t:2}\} \quad (F.3)$$

However, the CM-ON City Manager at time $t:2$ still does not know for sure the future flood damage level $FD_{t:5}$ as a function of his decisions $s_{t:2}$ and $\ell_{t:2}$ at time $t:2$ because $FD_{t:5}$ in (F.1) also depends (through $Q_{p,t:5}$) on the random event $\text{Precip}_{t:5}$. Thus, from the vantage point of $t:2$, year- t CSW is an $(s_{t:2}, \ell_{t:2})$ -conditioned random variable of the form

$$\text{CSW}(s_{t:2}, \ell_{t:2}, c(X_{t:3}^F), r(X_{t:3}^F), \text{Precip}_{t:5}) \quad (F.4)$$

gation. Ideally, this full stream of returns should be taken into account in the specification of CSW. However, for the watershed application, it is assumed for simplicity that the CM-ON City Manager at each time $t:2$ only considers year- t returns to levee investment.

¹²In game theory terms, this makes the CM-ON City Manager a Stackelberg leader, able to determine the response of the Farmer-follower at time $t:3$ to each of his possible decisions $s_{t:2}$ at time $t:2$.

where the only aspect that is random as of time $t:2$ is the precise realization for $\text{Precip}_{t:5}$. Consequently, at time $t:2$ the CM-ON City Manager forms an *expectation* for year- t CSW, conditional on each of his possible choices for $(s_{t:2}, \ell_{t:2})$, where the expectation is taken with respect to the known probability distribution for $\text{Precip}_{t:5}$.

The CM-ON City Manager's expected CSW maximization problem at time $t:2$ thus takes the following form:

$$\max_{s_{t:2}, \ell_{t:2}} \mathbb{E}[\text{CSW}(s_{t:2}, \ell_{t:2}, c(X_{t:3}^F), r(X_{t:3}^F), \text{Precip}_{t:5}) \mid X_{t:2}^{CM}] \quad (\text{F.5})$$

subject to (F.3), the calculated forms of the response functions $c(X_{t:3}^F)$ and $r(X_{t:3}^F)$, and the constraints

$$0 \leq s_{t:2} \quad (\text{F.6})$$

$$0 \leq \ell_{t:2} \quad (\text{F.7})$$

$$s_{t:2} + \ell_{t:2} \leq 1 \quad (\text{F.8})$$

For analytical tractability, the City Manager's decision domain D^{CM} in (5) – represented by constraints (F.6) through (F.8) above – is approximated by a finite subset AD^{CM} , constructed as follows. The range of possible values for the City Manager's subsidy portion s and levee investment portion ℓ are restricted to the following subsets:

$$s \in \mathbb{S} = \{0.0, 0.1, \dots, 0.9, 1.0\} \quad (\text{F.9})$$

$$\ell \in \mathbb{L} = \{0.0, 0.1, \dots, 0.9, 1.0\} \quad (\text{F.10})$$

Then AD^{CM} is given by

$$AD^{CM} = \{(s, \ell) \mid s \in \mathbb{S}, \ell \in \mathbb{L}, s + \ell \leq 1\} \quad (\text{F.11})$$

Finally, if the expected CSW maximization problem (F.5) for any year t has multiple possible solutions, the CM-ON City Manager uses a pseudo-random number generator to select one of these solutions at random.